Climate modelling for road planning using Geographical Information Systems

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INTRODUCTION

By constructing a local climate map with a geographical information system (GIS), much time can be saved. When a computerised method for this process is developed, it is also standardised in a way that the map will look exactly the same no matter who made it. The local climatological mapping of today is most often performed by field measurements and analysis of aerial photographs and maps. Geometrical calculations, of for instance incoming solar radiation, are carried out by measurements on topographical maps. This usually takes a lot of time and effort. GIS however, allow mathematical calculations at a fraction of the time previously required. Grouping and classification of map data is still necessary, but handling, updating and merging of these data sets will be easier. Above all, GIS imply that the information shown on a map can be adapted to different situations and the display can be adjusted as required. Furthermore, the data gathered can be dealt with statistically.

When planning new climatological influences are just one of the many factors which have to be considered. Lowell (1966) published one of the first studies which showed that local climatological variations are important in planning of new roads. In his study it was shown how weather became a deciding factor in the choice between alternate routes of the M62 between Liverpool and Hull. In the planning process, information on sections sensitive to climatological hazards are of interest. It is also important to know which stretch of road has the highest winter maintenance costs as a consequence of its local climate. Stretches with a higher frequency of road slipperiness require more frequent preventive actions such as salting and gritting. A map considering the above mentioned facts under different weather conditions, would be useful in this context. It can then be shown which areas in the terrain have a higher frequency of low temperatures and risk of road icing on the whole, i.e. areas that should be avoided as far as possible for new construction of roads.

As hazardous road conditions occur for different reasons during different weather situations, each case has to be studied separately. In general studies it is important to differentiate the basic weather situations existing. From a combination of these, more complicated situations can be modelled. The statistical analysis can furthermore be used to give an idea of the spectrum of climate conditions which are likely to be found in an area.

The aim of this study is to develop a method of evaluating the topo-climate in an area using GIS. The final result will be a map which can be used in minimising winter-time weather problems of new roads already at the planning stage. The map will therefore only show relative differences and no exact values of any parameters. The method is based on risk of low surface temperatures including the frequency of occurrence for the respective weather situation.

METHODS

When mapping the local climate, a test area of 25 x 25 km was chosen. It is situated on the southern Swedish west coast. A digital elevation model (DEM) with a resolution of 50 meters was used as original source. IDRISI is a raster-based software for the processing of geographical information and images (Clark University, 1995), which it was used for the map analyses.

Previous studies, by for example Bogren (1991) and Gustavsson and Bogren (1993), have shown that it is possible to separate a specific number of weather situations which are especially important to deal with in modelling of local climate. These three situations are: i) clear and calm nights, ii) clear days and iii) cloudy and windy weather. During these situations different factors interact and give rise to local temperature variations. By modelling these situations, and taking into account all the parameters that can be important, the basic climatological factors are covered, e.g. short wave and long wave radiation and their variation due to sheltering etc., cold air patterns and variations in altitude.

It is important to know how frequent each situation is in the area of interest. On the basis of this statistics, it is possible to compile maps for different weather situations. A climatological feature for each weather situation was given a different value according to the relative influence it has on the temperature pattern. Three risk classes were used for low temperatures (2, 1 and 0), where the lowest temperatures were assigned the value 2. The average of the whole area is represented by 0 and 1 is an intermediate class. For areas where a higher than average temperature is expected, classes -1 and -2 are used. An urban heat island or a sun exposed slope has a positive effect on the local climate, i.e. results in a somewhat higher temperature, while a cold air pool or a shady slope exerts a negative influence. This classification was combined with the frequency of that specific weather situation. The result is a map showing where the local climate deviates from the "average" climate in terms of risk frequency of low temperatures.

Cloudy and windy situations

On these occasions, temperature decreases with altitude according to the dry adiabatic lapse rate, i.e. $\partial T/\partial z$ is approximately 1°C/100m. When the temperature is around zero degrees, precipitation can fall in the form of snow instead of rain depending on elevation or if the road surface is moist, it can be covered with ice. Especially the latter case can take drivers by surprise, if the road runs from low-lying, non frozen areas, to more elevated sections with a greater risk of slipperiness. A division of the DEM was made into three classes equal in size (Table 1).

Clear and calm night

The distribution of cold air is one of the most important factors for the occurrence of ground temperature differences during clear and calm nights. Lower wind speeds generally cause larger differences in temperature between valleys and their surroundings, while stronger winds, exceeding about 3 m/s, level out the differences if the valley is not sheltered by steep valley sides, trees etc (Bogren and Gustavsson 1991).

In order to distinguish areas in which cold air forms and gathers, a map showing sparsely vegetated areas and forests, respectively, is required. It was made by digitising a topographical map on the scale of 1:50 000. Areas in which cold air could gather were defined by studies of the topographic map and aerial photographs, as well as by using previous studies (Lindqvist et al., 1983) and field control. Higher temperatures may occur in urban areas when compared to rural areas during clear and calm nights. All built-up areas were therefore classified with negative risk-values. Like the map showing variations in altitude, the cold air map was divided, according to Table 1, into three risk classes.

Table 1. The classification and weighting factors used in producing the climatological risk map.

	Weather situation		
	Cloudy and windy	Clear and calm night	Clear day
Class (A)	**Classification method**		
	Height a.s.l., $u \geq 5$m/s and clouds $\geq 8/10$	Cold air potential, $u \leq 1.5$m/s and clouds $\leq 2/10$	Sun exposition
Maximum temperature amplitude	Lapse rate: about 1°C/100m	Geometrical size of cold air pool: about 6°C	Difference between shaded and exposed surface: about 15°C
-2			$\cos \Theta > 0.6$
-1		Urban areas	$\cos \Theta = 0.4 - 0.6$
0	0-66m	Forest	$\cos \Theta = 0.2 - 0.4$
1	66-132m	Sparsely vegetated	$\cos \Theta = 0 - 0.2$
2	>132m	Pools	$\cos \Theta < 0$
Climatological frequency in February (B)	37%	10%	15%
Risk	$= \Sigma$ weighting factors $* A * B$		

Clear day

On clear days, the amount of incoming solar radiation incident on a surface plays an important role in explaining the temperature pattern (see e.g., Gol'tsberg 1969, Oke 1987). Only the amount of direct short-wave radiation is dependent on the angle of incidence to the ground. According to Oke (1987), the diffuse incoming radiation has a small spatial variation and is thus approximately equally large, independent of the topography. The absolute differences in altitude in the study area is small (<200m) and atmospheric effects, like optical depth, can be considered constant.

Geometrical equations from Oke (1987) have been used in the calculations of relative differences in intensity of incoming direct radiation (S) to each pixel (raster map unit).

$$S=S_i * COS(\Theta)$$

$$COS\Theta = COS l * COS Z + SIN l * SIN\ Z * (COS\Omega * COS\ \alpha + SIN\Omega * SIN\alpha)$$

S_i = Intensity of radiation perpendicular to the rays, Θ = The angle of incidence, l = slope, α = aspect, Z = zenith angle, Ω = solar azimuth angle. l and α were represented by the IDRISI maps showing slope and aspect in degrees from 0 to 360. The slope of a pixel is ascertained by comparing it to the one closest above, below and the two on each side. This calculation method is called "Rook's case procedure". The aspect is the direction in which the maximum slope faces.

The extent of areas completely shaded will change markedly during that time and, consequently, also the temperature pattern. The map with the occasion "12 noon in February" was chosen as an example for classification and weighting against the other maps. This gives an example when the range of temperatures is large and also when the solar elevation is low enough to give some areas of very low radiation intensity. In Table 1 the classification of the map showing cosΘ is given, which is proportional to the intensity of incoming radiation.

Compiling the maps

Statistics of the frequency of cloudy/windy weather, clear/calm nights and clear days, respectively, is required in order to combine the maps from all weather situations to one final map. Each classified map was multiplied by the percentage stating how frequent the situation is, see Table 1. Then the maps of all situations were added and the highest values of the resulting map now represent areas with the most frequent risk of low temperatures. A specific risk value on the final map does not have an exact meaning of temperature or frequency of slipperiness, but it is an indication of the conditions on one place compared to another.

RESULTS

Since cloudy/windy weather occurs more frequently than clear situations, this classification will dominate the map and give elevated areas a greater total risk. This does not have to be the case for a different area, where other situations may dominate the climate. A theoretical maximum value for the risk map would be 800, which implies that four classes with the highest risk (class 2) overlap each other both during day- and night-time, while at the same time all weather situations have been covered to 100%. At midday in February the values of the risk map vary between -29.2 (low risk) and 103 (high risk).

Application of the method

It proved possible to compare the climate along two (or more) road stretches in a simple way by summing up their "climatic risk-points". The variation of temperature and associated risk of slipperiness along a road is important because it can easily take a driver by surprise. The top diagram in Figure 1 describes the modelled local climate along a section of the Swedish national highway 45 (RV45).

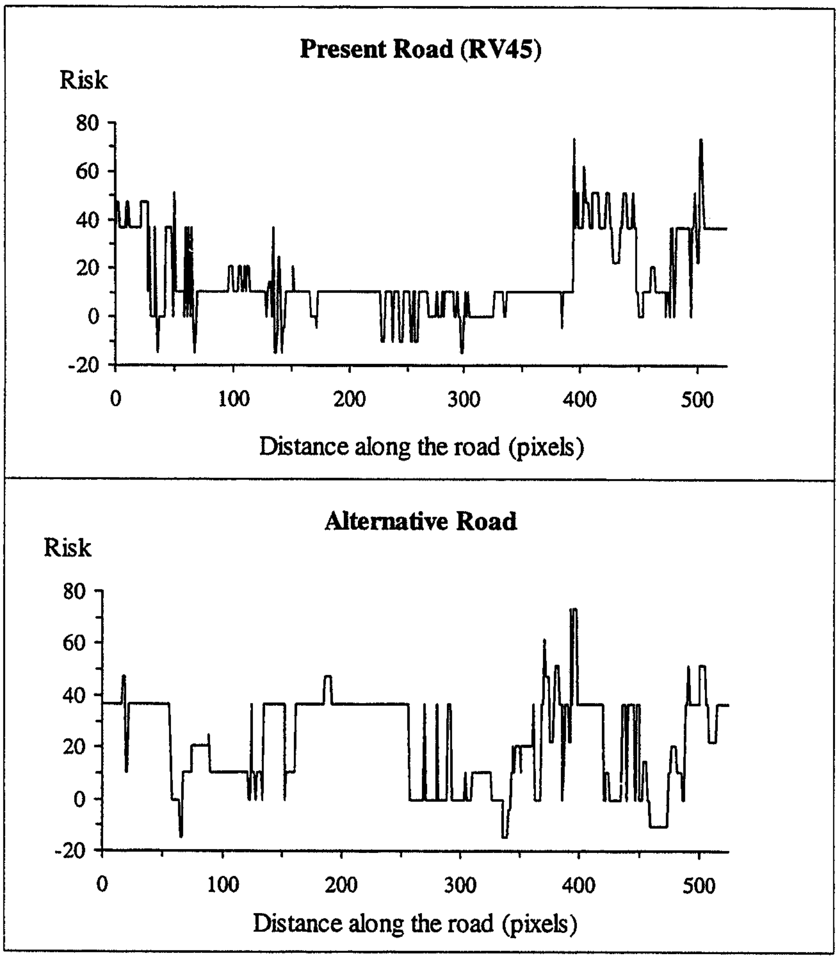

Figure 1. Comparison of the climate along two different road stretchings.

The larger part of this road has a quite uniform and low risk (around 0), but the first and the last part shows major changes in character of the climate (40-70). The second profile shows a planned alternative of the present road, situated a few kilometres further east in a more elevated terrain. This time the variations are larger and present along the entire stretch, indicating a road climate which is more difficult to predict. According to the model, the average risk is also higher along the planned road than along the present, making it a poorer alternative. Total risk for the whole road section can be calculated by summing up every pixel that is crossed by the road.

The modelled climate along the two alternative runs of RV45 was compared with a local climatological evaluation made by Bogren (1994) in the same area. The study showed that the local climate does not vary as much along the present stretch as along the eastern alternative where elevated areas are interrupted by open valleys. Bogren (1994) also points out that it is these changes of different climatological environments with slipperiness during a number of different weather situations that should be avoided in the planning of a new road stretch. The modelled climate map concurs well with the above-mentioned study in the areas along the road stretches in question.

Concluding remarks

This method provides a general way of comparing different situations, with only main features included. It is not yet a completely consistent model, since the comparison between situations is not connected to precise temperature differences, meaning that risk class number two for one situation does not necessarily mean that it is twice as large risk as class number one for another situation. Another important factor is that the temperature fluctuations around zero are crucial when road slipperiness is concerned. This problem can be accounted for, in a further development of the model, by incorporating more statistics in the model as well as weighting weather situations according to their effect on traffic safety. An ongoing study aims to relate weather parameters to winter road maintenance and traffic accidents.

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