Niclas Hjerdt

Soil moisture distribution predicted from topography and gamma radiation
Niclas Hjerdt

Soil moisture distribution predicted from topography and gamma radiation
ABSTRACT
SOIL MOISTURE DISTRIBUTION PREDICTED FROM TOPOGRAPHY AND GAMMA RADIATION

In this study, GIS methods were used in order to evaluate different wetness indicators - topographic indices and airborne gamma radiation measurements - from their ability to distinguish wet areas from other areas. As a surrogate measure of extreme wetness, the occurrence of mires from land use maps were used. The evaluation of each wetness indicator was made in two ways. First, mire and non mire values for each measure was tested for similarity. Then, predicted mire maps were produced by defining mire area class limits (threshold values), which gave the same fraction of mire area in the catchments as in the land use maps. The predicted mire maps were then compared to the map showing mires from land use surveys. The best predictions were made by the drainage efficiency index (46.8% correct mires of all mire cells), which was proposed as an alternative to the ln(a/tanβ) index (the TOPMODEL index) and slope. This index quantified the downslope drainage ability for any point in the catchment, which is likely to be important for the wetness status. Mire predictions from K-40 gamma radiation were correlated to the different geological regions in the area and did not reproduce an accurate overall mire pattern. The TOPMODEL index class limits were strongly correlated to the fraction of mire area, which prevented it from being a good indicator of mires. It did not reproduce accurate amounts of area in the subbasins from a global threshold value. However, the general pattern of the predicted mires agreed relatively well with the pattern of actual mires from the land use map.

REFERAT
FÖRDELNING AV MARKFUKTIGHET SIMULERAD UR TOPOGRAFI OCH GAMMASTRÄNLNING


Copyright © 1997, Niillas Hjerdt and the Institute of Earth Sciences, Hydrology, Uppsala University. Printed at the Department of Earth Sciences, Uppsala/Sweden 1997
Contents

ABSTRACT .......................................................................................................................... II

REFERAT .............................................................................................................................. II

CONTENTS .......................................................................................................................... III

INTRODUCTION ................................................................................................................... 1

BACKGROUND .................................................................................................................... 1

PEATLAND HYDROLOGY ...................................................................................................... 3

TOPOGRAPHY AND SOIL MOISTURE ............................................................................... 3

SOIL MOISTURE FROM REMOTELY SENSED DATA: NATURAL GAMMA RADIATION ............ 6

METHODS ............................................................................................................................. 10

STUDY AREA ....................................................................................................................... 10

DATA DESCRIPTION AND PRE-PROCESSING METHODS ................................................... 12

Topographic data ................................................................................................................ 13

Gamma radiation data .......................................................................................................... 13

Land use data ...................................................................................................................... 14

Geologic data ...................................................................................................................... 14

Hydrologic data .................................................................................................................. 15

DIGITAL TERRAIN ANALYSIS AND INDEX CALCULATIONS ............................................. 15

SPATIAL ANALYSIS FROM A GIS PLATFORM .................................................................... 17

TESTING THE BASIC HYPOTHESES .................................................................................. 18

Comparing the distributions of mire and non mire cells ..................................................... 19

Predicting the spatial distribution of mires ........................................................................ 20

OTHER TOPOGRAPHIC INDICES ....................................................................................... 20

THE INFLUENCE OF GEOLOGY ......................................................................................... 21

RESOLUTION EFFECTS ...................................................................................................... 21

RESULTS ............................................................................................................................... 22

TESTING THE HYPOTHESES ............................................................................................. 24

OTHER INDICES .................................................................................................................. 28

GEOLOGY ............................................................................................................................. 31

RESOLUTION ....................................................................................................................... 31

DISCUSSION ......................................................................................................................... 33

CONCLUSIONS .................................................................................................................... 36

ACKNOWLEDGEMENTS ...................................................................................................... 36

REFERENCES ...................................................................................................................... 37

SPATIAL DATA SOURCES ................................................................................................. 39

ADRESSES .......................................................................................................................... 39

APPENDIX A ....................................................................................................................... 40

APPENDIX B ....................................................................................................................... 41

APPENDIX C ....................................................................................................................... 43
Introduction

Soil moisture is recognized as a key variable in environmental sciences. Understanding catchment hydrology is basically a matter of knowing the quantity and distribution of water in the soil. This knowledge is not easily obtained, since soil wetness is highly variable due to soil heterogeneity, topography, vegetation cover and the non-uniformity of input from rainfall and snowmelt. Nevertheless, soil wetness controls important hydrological variables such as evaporation, groundwater recharge and runoff in most hydrological models. Consequently, there is a great interest in the development of techniques for obtaining spatially distributed estimates of soil moisture.

Traditionally, soil moisture has been difficult to measure in a way that is representative of more than one point. As Engman and Gurney [1991] points out, averages of point measurements are used to characterize the soil moisture of an area, but these averages seldom yield information that is representative of other hydrologic processes (e.g. evapotranspiration, runoff, groundwater recharge). Today, a main goal in hydrological research is to advance operational routines for obtaining spatially distributed soil moisture measurements. This involves the development of various remote sensing methods, both on satellite and airborne platforms, which have a potential of providing spatial information at a relatively low cost. However, many hydrologists have chosen to focus their attention at yet another way of obtaining spatially distributed soil moisture information. If temporal variability is neglected, topographic maps are likely to contain information on the relative distribution of soil moisture in natural catchments. One way of using this information has been to develop indices that scale the influence of topography on moisture distribution at any point from knowledge of areal mean or representative values over a given area (Moore et al., 1993).

This study examined the use of these two different types of spatially distributed information commercially available for predicting the soil moisture pattern in a forested till catchment. The fundamental aims are to (1) investigate the relationship between landscape topography, in the form of topographic indices, and soil moisture regimes; (2) examine the relationship between soil wetness and natural gamma radiation emitted from the bedrock and mineral soil (estimated from airborne gamma-ray spectrometer measurements); and (3) appreciate the effects on these relationships as data resolution and geological setting change. As mires and peatland most often constitute the wettest parts of Scandinavian catchments, the distribution of mires from land use maps is used as surrogate for soil moisture measurements. The general work plan departed from two main hypotheses:

1. The topographically based TOPMODEL wetness index, which estimates the depth to the water table at any point in a catchment, is higher for predominantly wet areas (i.e. mires) than for other areas.
2. The natural gamma radiation, originating from the bedrock and mineral soil, is lower from predominantly wet areas (i.e. mires) than from other areas.

The area selected for this study was the former IHD representative basin Kassjöån in north central Sweden. The study continued from the results obtained in a previous study by Rodhe and Seibert [1996], in which the distribution of mires in four subbasins of Kassjöån was compared to the distribution of topographic index values. Their results suggested that topographic gradient (tanB) is a somewhat better indicator of mire occurrence than the
TOPMODEL index although neither attribute explain more than 40-50% of the actual mire area when each measure is set to reproduce the actual mire area in the catchments.

This study continued to examine topographic gradient as an alternative wetness index. Furthermore, as downslope conditions are likely to be important for the development of mires, an index which accounts for downslope drainage efficiency was proposed and tested. This index (henceforth referred to as the drainage efficiency index) quantifies in a simple manner the flowpath morphology locally downslope any point in a catchment.

Since this study aimed to evaluate the performance of various types of spatial information for predicting the soil moisture distribution, one important task was to find adequate evaluation methods which are able to quantify the success of different wetness indicators. Some of the measures used originate from general statistics while others have been developed specifically for this task. Basically, the performance of any wetness indicator was evaluated in two ways: (i) mire and non mire areas were separated in index and gamma radiation maps and the distributions were compared using general statistics, and if mire and non mire distributions were significantly different from each other, this signified a unique relationship between mire occurrence and index/gammaray data; (ii) a class limit was defined for each of the index and gamma radiation data sets, yielding predictive maps of mire cells that could be compared to the actual mire map. Since the relevant index/gammaray class limits relating to the specific soil water regime (i.e. mires) is not known a priori, these class limits, expressed as threshold values, had to be defined. Threshold values were selected to reproduce the same amount of mire area as given in the land use map. The predictive mire maps were then analysed both quantitatively (i.e. the amount of mire area predicted in each subbasin) and qualitatively (i.e. the location of the predicted mires) - and the results from these two evaluation methods were compared and discussed.

In comparison, topographic attributes and gamma radiation data differ systematically in the type of information they provide. Topographic attributes express flow convergence, divergence and gravitational driving force on the redistribution of soil water, while gamma radiation data estimates a spatially (and temporally) variable electromagnetic signal and the equally variably environmental interference on this signal. Moreover, the gamma radiation data used in this study represent an instant in time, possibly containing soil moisture information from that specific moment, while topography may provide information about the predominant and relative soil moisture regimes of the area.

Since the study involved three different fields in hydrology, peatland hydrology, topography and remote sensing, it is necessary to give an introductory treatment of these fields before the general methods of the study are described.
Background

Peatland hydrology
Obtaining spatially distributed soil moisture content from field measurements is a difficult and expensive task. Therefore, this report uses the assumption that mires constitute a wet extreme in a landscape, while non mire areas are dryer in general, thus facilitating the use of readily available land use data for validation purposes. How valid is the method of using mire occurrence as an extreme measure of wetness conditions? In this context, the processes that control peat formation need to be considered.

Historically, mires have been modelled from two different angles: the biological approach and the hydrological approach (Skellern et al., 1995). The biological model simulates net peat depth by considering the balance between vegetation growth rate and the rate of plant decomposition. In this approach an equilibrium is achieved when the rate of decomposition is matched by the rate of net primary production. The hydrological approach, on the other hand, assumes that the mire surface is in equilibrium between the inflows from net rainfall and the groundwater outflows. Continuous peat growth requires that the decomposition process is halted so that the lowest layer of the acrotelm (i.e. the oxidizing top layer of the mire) becomes the uppermost layer of the catotelm (i.e. the anoxic lower layer of the mire). Consequently, it follows that a continuous rise of the (mire) water table is the decisive prerequisite for peat formation (Eggelsmann et al., 1993).

In raised mires, drainage conditions are essentially controlled only by the conductivity in the upper and lower peat deposits, since the water table of raised mires does not receive inputs from the surrounding water table. In sloping and spring-water mires, on the other hand, the surrounding topography has a more clear effect on peat forming processes. Here, an increase in the height of the groundwater table can also result from external inputs. In addition, the plant cover and underlying peat layers have a relatively low hydraulic conductivity, which has a profound feedback effect on the water table. As the upper limit of the catotelm rises there is a positive feedback between mire growth and the water table rise (Eggelsmann et al., 1993). Therefore, it is likely that sloping mires are affected by topographic effects to a great extent. As topography dictates much of the soil water regime, it is an important factor to the total potential for mire formation.

Skellern et al. [1995] use a method described by Kirkby et al. [1995] in which both biological and hydrological prerequisites for peat formation are combined in a climatic potential parameter. Furthermore, Skellern et al. add the topographic influence on peat formation by uniting the climatic potential with a topographic index, a/s, where a is the upslope area drained per unit contour length, and s is the surface gradient. Thus, it is interesting to notice that this model couples the concepts in peatland hydrology with semi-distributed catchment modelling, such as the TOPMODEL, where the depth to the groundwater table at any position in a landscape is estimated from a topographic index.

Topography and soil moisture
There are many factors affecting the redistribution of soil water in a catchment. Moore et al. [1993] conclude the most important: (1) soil characteristics (conductivity, soil thickness, effective porosity, macropores etc.); (2) topography (slope, aspect, curvature, topographic shading, position); (3) vegetation (spatial and temporal variation); and (4) climate (precipitation, radiation and temperature). These variables cause an infinite number of combinations within a very limited area, which is highly inconvenient from a modeller's point
of view. In addition, spatially distributed data are typically not available for all of these variables. Thus, any model includes a degree of simplification and approximation of system behavior.

The index approach is based on simplified representations of the underlying physics of landscape processes but includes the key factors that modulate system behavior (Moore et al., 1993). It is assumed that all other factors not explicitly accounted for by the index either have low variance within the landscape or are correlated to any of the included factors. Dawes and Short [1994] state that in some cases, a sophisticated treatment of topography can be balanced with little or no treatment of small-scale random soil heterogeneity, simply because much of the soil formation processes are tightly connected with topography. In other words, much of the variation in soil characteristics may be implicitly included in topography itself. This conclusion is also supported by other studies (e.g. in Wood et al., 1990).

Table 1. Primary topographic attributes which can be derived from elevation data using digital terrain methods (adapted from Moore et al., 1993). *This attribute is represented by one value for the entire catchment.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Definition</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude</td>
<td>Elevation</td>
<td>Climate, vegetation, potential energy</td>
</tr>
<tr>
<td>Upslope height</td>
<td>Mean height of upslope area</td>
<td>Potential energy</td>
</tr>
<tr>
<td>Aspect</td>
<td>Slope azimuth</td>
<td>Solar insolation, evapotranspiration, flora and fauna distribution and abundance</td>
</tr>
<tr>
<td>Slope</td>
<td>Gradient</td>
<td>Overland and subsurface flow velocity and runoff rate, precipitation, vegetation, geomorphology, soil water content</td>
</tr>
<tr>
<td>Upslope slope</td>
<td>Mean slope of upslope area</td>
<td>Runoff velocity</td>
</tr>
<tr>
<td>Dispersal slope</td>
<td>Mean slope of dispersal area</td>
<td>Rate of soil drainage</td>
</tr>
<tr>
<td>Catchment slope*</td>
<td>Average slope over the catchment</td>
<td>Time of concentration</td>
</tr>
<tr>
<td>Upslope area</td>
<td>Catchment area above a short length of contour</td>
<td>Runoff volume, steady state runoff rate</td>
</tr>
<tr>
<td>Dispersal area</td>
<td>Area downslope from a short length of contour</td>
<td>Soil drainage rate</td>
</tr>
<tr>
<td>Catchment area*</td>
<td>Area draining to catchment outlet</td>
<td>Runoff volume</td>
</tr>
<tr>
<td>Flow path length</td>
<td>Maximum distance of water flow to a point in the catchment</td>
<td>Erosion rates, sediment yield, time of concentration</td>
</tr>
<tr>
<td>Upslope length</td>
<td>Mean length of flow paths from a point in the catchment to the outlet</td>
<td>Erosion rates, sediment yield, time of concentration</td>
</tr>
<tr>
<td>Dispersal length</td>
<td>Distance from a point in the catchment to the outlet</td>
<td>Impedence to soil drainage</td>
</tr>
<tr>
<td>Catchment length*</td>
<td>Distance from highest point to the outlet</td>
<td>Overland flow attenuation</td>
</tr>
<tr>
<td>Profile curvature</td>
<td>Slope profile curvature</td>
<td>Flow acceleration, erosion/deposition rate, geomorphology</td>
</tr>
<tr>
<td>Plan curvature</td>
<td>Contour curvature</td>
<td>Converging/diverging flow, soil water content, soil characteristics</td>
</tr>
</tbody>
</table>

Nevertheless, interactions between topography, soil and water constitute a complicated system with multiple threshold processes and non-linear properties. It is therefore natural to question how useful a static index can be to describe a temporally dynamic system such as the redistribution of soil water (Burt and Butcher, 1986). Another problem with the index approach is illuminated by Wolock and Price [1994], who demonstrate that index calculations carried out in different scales and grid resolutions affect the distribution of topographic
indices. The reasons are that topographic indices attempt to characterize the topography of natural landscapes, which is inherently scale dependent. Consequently, depending on the scale and resolution of the digital elevation model (DEM) from which indices are derived, the resulting index values will reflect this choice. The problem is that there is no general "best choice" for all catchments since each landscape have its own representative scale. As a result, researchers are looking for a way to formalize the procedure of selecting an appropriate scale and resolution for distributed modelling.

According to Moore et al. [1991], topographic indices (or attributes) can be classified into two different categories: (1) primary attributes (table 1); and (2) compound (or secondary) attributes. Primary attributes include both attributes that quantify the geometric shape of a topographic surface, and conceptual attributes (i.e. measures of certain positional characteristics).

In the first attempts to quantify the geometry of the land surface, geomorphologists explored different calculation methods. Evans [1980] describes the automatization of a local interpolation method for deriving first and second derivates (i.e. slope and curvature) of the land surface at any point. Heerdegen and Beran [1982] uses this method to locate quickflow source areas, but their results were only partly successful. Zevenbergen and Thorne [1987] modifies the interpolation method by fitting a cubicepolynom to the DEM instead of Evans' quadratic polynom, but it has never been confirmed whether this modification actually describes the surface better than Evans' method. In both methods the different primary attributes are described as functions of the coefficients in the fitted polynom.

Compound (or secondary) attributes can be either simple combinations of primary attributes (e.g. the compound curvature, which is the difference between plan- and profile curvature) or theoretically derived attributes, based on theoretical descriptions of physical processes. Sinai et al. [1981] demonstrate a high correlation between compound curvature and soil moisture in a gently sloping agricultural region. The foremost example of a theoretically derived compound index is the TOPMODEL wetness index, which reads:

\[ I = \ln(a/\tan\beta) \]

where \( \ln \) is the natural logarithm, \( a \) is the upslope drainage area per unit width of contour, and \( \tan\beta \) is the topographic gradient (slope). This index was originally developed to quantify the portion of saturated areas within catchments, based on the variable contributing source area concept (Beven et al., 1995). In doing so, it makes use of simple steady-state drainage theory, which is outlined in Appendix C.

There have been a few attempts to validate the ability of the TOPMODEL index to predict the depth to the water table in natural catchments and results vary greatly (Seibert, 1997; Burt and Butcher, 1986; Anderson and Kneale, 1982). Burt and Butcher [1986] conclude that a combination of the TOPMODEL index and plan curvature make the most satisfactory estimation of the soil moisture distribution, but only at times of high soil wetness. Anderson and Kneale [1982] report that the TOPMODEL index fits steeper slopes better where downslope conditions are of minor importance in comparison with the topographic gradient. This is indicated by large temporal and spatial shifts for regions of soil-water convergence on flat hillslopes.

Yet another approach is taken by Gessler et al. [1995] and Merot et al. [1995] in their attempt to correlate the TOPMODEL index with soil water regimes determined from soil surveys. Both these studies follow the reasoning from above that topography is a driving force of soil formation processes, thus implicitly contain information about the soil.
Barling et al. [1994] raise an important issue in their proposal of a quasi-dynamic wetness index. They question the applicability of the TOPMODEL index, which relies heavily on the assumption of steady-state flow conditions, when this assumption is rarely (if ever) fulfilled in reality. As an extension of this argument, they illuminate the problems from using the upslope area in a wetness index without any consideration of the shape of the upslope region. They propose an alternative index in which the upslope area is replaced by an "effective upslope area", defined for a specific maximum flow time set by the user. However, although the new index is said not to be constrained by the steady state assumption, it still makes use of this assumption for calculating flow times. Therefore, it is uncertain if this is an appropriate way to add upslope information to the TOPMODEL index. Regardless of this, it is a fact that a lot of topographic information (e.g. upslope shape and downslope conditions) is never utilised by the TOPMODEL index.

Apart from theoretical problems with the TOPMODEL index and the assumptions it relies on, there are also technical problems in designing an appropriate algorithm for the calculation of the index. This has been illuminated by Quinn et al. [1995], who lists a number of questions which need to be carefully considered in order to succeed with index calculations. Most questions concern the design of the area-routing algorithm which estimates the accumulated upslope area for any point. First, upslope area was calculated using a single flow direction (sfd) algorithm, in which all accumulated catchment area was routed in the direction of steepest descent. This is not a very natural way to simulate the distribution of drainage area since it cannot account for divergent flow conditions. Also, it makes the drainage pattern very sensitive to the resolution of the elevation data. Therefore, a second method was developed, the multiple flow direction (mfd) algorithm, which routes area to all downslope cells within the same distance. Wolock and McCabe [1995] compares the performance of these two different algorithms in a number of American catchments. They conclude that the mfd algorithm produces higher index mean values than the sfd algorithm, and that these differences were independent of DEM resolution and catchment size.

Another question related to the area-routing algorithm is the treatment of drainage network. It is clear that once a volume of water enters a stream, subsurface flow equations no longer describe the movement of that volume properly. Also, water that has entered a stream channel no longer contributes to wet areas downslope. Quinn et al. [1995] solves this by defining a channel initiation threshold (CIT) value. Below this threshold value, the movement of water is described by subsurface flow equations based on Darcy's law. However, when the CIT threshold value is exceeded, the cell (along with all cells in the steepest descent downslope) is flagged as containing a stream. This implies that all area from this cell is routed in the steepest descent. Possible modifications of this concept include the option of letting the CIT be routed further downslope or, alternatively, constantly subtracting CIT from any newly found stream cell.

The literary review listed above only represent a minor fraction of all articles in this the rapidly expanding branch of hydrology. This brief overview has attempted to conclude the most important advances in topographic modelling that was relevant to this study. A quite different approach of obtaining soil moisture estimates is to use remote sensing methods. In order to eventually compare these two approaches, an introduction to current remote sensing methods is also given here.

**Soil moisture from remotely sensed data: natural gamma radiation**

Remote sensing of soil moisture can be accomplished to some degree or other by all regions of the electromagnetic spectrum. Successful measurement of soil moisture by remote sensing
techniques depends upon the type of reflected or emitted radiation. A brief overview of current techniques is given by Engman and Gurney [1991] in table 2.

Today, most environmental scientists agree that only the microwave region offers the potential for truly quantitative measurements of soil moisture from space. However, gamma radiation methods are still interesting as these measurements contain soil moisture information from a considerable depth of the soil column as compared to other methods. Grasty [1976] states that approximately 90% of the total gamma radiation from a dry soil is received from the top 30-45 cm. If sampling frequency is not a decisive factor, gamma radiation methods are potentially useful for providing measures of the soil water regime and soil characteristics in natural landscapes.

Electromagnetic radiation is generally referred to as gamma radiation when emitted by the nucleus of instable isotopes. Gamma radiation is emitted in quanta or energy levels depending on the material source of the decay. Practically all rocks and soils are radioactive and emit gamma radiation of which the three major sources are (Grasty, 1976):

1. Potassium-40, which is 0.012% of the total potassium, and emits gamma-ray photons of energy 1.46 MeV;
2. Decay products in the uranium-238 decay series and

Table 2: Summary of remote sensing techniques for measuring soil moisture (adapted from Engman and Gurney, 1991).

<table>
<thead>
<tr>
<th>Wavelength region</th>
<th>Property observed</th>
<th>Advantages</th>
<th>Disadvantages or noise sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma radiation</td>
<td>Attenuation of natural gamma radiation</td>
<td>Includes soil wetness information from a depth in soil column (20-30 cm)</td>
<td>Expensive; relatively low resolution; requires extensive calibration</td>
</tr>
<tr>
<td>Reflected solar</td>
<td>Albedo; index of reflection</td>
<td>Data available, high spatial resolution</td>
<td>No unique relationship between spectral reflectance and soil moisture; thin surface layer only; cloud interference</td>
</tr>
<tr>
<td>Thermal infrared</td>
<td>Surface temperature (measured diurnal range of surface temperature or crop canopy temperature)</td>
<td>High spatial resolution, large swath; relationship between temperature and soil water pressure is independent of soil type</td>
<td>Bare soil only; cloud interference; surface topography and local metrological conditions can cause noise; surface layer only (2-4cm)</td>
</tr>
<tr>
<td>Active microwave (1-100 cm)</td>
<td>Backscatter coefficient; dielectric constant</td>
<td>All-weather high resolution</td>
<td>Surface roughness; vegetation; topography</td>
</tr>
<tr>
<td>Passive microwave (1-100 cm)</td>
<td>Brightness temperature (microwave emission); dielectric constant; soil temperature</td>
<td>All weather; penetrates some vegetation; large area coverage</td>
<td>Limited spatial resolution; soil temperature; surface roughness; vegetation; interference from communications</td>
</tr>
</tbody>
</table>

The gamma-ray spectrum from the uranium and thorium decay series is extremely complex, and in order to measure the amount of each material present in the top layers of the ground all components of the decay series must be in a radioactive equilibrium since it is the daughter products that are measured. Measurements rely on the assumption that no daughter products are withdrawn from the chain of isotopes as radioactive decay progresses. However, this assumption can be violated through earth surface transport processes. Potassium-40, on the
other hand, decays straight to argon-40 without intermediate chain reactions, and is therefore not subject to this problem.

As mineral soils and bedrock emit gamma radiation, there are several processes that affect gamma-rays before they reach the spectrometer. Basically, three main processes affect gamma radiation (Grasty, 1976): (1) the photoelectric effect; (2) Compton scattering; (3) pair production. Because most materials (rocks, air and water) encountered in airborne radioactivity surveys have a low atomic number, Compton scattering is the predominant absorption process occurring between the ground and the detector (Grasty, 1976).

Minell [1983] presented a detailed report on the fundamental characteristics of natural gamma radiation in Swedish soils, comparing physiochemical analyses with on-the-ground gamma-ray measurements and gamma radiation methods. This report examined the dependence of gamma radiation signatures with soil porosity, soil wetness, overlays of peaty soils and biomass, and grain size. In general, K-40 is most abundant in rocks, it shows least noise for wet/dry soil ratios and is not dependent on daughter isotopes (Minell, 1983). Results using potassium count rates are more accurate than those from other count rates, due to the background presence of radon and its decay products in other count rate measurements (Grasty, 1976). These factors led to an early concentration on using gamma radiation only from K-40 for this study.

Water is about 1.11 times as effective as air in absorbing gamma rays (Grasty, 1976). Hence, the measured count rate is dependent on soil moisture content and for a uniformly radioactive ground will decrease almost linearly with increasing soil moisture (Grasty, 1976). This is the fundamental property which enables the use of gamma radiation for soil wetness mapping purposes. The attenuation by soil moisture, of natural gamma radiation emitted by the ground, has the potential of permitting continuous measurement of average water content over large areas avoiding many of the problems associated with point measurements.

Traditionally, hydrologists have used gamma radiation data for snow cover surveys (Grasty, 1976; Bergström and Brandt, 1983; Carroll and Carroll, 1989), where this type of information can provide accurate areal estimates of snow water equivalent. Zotimov [1971] was one of the first hydrologists to test the potential use of natural gamma radiation for soil moisture measurements. An experiment with on-the-ground portable gamma ray detectors gave encouraging results; soil moisture was measured within 5-10% of control measurements from the gravimetric method. Carroll [1981] uses an airborne gammaray spectrometer to estimate soil moisture measurements along flight lines. Results from this experiment showed a root mean square (RMS) error of 3.2% soil moisture from ground measurements. In a later study, Carroll and Schaaake [1983] obtain results with an RMS error of 3.9% soil moisture. More recently, Peck et al. [1992] carried out gamma radiation measurements on the FIFE program, where results could be correlated to ground measurements giving an RMS error of approximately 2.5%. They also noted that the gamma radiation was not significantly dependent on biomass, but concluded that an extensive ground measurement set is required for the calibration due to the coarse resolution of gamma radiation data.

Common to all these soil moisture measurements from gamma radiation methods is the assumption that the gamma radiation from the bedrock and mineral soil does not change significantly with time, and that the area under investigation must be surveyed at least twice in order to calibrate the gamma radiation measurements with extensive ground data on soil moisture conditions from the time of the overflight. From this point of view, gamma radiation methods requires quite a lot of efforts and preparations before it can be used operationally, and this fact has prevented the extensive use of this method for obtaining soil wetness information.

Another use for gamma radiation methods is explored by Ek [1987] and Virtanen [1986; 1990], who apply these methods in the mapping of peat deposits. At the core of this
application lies the similarity between peat and water for attenuating gamma radiation. The absorption of water can be calculated, which means that when the thickness of an overlaying water layer is 57 cm only about 5% of the initial gamma radiation can pass through it. Consequently, as the water content of peat is about 90%, practically all gamma radiation is attenuated by a peat layer which is 0.6 meters thick (Virtanen, 1986). As a result, gamma radiation maps have proved to be very efficient mapping tools in peat- and wetland surveys (Ek, 1987).
Methods

Study area
Since no field work was included in this study, the description of the study area is refers to earlier studies (for more details, see Waldenström, 1977). The Kassjöån basin is located in the forested areas of north central Sweden with undulating hilly land, till soil and moderate relief (figure 1). The basin is assumed to be representative of this region of the country. In a broad perspective, the basin consists of two equally large subbasins, which are separated by a distinct ridge. In addition, these two subbasins are divided into a total of 16 smaller subbasins (figure 2).

The bedrock is mainly covered with till soil of variable depth. However, larger areas with exposed bedrock occur at the faults. The bedrock mainly consists of dolerite, sandstone, granodiorite and alkaline rocks (figure 3). Some differences in the soil fractions can be distinguished between the above and below the highest shoreline, which is at 255-260 m.a.s.l. Below this level fine particles have been washed out by wave erosion and carried away to lower areas. The strictly sedimentary soils consist mainly of coarse material, gravel and sand.

These areas are partly at the altitude of the highest marine shoreline, where deltas were built up in the ancient sea, and partly at higher altitudes, where they consist of deltas built up in ice-dammed lakes. Mires are mainly small and spread out over nearly all the basin. The concentration is higher in the western part.

The hilly landscape is cut by small streams, some of which earlier were regulated for timber floating purposes. However, these dams are not maintained any longer. The forest in the area is subject to extensive timber cutting, which in this part of the country means that quite large areas are clearcut. This will affect both discharge conditions and results from
gamma radiation techniques, since a reduction in biomass tends to decrease the attenuation of gamma radiation.

![Figure 3: Geology in Kassjöån](image)

Table 3: Land use in percent and topographic characteristics for each subbasin and the total area of Kassjöån.

<table>
<thead>
<tr>
<th>Areas</th>
<th>Lakes</th>
<th>Mixed forest</th>
<th>Cleared</th>
<th>Agr. land</th>
<th>Other</th>
<th>Mire area [% of land]</th>
<th>Mean slope [%]</th>
<th>Elevation [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.4</td>
<td>60.4</td>
<td>28.0</td>
<td>0.0</td>
<td>9.2</td>
<td>17.6</td>
<td>9.0</td>
<td>391.3-531.8</td>
</tr>
<tr>
<td>2</td>
<td>2.8</td>
<td>68.7</td>
<td>23.4</td>
<td>0.1</td>
<td>5</td>
<td>10.2</td>
<td>7.4</td>
<td>246.5-440</td>
</tr>
<tr>
<td>3</td>
<td>6.0</td>
<td>84.2</td>
<td>4.8</td>
<td>0.0</td>
<td>5</td>
<td>11.7</td>
<td>8.3</td>
<td>376.4-491.8</td>
</tr>
<tr>
<td>4</td>
<td>1.6</td>
<td>80.5</td>
<td>16.5</td>
<td>0.0</td>
<td>1.4</td>
<td>6.3</td>
<td>8.7</td>
<td>241.7-461.2</td>
</tr>
<tr>
<td>5</td>
<td>2.3</td>
<td>88.8</td>
<td>4.7</td>
<td>0.1</td>
<td>4</td>
<td>8.8</td>
<td>9.1</td>
<td>301.7-476.9</td>
</tr>
<tr>
<td>6</td>
<td>27.4</td>
<td>60.0</td>
<td>9.4</td>
<td>0.7</td>
<td>2.4</td>
<td>4.3</td>
<td>9.1</td>
<td>241.6-412.6</td>
</tr>
<tr>
<td>7</td>
<td>9.4</td>
<td>71.3</td>
<td>10.9</td>
<td>0.0</td>
<td>8.4</td>
<td>13.8</td>
<td>8.8</td>
<td>322.8-514</td>
</tr>
<tr>
<td>8</td>
<td>1.3</td>
<td>77.3</td>
<td>8.7</td>
<td>0.0</td>
<td>12.7</td>
<td>21.4</td>
<td>8.3</td>
<td>368.9-506.6</td>
</tr>
<tr>
<td>9</td>
<td>0.0</td>
<td>55.6</td>
<td>0.0</td>
<td>30.6</td>
<td>13.9</td>
<td>0.0</td>
<td>4.3</td>
<td>243.2-254.9</td>
</tr>
<tr>
<td>10</td>
<td>7.0</td>
<td>80.6</td>
<td>8.4</td>
<td>0.0</td>
<td>4</td>
<td>10.3</td>
<td>8.5</td>
<td>275.3-399.1</td>
</tr>
<tr>
<td>11</td>
<td>11.4</td>
<td>78.0</td>
<td>5.4</td>
<td>0.0</td>
<td>5.3</td>
<td>5.7</td>
<td>12.5</td>
<td>321.6-460.7</td>
</tr>
<tr>
<td>12</td>
<td>2.1</td>
<td>84.1</td>
<td>7.9</td>
<td>0.0</td>
<td>5.9</td>
<td>12.9</td>
<td>8.2</td>
<td>235.7-500.8</td>
</tr>
<tr>
<td>13</td>
<td>5.9</td>
<td>88.5</td>
<td>0.2</td>
<td>0.2</td>
<td>5.2</td>
<td>11.4</td>
<td>9.0</td>
<td>226.6-419.8</td>
</tr>
<tr>
<td>14</td>
<td>3.1</td>
<td>90.1</td>
<td>1.2</td>
<td>1.0</td>
<td>4.5</td>
<td>14.7</td>
<td>8.9</td>
<td>227-320.8</td>
</tr>
<tr>
<td>15</td>
<td>9.9</td>
<td>83.3</td>
<td>6.1</td>
<td>0.0</td>
<td>0.6</td>
<td>4.0</td>
<td>9.7</td>
<td>226.7-328.8</td>
</tr>
<tr>
<td>Total</td>
<td>5.5</td>
<td>77.2</td>
<td>11.1</td>
<td>0.1</td>
<td>6.1</td>
<td>12.4</td>
<td>8.6</td>
<td>226.6-531.8</td>
</tr>
</tbody>
</table>

The two main valleys in Kassjöån, the Kassjöå-valley in the south and the Tivsjöå-valley in the north and east, join in the south-east part of the basin just upstream the outlet station.
(Storsillret, in subbasin no. 16, according to figure 2). The terrain in some parts of the basin is rather steep, especially in the western part of the Kassjöå-valley.

Kassjöån has been a target of intensive hydrological investigations since the 1960s, when it was appointed representative basin on the International Hydrological Decade (IHD) program. The core purpose of all research in the area was to study the water balance and the hydrological processes. Fluxes in the storages of the soil, groundwater and snowcover were evaluated on a monthly basis. The water balance method was used to estimate monthly and annual evaporation. Apart from Kassjöån, there are two other representative basins in Sweden (Velen and Lappräsket). Together, these serve as key areas for determining the distribution of evaporation in Sweden.

![Figure 4: The hypsogram for Kassjöån](image)

**Data description and pre-processing methods**

At an early stage of the study, much work involved the challenging task of data conversion and pre-processing. This is mostly not recognised as a major part of GIS analyses, although my experience is that this is an underestimated obstacle indeed. The rapid development of computer hard- and software has created numerous data file protocols and standards, which are rarely compatible with each other. Conversion programs are often not up to date, leaving the worker a time-consuming task of first learning the structure of each file format and then designing her/his own appropriate conversion routines. Solutions may be available from the other researchers, but these programs can be extremely difficult to locate.

Most GIS analysing methods work from a raster-based platform. This implies that all data must be stored in uniform system, where resolution and grid coordinates are identical. Therefore, it is necessary to identify a GIS working projection and reference grid at an early stage of the analysis (figure 5), and adapt all sources of data to this reference (Bonham-Carter, 1994). Sometimes, this can be a quite difficult task since data may be based on different reference coordinate systems of various geometric projections. This step, called data
georeferencing, is recognized as a fundamental part of GIS methods. In this study, however, nearly all data sources were given in the national metric plane coordinate system RT 90 (Rikets när), which made the conversion to a reference grid relatively easy.

**Topographic data**
The digital elevation data was obtained from the basic contour topographic map (1:50,000, 'Gröna Kartan') from the National Survey of Sweden. The contour map has an equidistance of 5 meters and this is gridded by the National Survey through an interpolation method to yield elevation data every 50th meter in the plane. Plane coordinates are given in meters.

The digital elevation data were imported to the GIS platform in a vector point file format. Thereafter, the vector points were projected on a raster grid resulting in a raster elevation grid. For this 50 meter grid, each vector point coordinate of the DEM was positioned in the center of each grid cell (figure 4), yielding the reference grid on which all analyses were carried out.

**Gamma radiation data**
Together with Finland, Swedish airborne gamma radiation survey methods for geophysical mapping are quite unique concerning the resolution of the data. Gamma radiation measurements are carried out at a height of 30 meters above ground surface at a speed of 250 km/h. Sampling is made every 40 meters along flight lines 200 meters apart, giving an approximate area coverage of 60% (Åkerblom, 1993). Abroad, most surveys are carried out at flight heights between 100 and 150 meters, and flight lines are usually 500-1000 meters apart. This means that the signal-to-noise ratio is comparatively high in Swedish data, and specific landscape features are not “drowned” in background radiation, which makes this type of remotely sensed data potentially suitable for wetness classification purposes.

Two adjacent gamma radiation maps were needed to cover the catchments in this study: 18G SV and 17G NV (according to the map sheet reference used by the National Survey of Sweden). These flight measurements were mainly made in July-August, 1978, and completed
in October-November in the same year. The lateral positional error is estimated to be less than 50 meters (Minell, 1983).

![Gamma radiation from K-40 in Kassjöan. Low values are dark cells.](image)

As the data analysis is performed in a raster mode with pixels of quadratic form, gamma radiation had to be interpolated to a 50 meter grid resolution adopted in this study (figure 6).

Several interpolation (or gridding) methods were examined, and two methods gave comparatively good results ("good" in the meaning of both visual quality and identity to the frequency distribution of the raw data): minimum curvature interpolation and kriging. Of these two, kriging was chosen as it was an exact interpolation method (Keckler, 1995), retaining as much as possible of the properties of the original data. Furthermore, kriging provides a measure of the uncertainty in the gridded data. A brief description of the geostatistical results that were used for the interpolation routine is given in appendix A.

**Land use data**

The land use data, given in vector polygon format, had to be converted to the working grid. The polygon file consists of a list of coordinates grouped into polygon identification numbers. An attributing value file carry a list of the polygon numbers and the corresponding value of each polygon. The conversion is done by projecting the polygons onto an empty raster grid image, where each pixel is appointed the value of the polygon that covers most of the pixel surface and then by assigning the corresponding polygon value to that pixel. As for all other data, a reference grid resolution of 50 meters was used for the projection.

**Geologic data**

Digitalal geologic maps over the area was not commercially available at the time of this study. Therefore, the Geological Survey of Sweden (SGU) issued a temporary permit to digitize this
data from existing paper maps and use it for this study (D.nr. 00-559/97). The Kassjöån basin is located on the edge of two different administrative regions in central Sweden (Jämtlands län and Västernorrlands län), and geological maps are available on a regional scale (1:200 000) from these two regions (Ca53 and Ba31 respectively).

The digitizing procedure was done by using the vector-based GIS MapInfo software. Since the two map sheets are based on different coordinate systems, a special solution was found to the problem of linking the maps. The standard procedure of linking these two maps could give positional errors of up to 500 meters [SGU, pers. comm.], and another routine was recommended for this study. It involved the use of the local hydrography (i.e. lakes and streams) for reference coordinates instead of map edges. However, there were still some difficulties linking edge regions from the different maps with each other. The error implemented by the digitizing routine is estimated to be approximately ±100 meters.

After the maps were digitized, data was stored in a vector polygon format. This file was then imported to IDRISI for Windows and projected on an empty reference grid, yielding a raster map with geologic information with identical properties as the other raster maps used in the study (figure 3).

**Hydrologic data**

Two different types of hydrologic data were used in this study. First, previously digitized sub-basin divides were available, which split the total area in 16 “subbasins”. The water divides have been determined from topographical maps (scale 1:20 000 and 1:10 000) by the Swedish Metrological and Hydrological Institute (SMHI). Verification by field inspection has not been undertaken. These divides were stored in vector polygon format and could easily be imported to the GIS platform. Second, the stream network in the area was available from the National Survey of Sweden (Lantmäteriverket) in the same format as land use data (ARC/INFO interchange format). This data was converted to vector line format using the same procedure as stated for land use data above.

**Digital terrain analysis and index calculations**

The DEM makes up the foundation for the entire branch of the study which is called digital terrain analysis (DTA). Here, this term also includes the calculation of topographic indices, such as the TOPMODEL index. The topographic indices and attributes used in this study include:

1. $\tan \beta$ Slope
2. $\tan \alpha_d$ Drainage efficiency index
3. $A_r$ Specific catchment area (upslope area)
4. $\omega$ Plan curvature
5. $\phi$ Profile curvature
6. $\chi$ Curvature
7. $\ln(a/\tan \beta)$ The TOPMODEL index

Attributes 1-5 are considered primary attributes, since they are derived directly from the DEM data. The TOPMODEL index is a theoretically based wetness index, which is also a compound attribute since it consists of two primary attributes: slope ($\tan \beta$) and upslope area.
per contour length \((a)\). Curvature \((\chi)\) is also a compound attribute, defined as the difference between plan- and profile curvature \((\omega - \phi)\).

For all of the primary attributes except from the drainage efficiency index, the standard procedure of calculation is to use local interpolation methods (see Appendix B). For upslope area, or specific catchment area \((A_s)\), as well as for drainage gradient index \((\tan \alpha_d)\), local interpolation methods cannot be used. This type of calculation requires special flow routing algorithms.

For the calculation of upslope area, a multidirectional flow algorithm proposed by Quinn et al. [1991] was used. Basically, starting from the highest point in the catchment, flow (or area) fractions are distributed to all downslope positions within the same distance from a cell. The fraction routed to each of these cells is weighted according to the slope between the cells. Moreover, weights are controlled by an exponent, \(h\), set by the user, and this relationship is given by:

\[
A_i = \frac{A_s (\tan \beta_i)^h}{\sum_{i=1}^{n} (\tan \beta_k)^h}
\]

where \(A_i\) is the area to be routed to cell \(i\), \(A_s\) is the accumulated area to be distributed, \(n\) is the number of downslope directions (cells), \(k = 1...n\), \(\tan \beta_i\) is the gradient to cell \(i\). If \(h = 1\), the weights will be linearly distributed (i.e. a cell in a direction which has twice the gradient of another cell will receive twice as much area), but as \(h\) grows, more weight will be given the cell in the direction with largest gradient. In practice, a value of \(h\) greater than 10 will produce a single directional flow algorithm where all area will be given to the cell of steepest descent. On the other hand, if \(h\) is less than one, the distribution of area will be less controlled by the relative gradient of each downslope cell.

The TOPMODEL index requires a “normalised” upslope area \((a)\), which is obtained by dividing upslope area \((A_s)\) with the contour length \((l)\). The total contour length around a cell is approximated by the circumference of a circle with an area equal to the cell area. The contour length in the direction of neighbouring cells is further estimated by fractions of the total contour length. A conceptual problem with this kind of normalisation is that the areal units in \(A_s\) is converted to length units in \(a\).

Moreover, the TOPMODEL index calculation is developed take the stream network into consideration. This is done by defining a channel initiation threshold, \(CIT\), above which a cell is treated as a stream cell. The threshold value is calibrated by visually comparing the distribution of cells with an upslope area greater than \(CIT\) with the actual stream network. The \(CIT\) value that produces best agreement between these images is then used throughout the study.

As an alternative to the TOPMODEL index and slope, a drainage efficiency index is proposed and tested in this study. This was derived in an attempt to quantify downslope conditions, which are not considered in other indices. The approximation of the groundwater table gradient with the land surface gradient at the same location \((\tan \beta)\) can yield errors in concave and convex regions, where the groundwater table is not parallel to the ground surface (figure 7a). The drainage efficiency index, \(\tan \alpha\), is defined as the gradient between a point on the surface of the ground and another point in the downslope direction which yields a vertical drop of \(d\) meters (figure 7b). In comparison with \(\tan \beta\), \(\tan \alpha\) generally gives lower gradients in concave regions and higher gradients in convex regions, and would thus be able
to quantify the drainage efficiency for these locations in a catchment better. Since there is no formal method to estimate an appropriate value of \( d \), a number of calculations were made with changing values of \( d \), and these were then compared to the distribution of actual mires.

Technically, a computer program written in Visual Basic (Jan Seibert, pers. comm.) was used for calculating both the TOPMODEL index and the drainage efficiency index for Kassjöan from raster elevation data.

**Spatial analysis from a GIS platform**

When all information is stored in a digital format, GIS computer software can be utilised to analyse the data spatially. The platform adopted for this study was *IDRISI 1.01 for Windows*, a commercial GIS program developed by Clark University, MA, USA. This software is raster based but also contains some support for the treatment of vector data. In practice, this means that all analyses is done from raster images, while vector files are used for simple visualisation purposes, e.g. displaying the boundaries of catchments on raster files. Numerous functions are embedded in this software, and the reader is referred to the manual and the on-line help for detailed descriptions of all commands. However, a brief overview of the most important GIS analysis commands used in the present study is given here, to give a sense of the working routines:

- **INITIAL** is a command used for the generation of new raster grid files.
- **LINERAS** and **POLYRAS** are used to convert vector data to raster data. LINERAS projects a vector line file onto a raster grid and assigns the vector attribute number to cells which overlap vector objects. POLYRAS works in a similar fashion for vector polygon files, but there is an important difference in the way it functions. In order for a cell to be assigned a polygon attribute number, the polygon must overlap more than half of the cell. This difference can be noted on raster maps which have been created by both commands; lakes, which are stored as polygon objects, must cover more than half of a grid cell to be visible, whereas all streams, which are line objects are fully visible in the raster map. As a result, there may be considerable gaps in raster images of the catchment drainage network, where lakes are simply too small to be presented.
- **ASSIGN** connects spatial and tabular information. If cells in a raster image are indexed with attribute numbers, this command looks up the attributes in a value file (tabular data file) and assigns information from another column in the value file to the raster cells. This
is one of the most powerful commands of the GIS, which allows tabular spreadsheet data to be visualised in maps.

- RECLASS works in a similar way as ASSIGN but is faster for easier raster map transformations. This command is used to classify variable images to binary maps where a specific threshold value has been identified.
- QUERY selects data from one raster image at geographic locations specified in mask image. This data can later be analysed statistically in the GIS or other spreadsheet software.
- OVERLAY performs operations between two different raster images, e.g. arithmetic or statistical operations. It performs operations between cells with the same geographic location.
- CROSSTAB performs a crosstabulation of two images, i.e. records the number of combinations when two images are overlayed, and reports similarity/association measures.
- HISTO reclassifies an image to a histogram showing both frequency and accumulated frequency.
- DISTANCE calculates the euclidian distance from any point to target cells (cells with a value greater than 0) in a raster image.

Together with other complementary computer software, IDRISI for windows offers a variety of opportunities for spatial analysis. Raster data is stored in a very easy and comprehensive format, one single column format, and is accompanied with an image documentation file which specifies coordinates, resolution and other vital parameters of the image. Since the data file can be stored in ASCII format, it can readily be imported to any spreadsheet or data visualisation software. In addition, data can also be imported from other sources.

For this study, four additional software programs were used for analysing purposes. A statistical software, STATISTICA, was used to extract advanced statistical measures from data sets. A mathematical programming language, MATLAB, was used for calculation of topographic attributes and complicated mathematical operations on raster images. A spreadsheet program, MS EXCEL, was used for constructing tabular value data files and pre-processing of data sets for visualisation. Last, a graphical illustration software, GRAPHER, was used for plotting diagrams.

Testing the basic hypotheses
The central aim of the study was to examine whether the topographic and gamma radiation measures could be used to make predictions of the soil moisture distribution, if the distribution of mires is used as a measure of extremely wet locations. In order to test the hypotheses, test methods had to be developed. As the area selected for this study is divided into a number of subbasins, it is possible to compare global results (obtained for the whole of Kassjöan) to local results (obtained for each subbasin in Kassjöan). In this way, it is possible to evaluate the hypotheses at different scales.

Two different methods evolved for the evaluation of the hypotheses: (1) comparison of mire to non mire distributions for different indices; and (2) analysis of mire images that were predicted from different indices.

The following images were analysed: (1) Five TOPMODEL index images using \( h \)-values of 0.5, 1, 2, 5 and 10; (2) one K-40 gamma radiation image.
Mires have higher topographic index values than other areas

1. Certain mire types are not compatible with the TOPMODEL index drainage theory.
2. Local climate differences (aspect, elevation).
3. No steady state conditions (e.g. shape of upslope area must also be considered).
4. Downslope conditions are not included.
5. Data resolution affects the representation of catchment geomorphology.
6. There are local variations in the permeability of the underlying bedrock, which to some extent controls peat formation.

Distributions overlap. Why?

Mires emit lower gamma radiation than other areas

1. Raw data resolution is coarser than grid resolution
2. Smaller mires cannot be detected due to reflected radiation from surrounding mineral soils.
3. Varying geology produces radiation differences.
4. Navigational errors, both in flight height AGL and lateral position.
5. The local variations in vegetation cover attenuates radiation differently.

Distributions overlap. Why?

- Can these hypotheses be confirmed?
- Can they improve our ability to predict the distribution of soil moisture?

Figure 8a: A conceptual picture of the aims in this study

Comparing the distributions of mire and non mire cells

By using the IDRISI command QUERY, topographic index values and gamma radiation values from mire and non mire areas was extracted. This data could then be plotted as distributions, using HISTO, and compared statistically using a statistics program. It was necessary to characterise these distributions and measure how different they are to each other, since a significant difference between the mire and non-mire distributions supports the hypotheses. Statistical measures, i.e. the median values and the Kolmogorov-Smirnov D-values, was obtained from analysing the distributions in STATISTICA.

![Figure 8b: The definition of a mire threshold value, T_{th}, from the histogram of a wetness indicator.](image-url)
Predicting the spatial distribution of mires

In this analysis, the first step was to define threshold values (i.e. class limits) for both the TOPMODEL index and gamma radiation values, above and below which cells are defined as mire cells respectively. These threshold values were defined as the values which reproduce the same mire area in the catchment as observed from the land use map. For the TOPMODEL index, this threshold value is defined as the value $T_{th}$ which gives the same amount of cells in region $C_2$ of the TOPMODEL index histogram (figure 8b) as the amount of mire cells from the land use map ("actual mires"). All cells in region $C_2$ (with values $> T_{th}$) are then predicted mire cells. The same method is used for the K-40 gamma radiation values, but then the lower tail of the histogram (region $C_1$ in figure 8b) is calibrated with actual mire cells, since for K-40, the lowest values represent the wettest areas.

Once these threshold values were estimated, RECLASS was used to derive maps showing predicted distributions of mires. These maps were then compared visually to each other and to the land use map.

Several methods were used to quantify the characteristics of the predicted maps. First, threshold values were defined both globally (i.e. for the total of Kassjöån) and locally (i.e. for each of the subbasins). This provided a useful measure of the regional properties of the threshold values. The subbasin threshold values were also plotted against the average altitude of each subbasin, the average slope of each subbasin, and the percentage of mires in each subbasin, in order to seek relationships that may affect the validity of the hypotheses.

In a second step, the predicted mire area in each subbasin predicted from setting a global threshold value was calculated. The idea was to investigate in which way the predicted mire area was distributed in different subbasins. From this method it was possible to identify the wetness indicator that gave the best mire area prediction for each subbasin.

An attempt was also made to quantify pattern similarity between predicted mire images and the actual mire image. A measure was developed to answer questions such as “how far away are the predicted mires from the real mires?” and “how far away are the real mires from the predicted mires?”. These two questions do not have the same answer. Thus, the DISTANCE command was used to calculate two images that each showed the euclidian distance from any location in the catchment to the nearest (a) predicted mire, and (b) actual mire. Subsequently, QUERY was used to extract the actual and predicted mire cells from these two distance images respectively. Thus, by analysing these data set, a illustrative measure of pattern similarity between predicted mires and actual mires could be obtained. By comparing plots showing the fraction of actual/predicted mire cells within the euclidian distance from predicted/actual mire cells, patterns produced by different wetness indicators could be compared.

Other topographic indices

For reasons given earlier, it is also interesting to compare the performance of the TOPMODEL index to alternative topographic measures. By using the same techniques as above, slope ($\tan \beta$), aspect, plan- and profile curvature and the proposed drainage efficiency index ($\tan \alpha_d$) could be examined and compared to the results from testing the TOPMODEL index and the K-40 gamma radiation. For the slope and drainage gradient index, the hypothesis is that mire areas are associated with lower values, and other areas with higher values. In the case of curvature, the hypothesis is that concave regions (both in the direction of slope – profile curvature – and in direction of the contours – plan curvature) are wetter than other regions. From the definition of these attributes (Appendix B) it follows that contour concave regions are signified by positive (+) plan curvature, and slope concave regions are
signified by negative (-) profile curvature. For compound curvature, a positive (+) sign signifies concave regions.

**The Influence of geology**

Another interesting question to consider is the effect of geology both on wetness conditions in natural landscapes and on the gamma radiation measures used this study. Can it be confirmed that the underlying bedrock in some way affects drainage conditions in Kassjöån? In order to investigate this, a hypothesis was formulated:

- If the hydrological prerequisites are similar for different regions (i.e. same climate and topography), these regions would have similar topographic index distributions. Any significant difference in mire area between the regions could be explained by different hydraulic conductivities and drainage abilities of the underlying geology.

This hypothesis could be tested by first calculating the distributions for different wetness indicators in each geological region. Then, the percentage of mire area was calculated for each geological region. Finally, local threshold values were calculated for each of the wetness indicators in each of the geological regions. These values were then compared to each other, which also enabled K-40 measurements to be compared with the underlying geology.

**Resolution effects**

Another way to appreciate pattern similarity between the wetness indicator maps and the land use map is to change the resolution of the images. Then, a linear regression method was used in order to perform regression analysis between mire and non-mire cells. To perform a regression, a finer measure of mire occurrence than simply a binary mire/non-mire status was needed. This could be done by defining raster images of coarser resolutions (100, 150, 200 m) by aggregating 50 m cells. This procedure was carried out for both the wetness indicator maps (TOPMODEL index and K-40) and for the land use maps showing the distribution of mires. As a result of this aggregation, mire images were obtained with cells expressing a gradual measure of mire content ranging from 0 (signifying no mire) to 1 (signifying all mire). Then, wetness indicator values were plotted against all cells containing any mire at all for different resolutions, and measures of correlations were obtained.
Results

Since much attention in this study is given to the methods of calculating the TOPMODEL index, it is appropriate to illustrate different results from this procedure. The first step involved the estimation of the channel initiation threshold, CIT, which controls the stream drainage pattern in TOPMODEL index calculations. Here, three specific calibration sites were selected from the Kassjöan basin A, B and C (marked in figure 2). Then, the actual and predicted drainage patterns in each of these areas were compared for changing values of CIT. The purpose was to estimate a CIT-value that gave best agreement between actual and predicted streams in all three areas. This proved to be rather difficult since a CIT-value that seemed appropriate at one site, failed to reproduce the stream channels at another site (figures 9-11a-c). As a result, the CIT-value that gave the best results in general (CIT=15 ha) was used for the rest of the study. However, when this value is used for the whole of Kassjöan, the simulated drainage network only approximates the actual network (figure 12).

![Figure 12: The predicted drainage pattern (in grey) and the actual drainage pattern (in black) for Kassjöan, using a CIT-value of 15ha](image)

Having calibrated the cta value with the actual drainage network, the TOPMODEL index map of Kassjöan could be generated. This was done using several different values of $h$, the flow...
Figures 9a-c (left column) showing the actual (black) and predicted streams using a CIT=5 ha, 10a-c (middle column) using a CIT=15 ha, 11a-c (right column) using a CIT=25 ha
partitioning exponent. From figure 13, it is clear that TOPMODEL index values are higher at the bottom of valleys.

![Figure 13: The TOPMODEL index in Kassjöån, using h=1 and CIT=15 ha. High values are dark cells.](image)

**Testing the hypotheses**

The distributions from mire and non mire cells for the TOPMODEL index values (figure 14a) were more separated than the distributions for K-40 (figure 14b). Also the K-S D-values was greater for the TOPMODEL distributions, signifying a better separation (table 4).

![Figure 14a: Mire and non mire distributions for the TOPMODEL index](image)
Table 4: Statistical properties of the distributions for different wetness measures.

<table>
<thead>
<tr>
<th></th>
<th>ln((a/\tan\beta))</th>
<th>K-40 [0.01% K]</th>
<th>tan(\beta)</th>
<th>tan(\alpha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median mire cells</td>
<td>10.08</td>
<td>100.14</td>
<td>0.0304</td>
<td>0.0230</td>
</tr>
<tr>
<td>Median non mire cells</td>
<td>7.78</td>
<td>151.25</td>
<td>0.0826</td>
<td>0.0849</td>
</tr>
<tr>
<td>K-S D</td>
<td>0.468</td>
<td>0.412</td>
<td>0.490</td>
<td>0.573</td>
</tr>
</tbody>
</table>

Although these distributions are derived from the entire Kassjöan basin, distributions for some of the subbasins display similar properties.

Maps showing the predicted mires from the TOPMODEL index and gamma radiation gave quite different patterns (figures 16-17). The TOPMODEL mire map show a very scattered distribution of mires, while the K-40 mire map produced more lumps of mires. None of them succeeded to exactly reproduce the pattern of mires from the land use map (figure 15), but there were also similarities between the patterns in different maps. The predicted mire maps were produced from the global threshold values in table 5a.

The local threshold values (from each subbasin) showed quite large variation, for both the TOPMODEL index and the K-40 gamma radiation (table 5b). The reasons for this variation was not clear, and relationships were sought between the threshold values and different subcatchment properties, such as average elevation, average slope and mire area. The K-40 was very weakly correlated to all of these properties, while the TOPMODEL index threshold values showed a remarkable correlation to the mire area in the subbasins (\(r^2=0.93\), figure 20a). In this and all following plots and tables, subbasins no. 9 and 11 were excluded because of their small sizes. Also the average elevation was somewhat correlated to the local TOPMODEL threshold values, however not strong as the mire area. The relationship between average TOPMODEL index values and subbasin mire area was also examined, but the correlation was very weak (figure 20b).

The amount of mire area in each subbasin, as predicted by each method from setting a global threshold value, showed quite large variation (table 6). K-40 seems to make the best predictions overall, but the large overestimations were made in subareas no. 5, 10 and 12 (which are all connected in the center of Kassjöan). The TOPMODEL index also overestimated the mire area in these subbasins, but not as much. Instead, the TOPMODEL index gave a very clear underestimation of mire area in subbasin no. 8.
Figures 15-19:

Mires according to the land use map (upper left), predicted mires from the TOPMODEL index (upper right), the K-40 gamma radiation (middle left), slope (middle right), and the drainage efficiency index, $d=2$ m (lower left).
Table 5a: Global threshold values for Kassjöan

<table>
<thead>
<tr>
<th>Method</th>
<th>Global threshold value</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-40</td>
<td>89.50</td>
</tr>
<tr>
<td>ln(a/tanβ)</td>
<td>h=0.5</td>
</tr>
<tr>
<td></td>
<td>h=1</td>
</tr>
<tr>
<td></td>
<td>h=2</td>
</tr>
<tr>
<td></td>
<td>h=5</td>
</tr>
<tr>
<td></td>
<td>h=10</td>
</tr>
<tr>
<td>tanβ</td>
<td>0.0259</td>
</tr>
<tr>
<td>tanα</td>
<td>d=1 m</td>
</tr>
<tr>
<td></td>
<td>d=2 m</td>
</tr>
<tr>
<td></td>
<td>d=3 m</td>
</tr>
</tbody>
</table>

Table 5b. Local threshold values for the subbasins in Kassjöan. *K-40 measures were not available.

<table>
<thead>
<tr>
<th>Subbasin no.</th>
<th>Mire area [%]</th>
<th>K-40</th>
<th>ln(a/tanβ) h=1</th>
<th>tanβ</th>
<th>tanα d=2 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.6</td>
<td>90.45</td>
<td>9.97</td>
<td>0.0320</td>
<td>0.0270</td>
</tr>
<tr>
<td>2</td>
<td>10.2</td>
<td>91.40</td>
<td>11.03</td>
<td>0.0215</td>
<td>0.0204</td>
</tr>
<tr>
<td>3</td>
<td>11.7</td>
<td>93.42</td>
<td>10.44</td>
<td>0.0263</td>
<td>0.0174</td>
</tr>
<tr>
<td>4</td>
<td>6.4</td>
<td>89.30</td>
<td>11.58</td>
<td>0.0227</td>
<td>0.0183</td>
</tr>
<tr>
<td>5</td>
<td>8.8</td>
<td>65.65</td>
<td>11.15</td>
<td>0.0243</td>
<td>0.0198</td>
</tr>
<tr>
<td>6</td>
<td>4.5</td>
<td>77.04</td>
<td>11.83</td>
<td>0.0175</td>
<td>0.0033</td>
</tr>
<tr>
<td>7</td>
<td>13.8</td>
<td>98.10</td>
<td>10.36</td>
<td>0.0293</td>
<td>0.0257</td>
</tr>
<tr>
<td>8</td>
<td>21.5</td>
<td>91.40</td>
<td>9.73</td>
<td>0.0343</td>
<td>0.0340</td>
</tr>
<tr>
<td>9</td>
<td>0.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>10.3</td>
<td>63.00</td>
<td>10.98</td>
<td>0.0276</td>
<td>0.0204</td>
</tr>
<tr>
<td>11</td>
<td>1.7</td>
<td>70.30</td>
<td>13.94</td>
<td>0.0040</td>
<td>0.0031</td>
</tr>
<tr>
<td>12</td>
<td>5.7</td>
<td>67.30</td>
<td>11.31</td>
<td>0.0171</td>
<td>0.0128</td>
</tr>
<tr>
<td>13</td>
<td>13.0</td>
<td>105.40</td>
<td>10.79</td>
<td>0.0254</td>
<td>0.0220</td>
</tr>
<tr>
<td>14</td>
<td>11.4</td>
<td>101.76</td>
<td>11.10</td>
<td>0.0200</td>
<td>0.0130</td>
</tr>
<tr>
<td>15</td>
<td>14.9</td>
<td>80.10</td>
<td>10.49</td>
<td>0.0209</td>
<td>0.0134</td>
</tr>
<tr>
<td>16</td>
<td>4.0</td>
<td>-</td>
<td>11.80</td>
<td>0.0172</td>
<td>0.0077</td>
</tr>
</tbody>
</table>

Different euclidian distance images were used to evaluate the patterns of the predicted mire maps. Actual mire cells were extracted from the TOPMODEL and K-40 distance images (the TOPMODEL distance image is shown in figure 21a). The cumulative frequency of these cells was plotted against the distance from predicted mire cells (figure 22a) for both the TOPMODEL index and the K-40 values. The plotted curves illustrate how large fraction of the actual mire cells that are found within a specific distance from the predicted mire cells. When distance is zero, the portion of mire cells which are correctly classified from each method can be found along the y-axis (these values are also given in table 7).

Clearly, the TOPMODEL index predictions gave a smaller portion of correctly classified cells than the K-40 predictions, but the TOPMODEL index showed a better overall pattern (i.e. the cumulative frequency curve rises faster for the TOPMODEL index).

According to the alternative distance analysis method, in which predicted mires are extracted from the euclidian distance map derived from the actual mires (figure 21b), the K-40 mires also performs better than the TOPMODEL index for the overall pattern (figure 22b).
Table 6: The absolute differences between predicted mire area and mire area from the land use map in the subbasins of Kassjöan. Subbasins no. 9 and 11 are excluded (see text). K-40 measurements from subbasin no. 16 was not available.

<table>
<thead>
<tr>
<th>area</th>
<th>Mire area [%]</th>
<th>ln(a/tanβ) h=1</th>
<th>tanβ d=2m</th>
<th>tanα</th>
<th>K-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>total</td>
<td>12.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>17.6</td>
<td>-5.9</td>
<td>-4.2</td>
<td>-3.9</td>
<td>-0.4</td>
</tr>
<tr>
<td>2</td>
<td>10.2</td>
<td>+3.6</td>
<td>+3.8</td>
<td>+1.8</td>
<td>-0.4</td>
</tr>
<tr>
<td>3</td>
<td>11.7</td>
<td>-1.6</td>
<td>-0.3</td>
<td>+3.0</td>
<td>-1.4</td>
</tr>
<tr>
<td>4</td>
<td>6.4</td>
<td>+4.3</td>
<td>+2.4</td>
<td>+2.2</td>
<td>+0.2</td>
</tr>
<tr>
<td>5</td>
<td>8.8</td>
<td>+2.7</td>
<td>+1.4</td>
<td>+1.7</td>
<td>+12.2</td>
</tr>
<tr>
<td>6</td>
<td>4.3</td>
<td>+5.9</td>
<td>+3.9</td>
<td>+6.4</td>
<td>+2.5</td>
</tr>
<tr>
<td>7</td>
<td>13.8</td>
<td>-2.2</td>
<td>-2.6</td>
<td>-2.6</td>
<td>-2.7</td>
</tr>
<tr>
<td>8</td>
<td>21.5</td>
<td>-9.0</td>
<td>-7.7</td>
<td>-9.3</td>
<td>-0.9</td>
</tr>
<tr>
<td>10</td>
<td>10.3</td>
<td>+2.0</td>
<td>-1.3</td>
<td>+1.3</td>
<td>+24.9</td>
</tr>
<tr>
<td>12</td>
<td>5.7</td>
<td>+3.2</td>
<td>+3.3</td>
<td>+4.3</td>
<td>+10.6</td>
</tr>
<tr>
<td>13</td>
<td>13.0</td>
<td>+0.7</td>
<td>+0.4</td>
<td>-0.3</td>
<td>-4.5</td>
</tr>
<tr>
<td>14</td>
<td>11.4</td>
<td>+2.5</td>
<td>+6.6</td>
<td>+8.9</td>
<td>-3.8</td>
</tr>
<tr>
<td>15</td>
<td>14.9</td>
<td>-2.1</td>
<td>+8.8</td>
<td>+10.6</td>
<td>+5.8</td>
</tr>
<tr>
<td>16</td>
<td>4.0</td>
<td>+5.7</td>
<td>+5.4</td>
<td>+7.5</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 20a-b: Correlation between TOPMODEL index local threshold values and mire area (left), and TOPMODEL average values and mire area (right). The large points represents the global values.

Other indices
Alternative indices of wetness status were also evaluated in this study. Initially, plan-, profile- and compound curvature (Appendix B) were included in these tests, but were excluded later on. The reason to this was that they did not provide a unique measure of mire occurrence. Plots of the distributions showed an almost complete overlap between mire and non mire distributions in the area. As a result, mire cells could not be distinguished at all from these measures. Instead, the study concentrated on the two remaining alternative indices: slope and the drainage efficiency index.
Figure 21a-b: The euclidian distance from any point in Kassjöån to a predicted mire from the TOPMODEL index (left), and to a mire from land use map (right). A zero distance is plotted in black.

Figure 22a-b: The cumulative frequency of actual mire cells plotted against the distance from predicted cells (left), and the cumulative frequency of predicted mire cells plotted against the distance from actual mires (right).

The mire and non mire distributions were more separated for slope and the drainage efficiency index than for the TOPMODEL index and K-40 gamma radiation (table 4, figures 19a-b). Apparently, the drainage efficiency index seems best at distinguishing mire from non mire cells, giving a K-S $D$-value of 0.57. Also, as compared to slope, the median values are more separated.
Figure 23a-b: Mire and non mire distributions for slope (left) and the drainage efficiency index, d=2 m (right).

The global and local threshold values from slope and the drainage efficiency index displayed certain characteristics (table 5a-b). As the value of d increases, the drainage efficiency index yields lower values (gradients decrease as the algorithm has to search further downslope). As for the TOPMODEL index and the K-40, local threshold values vary between different subbasins for both slope and the drainage efficiency index. Moreover, both slope and the drainage efficiency index local threshold values were correlated to mire area, but not as strongly as the TOPMODEL index.

Table 7: The correctly predicted mire cells as the percentage of all mire cells

<table>
<thead>
<tr>
<th>Measure</th>
<th>Correctly classified mire cells [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-40</td>
<td>41.6</td>
</tr>
<tr>
<td>tan(a/ tanβ), h=1</td>
<td>37.6</td>
</tr>
<tr>
<td>tan β</td>
<td>41.6</td>
</tr>
<tr>
<td>tan c, d=1m</td>
<td>45.1</td>
</tr>
<tr>
<td>d=2m</td>
<td>46.8</td>
</tr>
<tr>
<td>d=3m</td>
<td>45.5</td>
</tr>
</tbody>
</table>

The mire maps predicted from slope (figure 18) and the drainage efficiency index (figure 19) seemed to agree better with the actual mire pattern (figure 15) than corresponding maps from both the TOPMODEL index and the K-40 gamma radiation. However, the drainage efficiency index tended to predict mires around every lake. The cause of this is the long horizontal distances produced by the algorithm in search of a vertical drop, hence giving very low gradients. If the value of d was chosen to be less than 2 meters, this problem disappeared. On the other hand, as d decreases the index also becomes more or less identical to slope.

Distance analysis methods produced relatively good results for both slope and the drainage efficiency index. The drainage efficiency index gave the highest percentage of correctly classified mire cells of all wetness indicators tested in this study (46.8% for d=2 m, table 7). From the plots in figure 22b, this index also show the best pattern agreement between predicted and actual mire cells, using this specific method. Using the alternative method
(figure 22a), the drainage efficiency index displayed worse pattern agreement than slope and the TOPMODEL index. The reason to this is that this method tends to concentrate the predicted mires in lower regions, and fail to detect many of the small and widely spread upland mires.

**Geology**

The average values for the different wetness indicators for the five geological regions show very small differences (table 8). An exception to this is the average K-40 value from dolerite, which is considerably less than for other regions. Also the TOPMODEL index average value is somewhat lower in this region.

The threshold values in table 9 show a greater variation than the average values. The low K-40 threshold value for the dolerite region seem to confirm the low average value for this region, but the low K-40 threshold value for the granite region cannot be correlated in the same way. The variation in both the TOPMODEL index and slope threshold values is relatively small, but the drainage efficiency index threshold value is very low for the granitic region. However, this geological region only represents about 1% of the total catchment area and may therefore not be statistically comparable with the other regions.

<table>
<thead>
<tr>
<th>Geology</th>
<th>ln(a/tanβ) h=1</th>
<th>K-40 [0.01% K]</th>
<th>tanβ</th>
<th>tanα, d=2m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolerite</td>
<td>8.05 1.95</td>
<td>129.69 43.35</td>
<td>0.1014 0.0790</td>
<td>0.1059 0.0870</td>
</tr>
<tr>
<td>Sandstone</td>
<td>8.35 2.06</td>
<td>156.88 50.03</td>
<td>0.0918 0.0659</td>
<td>0.0938 0.0742</td>
</tr>
<tr>
<td>Granite</td>
<td>8.67 2.27</td>
<td>153.22 48.22</td>
<td>0.1328 0.1132</td>
<td>0.1256 0.1208</td>
</tr>
<tr>
<td>Granodiorite</td>
<td>8.55 1.91</td>
<td>156.13 49.38</td>
<td>0.0785 0.0514</td>
<td>0.0801 0.0558</td>
</tr>
<tr>
<td>Alk. &amp; carb. rocks</td>
<td>8.56 1.90</td>
<td>140.30 42.43</td>
<td>0.0771 0.0539</td>
<td>0.0773 0.0584</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Geology</th>
<th>Mire area [%]</th>
<th>ln(a/tanβ) h=1</th>
<th>K-40</th>
<th>tanβ</th>
<th>tanα, d=2m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolerite</td>
<td>11.8</td>
<td>10.45</td>
<td>77.10</td>
<td>0.0273</td>
<td>0.0241</td>
</tr>
<tr>
<td>Sandstone</td>
<td>11.4</td>
<td>11.86</td>
<td>95.80</td>
<td>0.0242</td>
<td>0.0190</td>
</tr>
<tr>
<td>Granite</td>
<td>8.6</td>
<td>11.86</td>
<td>76.90</td>
<td>0.0214</td>
<td>0.0076</td>
</tr>
<tr>
<td>Granodiorite</td>
<td>15.2</td>
<td>10.51</td>
<td>106.30</td>
<td>0.0274</td>
<td>0.0245</td>
</tr>
<tr>
<td>Alk. &amp; Carb. rocks</td>
<td>12.9</td>
<td>10.72</td>
<td>92.80</td>
<td>0.0251</td>
<td>0.0210</td>
</tr>
</tbody>
</table>

**Resolution**

An elevation profile along a 4 km long stream in Norrsjön (subbasin no. 1) illustrated the problems in using a digital elevation model to characterise natural landscapes (figure 24). Here, the scale of the model is too coarse to register the proper elevation profile, and the progression downslope the stream channel is interrupted by frequent peaks.
As raster grid resolution successively was changed from a 50 m grid m to 100, 150 and 200 m grid, the correlation between mean TOPMODEL index values and mire occurrence (percentage mire per cell) was strengthened (figure 25a). Even the mean K-40 values were better correlated for a coarser grid resolution (figure 25b).

Figures 25a-b: The correlation between mire percentage and mean TOPMODEL values (left) and mean K-40 values (right) for the 200 meter grid resolution.
Discussion

The areal pattern of mires predicted from the topographic indices and gamma radiation agreed roughly with the expected wetness pattern in Kassjöån basin (figures 15-19). Slope and the TOPMODEL index display almost equally good pattern agreement. For these two indices, about 90% of the actual mire cells are within a distance of 110 meters from predicted mire cells (figure 22a). On the other hand, to locate 90% of the mires predicted by the TOPMODEL index, we need to go as far as 225 meters from the actual mires (figure 22b). Using this measure, slope and the drainage efficiency index perform much better in comparison with both the TOPMODEL index and the K-40 radiation (e.g. for the drainage efficiency index, 90% of the predicted mires are within about 150 meters from the actual mires.

In order to evaluate the performance of any mire prediction, both distance analysis measures need to be considered. The best prediction shows a good performance from both methods. A map with randomly distributed mires would give a very quickly rising curve for the first method (a randomly distributed mire is always quite close to an actual mire), but a very slowly rising curve for the second method (a lot of randomly distributed mire cells are far from actual mires). These random properties are also visible in the TOPMODEL index mire map (i.e. a quickly rising curve in figure 22a, and a slowly rising curve in figure 22b). These random properties are not so obvious in the performances of the other wetness indicators. In this sense, these two different approaches to quantify pattern agreement between different wetness indicators and actual mires have been very helpful.

Considering the distributions of mire and non mire cells for the different wetness indicators, the proposed index of drainage efficiency displays a much better separation of mires and non mires than do other indices (K-S $D=0.57$, table 4). This is consistent with the arguments by, e.g. Anderson and Kneale [1982], that downslope conditions become very important to flow conditions on gentle slopes. Most of the mires in Kassjöån are located in quite flat regions, which explains why the drainage efficiency index and slope are so successful in their predictions.

The calculation of both global and local threshold values in Kassjöån gave valuable insights to the relationship between topographic indices, gamma radiation and mire occurrence in Kassjöån. If the local threshold values had been identical for any of the wetness indicators, it would be able to give accurate soil moisture estimates in any region without a priori knowledge of landscape characteristics. This would imply that, e.g. identical TOPMODEL index values would represent the same soil moisture content regardless of their geographical position.

One of the most important reasons to the development of the TOPMODEL index was that it enabled a catchment to be divided into classes of hydrologically similar units. This is done by descretisation of the index distribution function (Beven et al., 1995). In this study, the opposite direction was taken: starting from a hydrologically similar unit (i.e. mires), the class limit of this unit was identified (i.e. the threshold value). If mires can be treated as hydrologically similar according to the TOPMODEL theory, they should have the same class limit. However, the variation of the local threshold values was quite large for all wetness measures in this study (table 5b).

For all topographic indices, this variation was found to be more or less correlated to the percentage of mire area in each subbasin. The TOPMODEL index, in particular, showed an almost perfect match with mire area ($r^2=0.93$, figure 20a). This is a troublesome discovery which undermines the hypothesis that the TOPMODEL index would yield independent soil
moisture measurements. It implies that the distributions for the TOPMODEL index in different subbasins are quite similar, and are not correlated to the fractions of mire area. This is supported by the poor correlation between average TOPMODEL index values and mire area fractions for the different subbasins (figure 20b), where there is no visible correlation between TOPMODEL average values and mire area fraction. Yet, the index explains almost 40% of the mires from the land use map (table 7). There may be several reasons to this.

One possible reason to the poor correlation of TOPMODEL index distributions (average values) with mire area fractions is that all mires cannot be predicted from the TOPMODEL index. The mires used in this study may not be hydrologically similar, thus violating the basic assumption for defining a threshold value for the entire mire class. For instance, mire development in some cases may be controlled by other factors than topography. In ombrotropic bogs (raised mires), all water inputs come directly from precipitation (Semádeni-Davies, 1996). These mires can develop on relatively flat plateaus which are not necessarily in lowland regions. Consequently, the upslope area for these locations can be very small. Considering that this attribute is an essential part of the TOPMODEL index, mire cells that represent raised mires could have relatively low index values. The relatively small topographic gradient of these cells may not be sufficient to produce a high index value. The importance of this problem is difficult to evaluate, since land use maps do not contain information about the type of mires present. This hypothesis could only be tested if a detailed field study was conducted beforehand.

Merot et al. (1995) obtained different soil water regime class limits (threshold values) in a study of TOPMODEL index values from two catchments in Brittany, France. They suggested that this difference could be caused by altering geology in the two catchments, since some rocks are known to have a higher hydraulic conductivity than others. This implies that it takes a high threshold value to develop mires on bedrocks with high hydraulic conductivity, since the vertical drainage capacity is large. However, this hypothesis is difficult to validate in Kassjöån. There are only small differences in average values and threshold values between the different geological regions (tables 8-9), if the granitic region is excluded (which only represents 1% of the area). There may be a small tendency of lower threshold values for dolerite, suggesting that this rock has a smaller drainage capacity than other rocks, but the deviation of these threshold values is quite small.

For the K-40 gamma radiation, the mire area in subbasins at the center of Kassjöån was heavily overestimated (table 6, figure 17). The may be several reasons to this, but there seemed to be a strong connection with the geology of this region (figure 3, tables 8-9). Dolerite typically emit lower gamma radiation than do most other rocks (Grasty, 1976). If the gamma radiation emitted from the bedrock and/or mineral soil is significantly lower from this region, this will give an overestimation of mires predicted from a global threshold value. In comparison, granodiorite is known to emit more gamma radiation, and areas with this geology (e.g. subbasin no. 13) have an underestimated fraction of mire area (figure 17), due to a higher local threshold value for this region (table 8). This illustrates the effects of a non-uniform bedrock/soil for wetness predictions from gamma radiation measurements. If non-calibrated gammaray measurements are to be used for wetness classifications, such as in this study, serious errors can be made unless the geology is homogeneous.

One explanation to the variation in local threshold values that has not been considered so far is the possible errors in the land use survey procedure. The land use data has been treated as a true measure of mire occurrence throughout the study, but the errors in this material are unknown. A large part of these surveys rely on airborne photographs over the area, and it is probable that small mires are underestimated since these are more difficult to observe from photographs.
The comparison of actual and predicted mire areas in each subbasin that resulted from setting a global threshold value (table 6) revealed some interesting patterns. For the TOPMODEL index, mire area was more underestimated in subbasins with large fractions of mire area and overestimated in areas with small fractions of mire area, as a direct consequence of the relationship between local threshold values and mire area. Hence, predictions from global threshold values were generally not able to reproduce extremes, and tended to smoothen out the differences between the subbasins.

The method for calibrating the channel initiation threshold (CIT) area from comparing predicted stream cells with the actual drainage network worked satisfactory. From both the specific cases in figures 9-11 and the general result in figure 12, it is clear that the concept of a channel initiation threshold works quite well in some cases, but also fails to represent the drainage network in other cases. Some areas in figure 12 show predicted streams where there are no streams, and also fail to predict some of the actual streams. There can be many reasons to this, but naturally, errors from DEM resolution are likely to affect the success of the predictions. Some landscape features have a smaller resolution than the GIS grid resolution, i.e. narrow valleys and thin ridges (e.g. the stream profile in figure 24). Moreover, it is also highly probable that the drainage pattern used as a reference in this study also have missed a few streams due to survey procedures. The criteria for registering a stream in the land use survey methodology may not be that well defined. In addition, there is also the geological factor. If the underlying bedrock in some locations is fractured or have a very high hydraulic conductivity, water could be drained downwards instead of forming channel flow at the surface. Thus, although the upslope area is a very useful indicator of the probable location of stream headwaters, many other factors seem to affect this relationship.
Conclusions

Of all the tested wetness indicators in this study, the best predictions were made by the drainage efficiency index (46.8% correct mire cells of all mire cells), which was proposed in the beginning of the study as an alternative to the TOPMODEL index and slope. The overall pattern of predicted mire distribution also agreed very well with the pattern of mires from land use maps.

Mire predictions from K-40 gamma radiation was strongly correlated to the geological characteristics in the area and did not reproduce an accurate overall mire pattern. The method also tended to give large lumps of mires, and this may be explained by the relatively coarse resolution of the raw which hindered many smaller mires from being detected.

The mire class limit (local threshold value) for the TOPMODEL index was strongly correlated to mire area, which prevented this index from being a good indicator of mires. It could not reproduce accurate amounts of area in the subbasins from a global threshold value that indicated mire occurrence. The general patterns of the predicted mires agreed relatively well with the pattern of mires from the land use map.

Acknowledgements

I would like to express my gratitude to everybody who have supported me during this demanding period:

First, I would like to thank my examiner, Professor Sven Halldin, who helped to keep the schedule tight. Also, many thanks to my supervisors, Dr. Allan Rodhe and Jan Seibert, who suggested the study and critically reviewed my work in progress. They were extremely supportive through their great experience from hydrology and computer modelling. Somehow, they were always ready to help me solve problems en route.

I would also like to thank Tomas Thierfelder for assisting with data conversions, Tony Persson for lending me his computer, Dr. Tomas Nord for the best on-line support available, Peter Hjelm for helping out with the digitizing procedure, Professor Mike Kirkby for sending me articles, and all other persons in- and outside academia who have assisted my work in any way.

Last, thanks Erpur for giving me all the thrilling rides on your back, and thanks Anna for just being there all the time.
References


Eastman, J. R., 1995. IDRISI for Windows user’s guide, version 1.0. Clark University. USA


Quinn, P. F., Beven, K. J., and R. Lamb, 1995. The ln(a/tanB) index: How to calculate it and how to use it within the TOPMODEL framework. *Hydrological Processes*, 9, 161-182


**Spatial data sources**


**Land use and hydrography (digital):** Sheets 17G NO, 17G NV, 18G SV, and 18G SO. The national topographic map (Gröna Kortan). Scale 1:50 000. Geografiska Sverigesdat (GSD), The National Survey of Sweden (Lantmäteriverket), Gävle, 1994.


**Water divide (digital):** Kassjön representative basin, the Swedish Meterological and Hydrological Institute (Sveriges Meterologiska och Hydrologiska Institut, SMHI), Norrköping.

**Addresses**

Jan Seibert
Institute of Earth Sciences, Hydrology
Norbyvägen 18B
S-752 36 UPPSALA
SWEDEN

Geological Survey of Sweden (SGU)
Box 670
S-751 28 UPPSALA
SWEDEN
Appendix A

In order to use the interpolation algorithm kriging, the semi-variogram had to be calculated for the K-40 gamma radiation. This was done by a computer program written in the MATLAB programming language. Basically, the program centers a moving circular matrix on every data node and calculates the semi-variance from the centre to all other nodes inside the circle. The circular matrix was limited to have a radius of 2000 meters, since beyond that distance, the semi-variogram was more or less identical with twice the variance value of the data set, i.e. there was no further spatial correlation beyond this point.

From the semi-variogram, a two-component exponential function was found to describe the semi-variance best. The parameters of this function was manually fitted, and they were then used in the kriging algorithm.

The semi-variogram suggested that a search radius of 1000 meters could be used in the kriging algorithm, in order to conserve the anomalies in the data as much as possible.

An exponential function was fitted to the semi-variogram for the $^{40}$K:

$$\gamma(h) = C_1 \left[ 1 - e^{-h_1} \right] + C_2 \left[ 1 - e^{-h_2} \right]$$

Where

$$h_i = \frac{\sqrt{\Delta x^2 + \Delta y^2}}{A_i} \quad \text{and} \quad i = 1, 2$$

Fitted parameters: $C_1=8200$, $A_1=160$, $C_2=2350$, $A_2=1100$
Appendix B

In order to calculate plan- and profile curvature, a program was written in MATLAB in which a cubic surface with nine coefficients, $Z$, is fitted to nine elevation spots in a moving 3*3 submatrix, $q$:

$$Z = Ax^2y^2 + Bxy + Cx^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I$$  \hspace{1cm} (B1)

According to Zevenbergen and Thorne [1987], primary topographic attributes can be expressed as functions of the coefficients in the fitted polynomial. In this study, the fitting of $Z$ to the elevation matrix was done by matrix algebra:

$$q = \begin{bmatrix} z_1 & z_2 & z_3 \\ z_4 & z_5 & z_6 \\ z_7 & z_8 & z_9 \end{bmatrix} \quad \text{relative (x, y) positions in } q = \begin{bmatrix} (-r, r) & (0, r) & (r, r) \\ (-r, 0) & (0, 0) & (r, 0) \\ (-r, -r) & (0, -r) & (r, -r) \end{bmatrix}$$

Where

$$R = \begin{bmatrix} r^4 - r^3 & r^3 & r^2 & r^2 & -r^2 & r & -r & 1 \\ 0 & 0 & 0 & r^2 & 0 & 0 & r & 0 & 1 \\ r^4 & r^3 & r^2 & r^2 & r^2 & r & r & 1 \\ 0 & 0 & 0 & 0 & r^2 & 0 & 0 & -r & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & r^2 & 0 & 0 & r & 1 \\ r^4 & -r^3 & -r^3 & r^2 & r^2 & r^2 & -r & -r & 1 \\ 0 & 0 & 0 & r^2 & 0 & -r^2 & -r & 0 & 1 \\ r^4 & r^3 & -r^3 & r^2 & r^2 & -r^2 & -r & r & 1 \end{bmatrix} \quad W = \begin{bmatrix} A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \\ I \end{bmatrix} \quad Q = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \\ z_6 \\ z_7 \\ z_8 \\ z_9 \end{bmatrix}$$

For each row in $R$, the xy-terms of the polynomial (B1) are evaluated for the (x,y) positions in submatrix $q$ ($i=1...9$). Here, the values of $x$ and $y$ are set to equal $\pm r$, which means that the horizontal and vertical resolutions are identical. $Q$ is a rearranged form of the moving elevation submatrix, $q$.

$$RW = Q$$  \hspace{1cm} (B2)

In MATLAB, (B2) can be solved through Gauss elimination with one single command:

$$W = R \backslash Q$$  \hspace{1cm} (B3)
From \textbf{W}, the attributes are solved for using the relationships given by Zevenbergen and Thornes [1987]:

\[ \text{Slope} = -\sqrt{G^2 + H^2} \]  \hspace{1cm} (B4)
\[ \text{Aspect} = \arctan \left( \frac{-H}{-G} \right) \]  \hspace{1cm} (B5)
\[ \text{Profile curvature} = \frac{-2(DG^2 + EH^2 - FGH)}{(G^2 + H^2)} \]  \hspace{1cm} (B6)
\[ \text{Plan curvature} = \frac{2(DH^2 + EG^2 - FGH)}{(G^2 + H^2)} \]  \hspace{1cm} (B7)

Slope is defined by (A4) in units of \([\text{meters/meters}]\), aspect from (A5) in \([\text{radians}]\), and profile- and plan curvature in \([1/\text{meter}]\).

Figure B1: Profile curvature in Kassjöän. Concave regions are dark and convex regions light.

Figure B2: Plan curvature in Kassjöän. Concave regions are dark and convex regions light.
Appendix C

One of the most popular models that take topographical variance into account is TOPMODEL (Beven et al., 1995). This model uses a distributed approach to lump a catchment into hydrologically similar units, which then are modelled separately. One reason to the success of TOPMODEL is the attractive simplicity of the model. The model relies upon four basic assumptions (Beven et al., 1995):

A1. The dynamics of the saturated zone can be approximated by successive steady state assumptions.
A2. The hydraulic gradient of the saturated zone can be approximated by the local ground surface gradient, tanβ.
A3. The distribution of downslope transmissivity with depth is an exponential function of storage deficit or depth to the ground water table.
A4. The recharge rate r (entering the ground water table) is spatially uniform.

Under these assumptions, the distribution of downslope transmissivity with depth is an exponential function of the depth to the water table (1):

\[ T = T_0 e^{-fz} \]

where \( T_0 \) is the lateral transmissivity when the soil is just saturated \( [m^2/h] \), \( z \) is the depth to the ground water table \( [m] \), and \( f \) is a scaling parameter \( [1/m] \). Assumption A2 implies that the saturated subsurface flow can be estimated by substituting (1) into Darcy’s law, yielding (2):

\[ q_i = T_0 e^{-fz_i} \tan \beta \]

where \( q_i \) is the downslope saturated subsurface flow rate per unit contour length \( [m^2/h] \) at any point on a hillslope. This flow rate can also be defined from assumption A4, yielding (3):

\[ q_i = ra \]

where \( r \) is the spatially and temporally constant recharge rate \( [m/h] \) and \( a \) is the upslope area that drains through a unit contour length at point \( i \). A combination of (2) and (3) gives an expression which relates the local depth of the ground water table to the topographic index \( \ln(a/\tan \beta) \) at any point \( i \) in a catchment (4):

\[ z_i = \frac{-1}{f} \ln \frac{ra}{T_0 \tan \beta} \]

The mean depth to the ground water table in the catchment \( z \) can be estimated by integrating (4) over the entire area of the catchment \( A \), i.e. summing all the cells in the area and dividing by the total area (5):

\[ z = \frac{1}{A} \sum_i \frac{-1}{f} \ln \frac{ra}{T_i \tan \beta} \]

Assuming a spatially constant \( r \), (4) can be substituted into (5), eliminating \( \ln r \) and giving a relationship between mean ground water table depth, local ground water table depth, the topographic variables and saturated transmissivity (6):
\[ f(z - z_i) = \left[ \ln \frac{a}{\tan \beta} - \lambda \right] - \left[ \ln T_0 - \ln T_e \right] \]

Where \( \lambda \) is the average topographic index of the area:

\[ \lambda = \frac{1}{A} \sum_i \ln \frac{a}{\tan \beta} \]

And \( T_e \) is the areal average transmissivity:

\[ \ln T_e = \frac{1}{A} \sum_i \ln T_0 \]

Thus, the distribution of the index \( \ln(a/\tan \beta) \) gives a direct measure of the relative depth to the ground water table in every cell of the catchment. A high index value (as compared to the average) means a relatively high ground water table and a high soil moisture content.