Risk evaluation by modelling exposure to direct sunlight on rural highways – A GIS approach

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Abstract: This paper describes a methodology for evaluating risk on rural highways by modelling exposure to direct sunlight using Geographical Information Systems (GIS) technology. The methodology that was followed is based on the road network geometry, the relief of the study area under investigation (Digital Elevation Model – DEM) and the sun position for a specific day. The hillshade creation function as well as various filtering techniques have been adopted. These techniques are based on the geometry of road segments in comparison to the sun position. The output of this analysis is the identification of road network parts that appeared at risk. Additionally, the implementation of the proposed method for a long time period allows a dynamic modelling of the conditions under investigation.

Key-Words: GIS, spatial modelling, direct sunlight exposure, DEM, road network risk.

1 Introduction

A Geographical Information System (GIS) integrates hardware, software and data for capturing, storing, updating, managing, analyzing and displaying all forms of geographically referenced information [1].

GIS technology supports a variety of applications in urban planning, electric/gas utilities, health sciences, telecommunications, transportation, archaeology, agriculture, environment, forestry, geology, hydrology and many other scientific fields (among others [2], [3]). The role of GIS in all these applications is to provide users, managers and decision makers, powerful tools for solving complex spatial problems.

A GIS based spatial decision support system (SDSS) is an advanced modelling framework for decision makers in order to analyze and simulate various spatial phenomena [4]. GIS provides also response to user queries and operates as the computational platform for advanced analytical demands and spatial modelling [5]. Additionally, GIS technology is an efficient way for the analysis and the presentation of complex spatiotemporal (ST) phenomena.

In this study, we use GIS for the modelling of the exposure to direct sun light in a rural road network. The main target is to build a system able to identify road sections at risk due to direct sunlight for a specific time period. When a vehicle on a road is moving towards the direction of the sun and the sun altitude is low drivers may be experience temporal blindness and lose control of their vehicle. Drivers are exposed to direct sunlight daily and in many cases this is a reason for accidents.

Due to the dynamic nature of the earth-sun system, the exposure to sun irradiance varies from location to location on the earth surface and from time to time. Hence this is a ST phenomenon and should be handled accordingly [6].

To the best of our knowledge, although there are many studies that use GIS in road risk assessment, studies related with the proposed analysis are limited. Most of them explore the frequency of occurrence of accidents based on specific factors [7] and other use GIS as a tool for visualization of accident data and analysis of hot spots in highways [8].

The first part of this work refers to the physical process and the main controlling factors such as sun position (sun altitude and azimuth relevant to the site under investigation), topographical construction and the spatial properties of each road unit. Afterwards, the study emphasize on the spatial data structures (Digital Elevation Model: DEM, and hillshade layers) used for the efficient irradiance modeling in GIS environment. Hillshade layers are derived from DEM. By modelling hillshading we can quantify the local illumination and whether an area falls in a shadow caused from topographic extrusions or not [9].

Therefore, this paper aims to present a methodology for evaluating risk on road network by modelling exposure to direct sunlight with the use of GIS technology. The discussion is organized as follows: after this introduction we describe the data of the study as well as the proposed methodology. Afterwards, we present the implementation of the methodology to the study area (Santorini Island) and finally, the conclusions of this study are presented with comments about the limitations of the study and the potential applications of the proposed method.

2 Data - Methodology

The data used in this analysis could be classified in two main categories, the background data (road network, topography) and the data concerning the position of the sun during a given time period.

2.1 Background data

One of the most important data sets in this study is the DEM of the area under investigation (Santorini Island). This earth surface model (raster format with cell 20X20m) has been created using the ANUDEM algorithm from digitized data [10],[11].

The DEM derived from contour lines (contour interval 20m), elevation points and streams that were digitized from topographical analogue maps form Hellenic Military Geographical Service (scale 1:50.000).
Standard derivatives of DEM are slope, aspect and hillshade layers of the study area. Slope and aspect are indirectly used for the creation of hillshade layers.
The hillshade (relative Rf radiation that each cell receive) is given by the following formula [12]:

$$Rf = \cos(Af - As)\, \sin Hf * \cos Hs + \cos Hf * \sin Hs$$

Where:
Rf = relative radiation
Af = cell aspect
As = azimuth of sun
Hf = cell slope
Hs = altitude of sun

Thus, for a given sun position, if slope and aspect of a cell is known we can calculate the hillshade of this cell. Hillshade analysis has been used in many different applications [13], [14], [15].
The next step was the creation of the road network layer. This layer was digitized from the topographical map of Hellenic Military Geographical Service (Thira Sheet, Scale 1:50.000) and updated during onsite data capturing with the use of GPS technology.
In the following subsection, we will focus on the other main data of the proposed method: data related with the position of the sun for a specific time period.

2.2 Sun position data

Data reflecting sun position during a specific time period were taken from the astronomical server of the United States Naval Observatory (USNO). (Table 1). These data provide information about the solar altitude and azimuth angles. Altitude of the sun is the angle above the horizon and azimuth represents the direction of the sun measured clockwise from the North. Both altitude and azimuth are measured in degrees. The parameters required for the calculation of sun position are geographical coordinates (lat, lon) of the study area, the date and the time interval [5].

Hour	Altitude	Azimuth (E of N)
04:00	-10.4	50.8
05:00	0.1	60.4
06:00	10.5	69.0
07:00	21.9	76.9
08:00	33.8	84.9
09:00	45.8	93.8
10:00	57.7	105.3
11:00	68.6	124.3
12:00	75.9	164.3
13:00	73.5	217.6
14:00	63.9	245.8
15:00	52.4	260.5
16:00	40.4	270.5
17:00	28.4	278.8
18:00	16.7	286.7
19:00	5.6	294.8
20:00	-5.1	303.8

Table 1. Sun position data, Santorini island, Jun 10, 2009 (http://www.usno.navy.mil/USNO/astro nomical-applications/data-services/rs-one-day-us).

For this study, the sun position above Santorini island (25.45° E, 36.40° N) was calculated for June 10th 2009 (time interval: 1 hour). These two values of sun's position are used in conjunction with DEM to produce hillshade layers as described in the previous subsection.

2.3 Analytical procedures – Data flow

The proposed methodology is based on GIS functions combining the data of the study area (fig. 1). Initially, the road network is divided into straight line segments with constant geometry. This division is based on the identification of vertices on every road line. The result of this operation is the split of road network in segments with constant direction. These line elements are more manageable and are the basis for the proposed methodology.

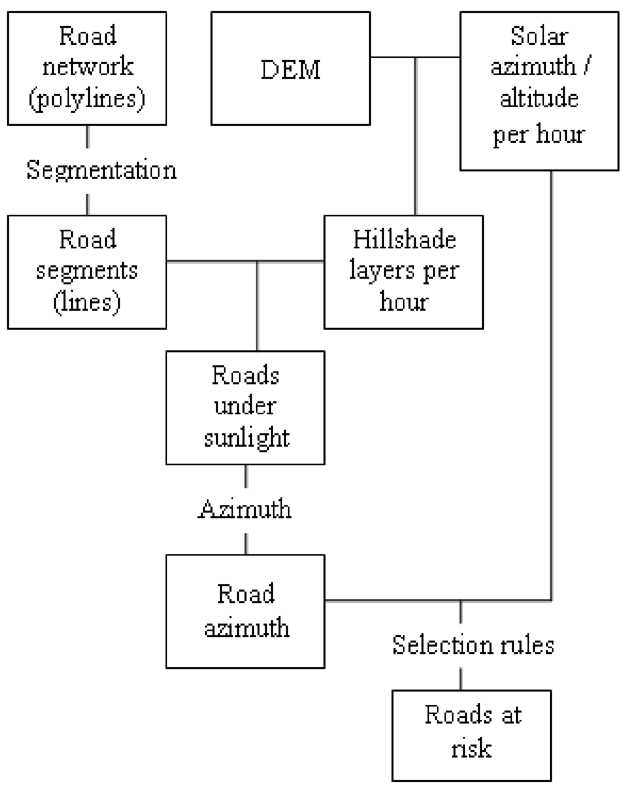

Fig.1 Data flow of the proposed methodology.

The next step is related with the production of hillshade maps in order to identify shaded areas. The derivation of a hillshade layer is based on the relief of the area (DEM) as well as the position of the sun for a specific time [16]. As the solar altitude and azimuth are known, the hillshade layers are created, from sunrise to the sunset.

Hillshade layers for each time snapshot enable selection of road segments that are under shadow or not. The road segments located in a shadowed area for a specific time snapshoot were marked as "safe" and excluded from the analysis, in order to continue the procedure with the remained road sections. After this filtering, the direction of the road segments in non-shadowed areas was calculated in order to compare it with the sun azimuth.

From this final check road segments that have somehow similar direction with the sun azimuth were classified as roads at risk as they are highly exposed to direct sunlight. It must be noted that this procedure is automated and repeated for every hour of the day under investigation.

3 Results

As study area the island of Santorini was selected (Fig. 2). Santorini is in South East Greece, in the Aegean Sea. It is also known as Thira and is the southernmost of the Cyclades Islands with an area of approximately 76 km² and population of 13670 permanent habitants (2001 census, National Statistical Service of Greece). It must be noted that Santorini is one of the major touristic destinations of Greece. Thus, in summer time the population of the island is highly increased due to massive arrival of tourists.

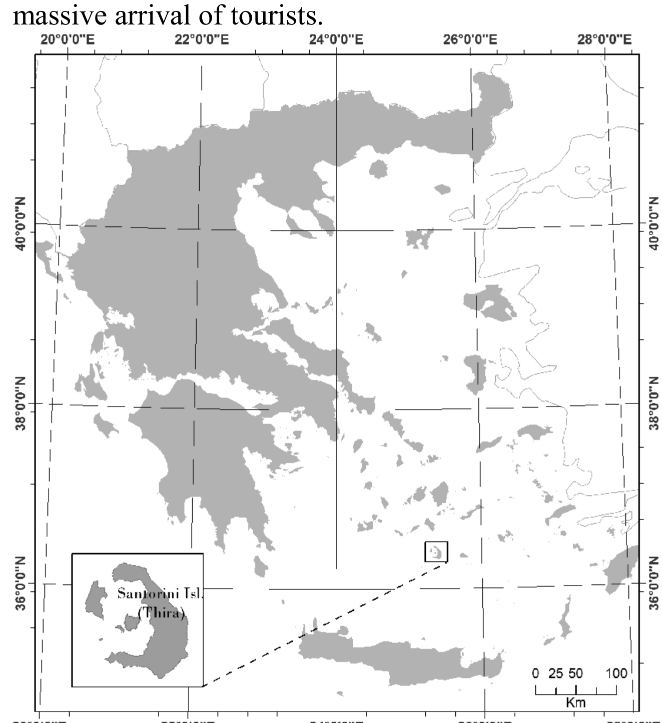

Fig.2 Study area: Santorini Island (Thira).

There are thirty five settlements on the island and the capital is the town of Thira. Thira is located in the central part of the island and has population of 2113 habitants. Other important settlements are Oia, Emporios and Kamari. It should also be noted that Santorini has a rather complex road network (Fig. 3).

The methodology described above was followed for 10th June, 2009. This time period was chosen because summer days have longer duration and the results cover more hours of the day. Additionally during the summer time more drivers are exposed to the risk under investigation because of increased traffic caused from the significant touristic activity.

According to the methodology described above, the road network was divided into straight line road segments. Afterwards, the hillshade layers were created for every hour using the corresponding sun altitude and azimuth. Sun position data for June 10 2009 (Table 1) shows that the sunrise began at 05:00 am and the sunset was after 19:00 pm. All time snapshots with solar altitude more than 40^o were excluded from the analysis as we assumed that if sun height is above this threshold there is no direct sunlight exposure. Sun position data shows that from 09:00 am to 15:00 pm the altitude of sun was more than 40^o, so these hours do not affect the road network with direct sunlight. Based on these, hillshade layers were created for every hour during 05:00 - 08:00 am and 16:00 - 19:00 pm.

Similarly, road network segment located under shadows were also excluded from the analysis. The direction for the remaining segments that are under sunlight was calculated. As the direction of each road section is known, it can be compared to the azimuth of the sun in order to check if it is affected by direct sunlight. Thus, direction was compared with solar azimuth for every time snapshot. All road segments that have the same azimuth (± 5^o) with azimuth of sun are classified as roads at risk. This threshold was added in order to overcome unclarities caused from spatial errors in road network layer as well as accuracy issues in sun position data.

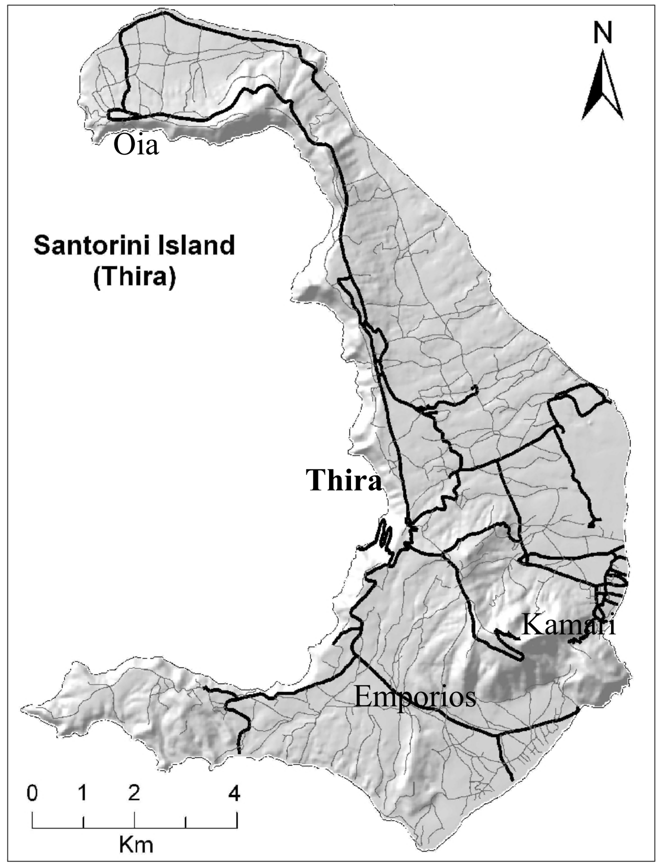

Fig.3 Santorini's Road Network. Bold lines: primary road network, gray lines: secondary road network.

Moreover, the length for each road segment was calculated. The result was that 6 km of the road network of Santorini are exposed to direct sunlight during the day of the modelling.

A first reading of the map with the risk zones at Santorini's road network (Fig. 4) shows up that most of the road segments at risk are on the secondary road network, while the length of the main road network at risk is 1.3 km, almost 21.6% of the total length of roads at risk zones.

It should also be noted that all roads are bidirectional rural roads, so the results show that most of them are exposed to direct sunlight both during the first sunrise hours (07:00 and 08:00 am) and the last sunset hours (16:00 and 17:00 pm).

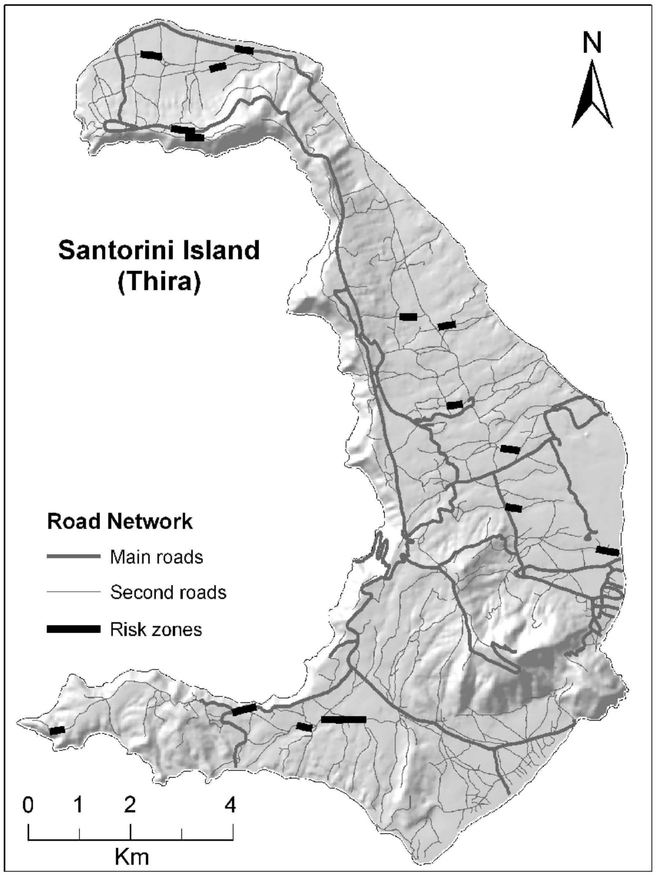

Fig.4: Highly exposed road segments – risk zones (for June 10, 2009).

4 Discussion - Conclusions

This study suggests that GIS technology can be used for the dynamic modelling of the exposure to direct sunlight on a rural road network. The method adopted in this paper use background data (road network, digital elevation model and its derivatives) and sun position data in combination with advanced GIS functionality for spatial analysis. Thus, we can dynamically model and map the exposure to direct sun light and point out the roads under high risk. Accordingly, the outputs of the analysis can support decision makers and enhance transportation planning and decision making process.

The identification of road segments that are at risk zones is very useful information in order to take appropriate decisions/acts to prevent accidents. Such acts could be the creation of visual barriers in high risk areas (e.g. row of trees) or even the placement of warning signs.

The implementation of the method in Santorini island shows that almost 2% of the total length of the road network is exposed to high risk conditions for at least 1h/day. Whether increased exposure actually means an increased risk of road accidents is a question that related to the limitations of the study (snapshots approach, road segments with extreme slope value, and special on site conditions). These are the main subjects of the future extension of the study.

In any case, GIS technology in co-operation with other similar technology can be used for the development of an automated real time warning system for the identification of high risk conditions.

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