A GIS-based spatiotemporal analysis of the exposure to direct sun light on rural highways

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Abstract: Geographical Information System (GIS) technology integrates hardware, software and spatial data for capturing, storing, updating, managing, analyzing and displaying geographical data and phenomena. Spatiotemporal analysis of such phenomena is one of the major tasks of a GIS. In this paper, we use GIS for the modeling of the exposure to direct sun light in a rural road network. When a vehicle is moving towards the direction of the sun, drivers may experience temporary loss of vision. The main target is to build a system able to identify road sections at risk due to direct sun-light for a specific time period. The proposed methodology is based on the road network geometry, the relief of the study area under investigation (Digital Elevation Model – DEM) and the sun position. The hillshade creation function and 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 for a specific time period. The proposed method is implemented in Santorini Island during summertime period. The results in this case study shows that a significant part (5% of the total road network length) of the road network is highly exposed to the risk under investigation during the summer. Additionally, the implementation of the proposed method for a long time period allows a dynamic modeling of the conditions under investigation, and the adoption of various preventing actions.

Key-Words: GIS, spatiotemporal modeling, direct sun-light exposure, DEM, road network risk analysis.

1 Introduction

A Geographical Information System (GIS) integrates hardware, software and spatial data for capturing, storing, updating, managing, analyzing and displaying all forms of geographically referenced information [1]. Geographical Information Systems have been proved an efficient technology for analyzing complex spatial phenomena. These systems have been successfully used in a wide variety of applications, such as earth science, urban utilities planning, transportation, natural resources protection and management, health sciences, forestry, natural disasters, and various aspects of environmental modeling and engineering [2],[3], [4], [5].

GIS technology supports applications from various fields (e.g. urban planning, electric/gas utilities, health sciences, telecommunications, transportation, archaeology, agriculture, environment, forestry, geology, hydrology and many other, (among others [6],[7],[8],[9]). The role of GIS in all these applications is to provide users, managers and decision makers, powerful tools for solving complex spatial problems. GIS provides also response to user queries and operates as the computational platform for advanced spatial analysis and modeling [4]. At the same time, a GIS based spatial decision support system (SDSS) is a powerful modeling framework for decision makers in order to analyze and simulate various spatial phenomena [10].

Additionally, GIS technology is an efficient way for the analysis and the presentation of complex spatiotemporal (ST) phenomena. In this paper, one aspect of road accident risk evaluation is considered as a spatiotemporal phenomenon and studied with the use of GIS technology. Road risk accident analysis may concern the study of accidents that had already occurred in an area and the study of risk factors which can be directly related to the occurrence of accidents [11], [12], [13]. Moreover, road risk analysis can identify high crash zones either between vehicles or in accidents with involved pedestrians [14]. A potential outcome of the proposed analysis is the prevention of accidents in rural road network. Therefore, risk analysis can be followed during a road network planning by considering spatial and thematic data [15].

In this study, we use GIS for the modeling of the exposure to direct sun light in a rural road network. The main aim of the current research effort was to build a system able to identify road sections at risk due to direct sun-light 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 in comparison with road gradient, drivers may experience temporary visual defects which are a common accident triggering factor [16].

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 [17].

To the best of our knowledge, although there are many studies that use GIS in road risk assessment, studies related to the proposed analysis are limited. The main part of these studies explore the frequency of occurrence of accidents based on specific factors [18], while others use GIS as a tool for visualization of accident data and analysis of hot spots in highways [19], [20].

The first part of this work refers to the physical process and the main controlling factors such as sun position (sun altitude and azimuth in a specific time in 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 sun-light modeling in GIS environment. Hillshade layers are derived from DEM. By modeling hillshade we can quantify the local illumination and whether an area falls in a shadow caused from topographic extrusions or not [21].

Thus, this paper aims to present a methodology for evaluating risk on road network segments by modeling exposure to direct sun-light with the use of GIS technology. After this short 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 future use of the proposed method.

2 Data

The data used in this paper could be classified in the following main categories:

a) Background spatial data concerning mainly the topography and the road network of the study area, and

b) Data concerning the position of the sun for a given time period.

2.1 Background spatial data

One of the most important data sets in this study is the Digital Elevation Model (DEM) of the area under investigation (Santorini Island). This earth surface model has been created using the ANUDEM algorithm from digitized data [22],[23]. The spatial resolution of the DEM of the study area was 20X20m and the reference system was the national Greek reference System (HGSA ‘87).

The DEM derived from contour lines (contour interval 20m), elevation points and stream network. These datasets were digitized from topographical analogue maps (source: Hellenic Military Geographical Service, scale 1:50.000).

Standard derivatives of DEM are slope, and aspect maps 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 [24]:

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

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

Thus, for a given position of the sun, if slope and aspect of a cell are known we can calculate the hillshade of this cell. Hillshade analysis has been used in many different applications in order to identify entities inside shadowed areas [25], [26], [27].

The next step was the construction of the road network layer (polyline geometry). This layer was digitized from the analog topographical map of Hellenic Military Geographical Service (Thira Sheet, Scale 1:50.000) and updated during field work (onsite data capturing with the use of GPS mobile devices).

In the following subsection, we will focus on the data related to 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) [28]. These data provide information about the solar altitude and azimuth angles. Altitude of the sun is the angle above the horizon while azimuth corresponds to the direction of the sun measured clockwise from the North. Both altitude and azimuth are measured in decimal degrees. The input parameters required for the calculation of sun position are geographical coordinates (Lat, Lon) of the study area, the date and the time interval [4].

Table 1. Sun position data: Altitude and Azimuth of the Sun for Santorini Island (E25° 27', N36° 24'), Zone: 2h East of Greenwich

Santorini Island, May 10, 2008.

h m	Altitude o	Azimuth o
05:00	-3.7	64.8
06:00	7.7	73.5
07:00	19.4	81.9
08:00	31.4	90.4
09:00	43.4	100.2
10:00	55.0	113.1
11:00	65.1	133.6
12:00	71.1	169.2
13:00	68.9	211.3
14:00	60.2	238.4
15:00	49.2	254.2
16:00	37.3	265.2
17:00	25.3	274.2
18:00	13.4	282.5
19:00	2.1	291.0
20:00	-9.1	300.3

Table 1 illustrates the data concerning the position of the sun over the study for May 10, 2008 (time interval: 1 hour). We can exclude some hours from further analysis on the basis of the comparison between sun altitude and maximum gradient of all road segments of the study area. From table 1 notice that between 09:00 – 15:00 the altitude of the sun is more than 40°. At the same time the maximum road gradient for the study area is less than 35°. Thus, for these hours of the day under investigation all road segments could marked as “safe”.

For this study, the sun position above Santorini island (E25° 27', N36° 24'), was calculated for various time periods during the summer of 2008. These two values for the definition of the sun position are further used in combination with DEM to produce hillshade layers as described in the previous subsection.

3. Methodology

The key point of the proposed modeling is GIS technology. GIS provides an effective mean to import, manage and analyze geographical data. The methodology used in this work comprised of three general phases (Fig. 1).

The first phase is related to the construction of the spatial database of the study area as described previously.

The second phase is dedicated on the creation of hillshade layers with the use of GIS spatial analysis functions and sun position data.

Finally, phase 3 consists of the implementation of an algorithm for the classification of road segments according to the exposure to direct sun light. This algorithm uses filtering techniques based on the comparison of the spatial features for each road segment with the values for the definition of sun position.

The spatiotemporal modeling was developed with the use of ArcGIS 9.2 GIS software, as well as 3dAnalyst and Spatial Analyst (SA) extensions and Model Builder tool [29], [30].

3.1 Spatial Database (SDB) creation

The proposed methodology is based on GIS functions and integration of various data of the study area (fig. 1). Thus, a spatial geodatabase was designed and implemented, using a standard commercial GIS environment (ESRI, ArcGIS). All GIS layers were georeferenced to the Greek Geodetic Reference System of 1987 [31].

This geodatabase consists of the following primary GIS layers:

- Road network (line topology)
- Contour lines (line topology)
- Elevation points (point topology)
- Stream network (line topology)
- Mainland (polygon topology)

The main source of these data is the Hellenic Military Geographical Service analog topographic

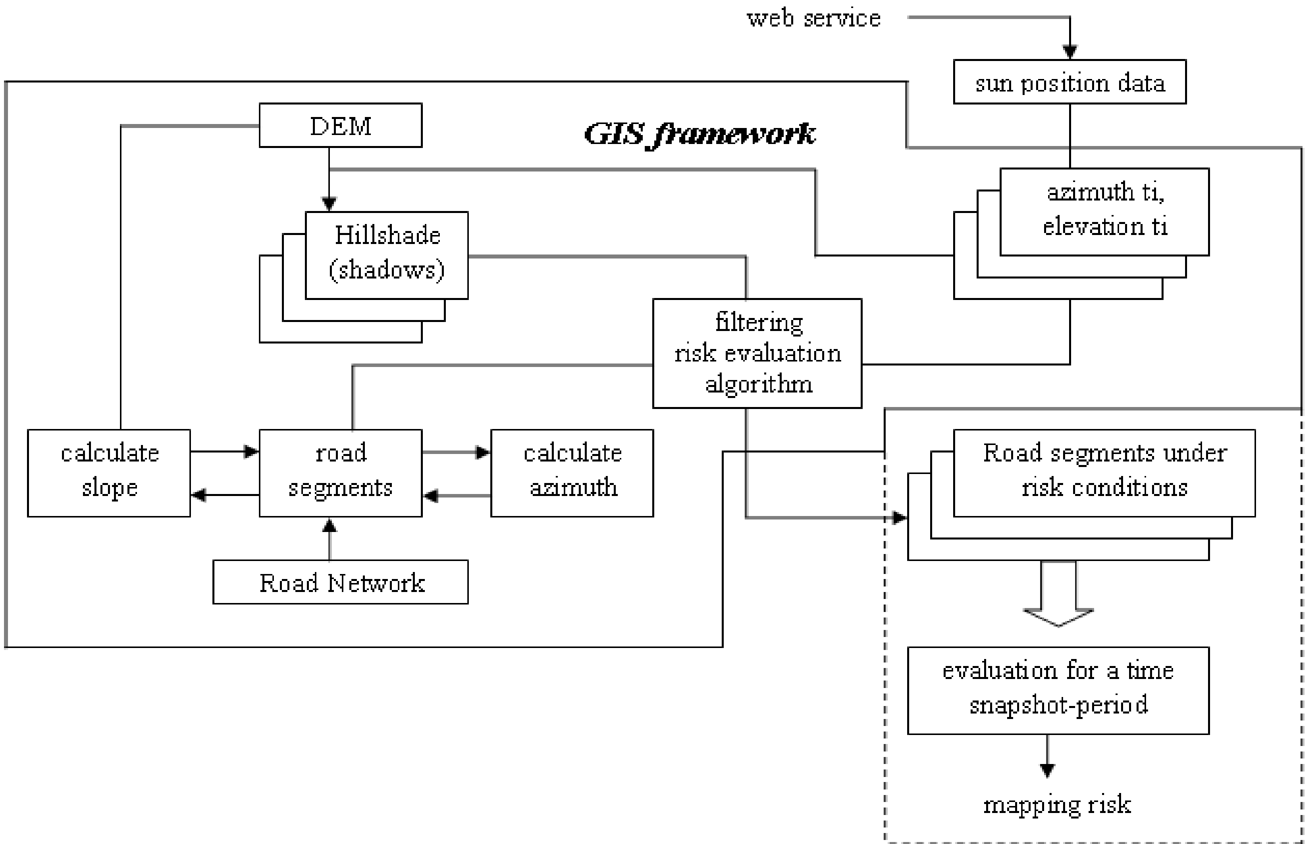

Fig.1 Data flow of the proposed methodology.

map, named Thira. The map scale was 1: 50.000 and the contour interval was 20m.

The post processing of these layers within GIS environment produce secondary thematic layers, e.g. Digital Elevation Model as well as segmented road network. Initially, the road network is divided into straight line segments with constant geometry. This division is a common GIS function (splitting) based on the identification of vertices for every road. The result of this operation is the segmentation of road network in parts (road segments) with constant direction. These line elements are more manageable and constitute the basis for the proposed methodology

3.2 Hillshade mapping

The next step is related to 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 [32].

The DEM for the study area was created with the use of ANUDEM algorithm within ESRI's ArcGIS environment [22], [23]. Thus, common derivables from DEM were created in order to produce hillshade maps. These outputs are slope and aspect maps. As the sun altitude and azimuth during one or more days are known, the hillshade layers could be created accordingly, from sunrise to the sunset, as described previously (section 2.1). The creation of hillshade layers for each time snapshot enables the selection of road segments in shadowed areas and furthermore the classification of each road segment based on its exposure to direct sun lights.

3.3 Road segment exposure to direct sun-light

The classification of all road segments according to the degree of exposure to direct sun-light is the final phase of the methodology. For this purpose an algorithm was implemented within the context of GIS environment. This algorithm utilizes the geometric features of each road segment (gradient, azimuth) as well as the sun position attributes for each time snapshot. The DEM of the study area in combination with the road network returns the gradient of each road segment (measured in decimal degrees). The azimuth of each road segment was calculated as a typical spatial routine from the x,y coordinates of the nodes for each line.

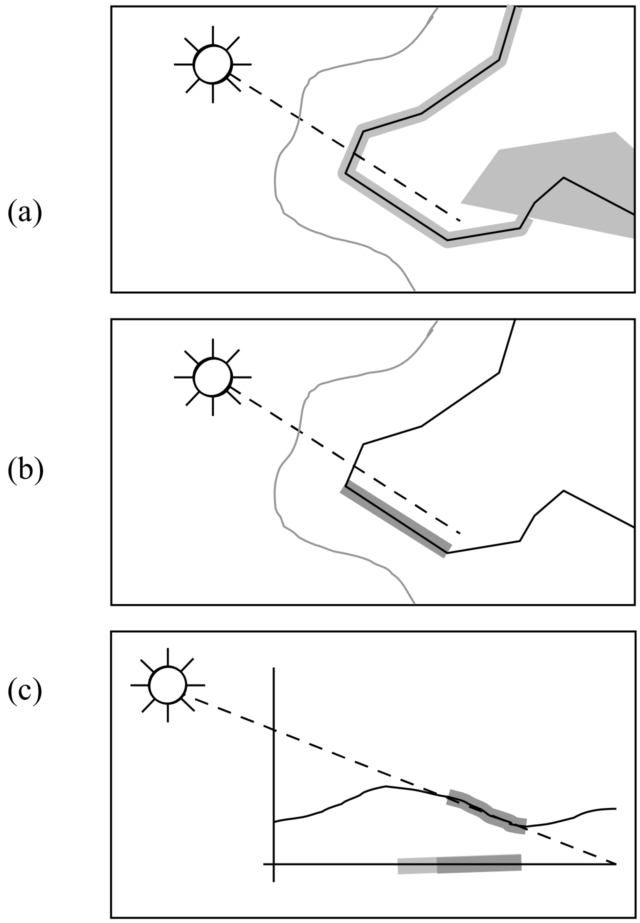

Fig. 2. The exposure of the road network to direct sun-light. Bold lines correspond to road segments with high values of according to: (a) shadowed areas, (b) azimuth filtering, (c) slope filtering

The first part of the proposed algorithm is related to the comparison between sun altitude and maximum road gradient. For the time period that sun altitude value is too high in comparison with road gradient further analysis has no meaning. This first check contributes to the reduction of the execution time of the proposed algorithm and provides as output the selection of the time snapshots for further analysis.

The next part of the algorithm is dedicated to the identification of road segments under shadowed areas. Thus, all road segments located in shadowed areas for a specific time snapshoot were marked as "safe" and excluded from further analysis, in order to continue the evaluation of direct sun-light exposure with the remained road segments (fig. 2a).

After this filtering of road network, the comparison of the direction of road segments with the sun azimuth was implemented. This procedure returns as output the selection of road segments that have identical direction (± 5°) with the sun azimuth (fig. 2b). It must be noticed that in this application, all rural roads are considered as double directional roads.

For all road segments with azimuth similar to the sun azimuth, we proceed to the comparison of their gradient with the sun altitude. From this last filtering procedure, road segments that have the same slope with the sun altitude are highly exposed to direct sun-light and they are considered as "road segments at risk" (fig. 2c).

The following pseudo code describes the road classification procedure:

1. INSERT location (lat, lon), time_period, time_interval
↓
2. CALCULATE LIST (ti, SunAlt_ti, SunAzm_ti)
↓
3. FOR EACH ti
↓
4. FOR EACH RJ
↓
5. IF shadows = Yes GOTO 9
↓
6. ELSE IF RjAzm ≠ SunAzm_ti GOTO 9
↓
7. ELSE IF RjAlt ≠ SunAlt_ti GOTO 9
↓
8. ELSE SET Rjti_risk = 1 GOTO 10
↓
9. SET Rjti_risk = 0
↓
10. REPEAT for all Rj
↓
11. REPEAT for all ti

It must be noted that the procedure described above was implemented with the use of GIS functionality, with the involvement of advanced spatial analysis procedures. Moreover, output data were further elaborated in order to create accumulated results for the time period under investigation.

4. Study Area

As study area the island of Santorini was selected. Santorini is in South East Greece, in the Aegean Sea (Fig. 3). 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).

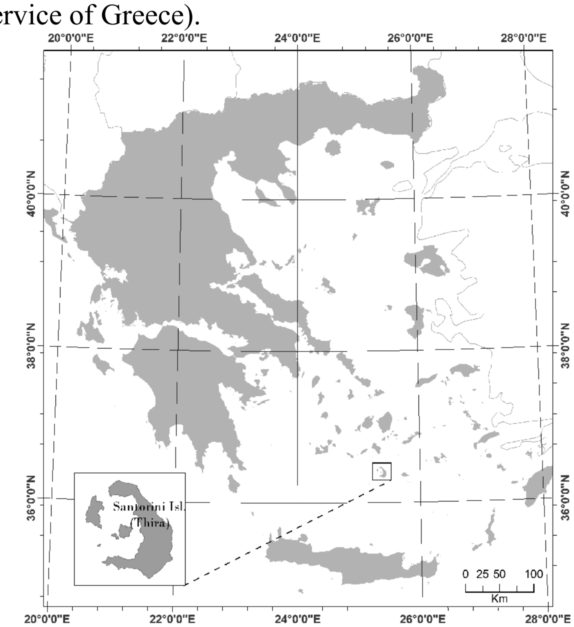

Fig.3 Study area: Santorini Island (Thira).

The island has a strong rural character as 37.6% of its area is covered by crop fields [33]. 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 arrivals of tourists.

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. 4).

The total length of road network is approximately 295 km while the mean gradient of road network is approximately 4° (fig. 5). Figure 5 presents statistical data for the road network of Santorini. X axis in this diagram corresponds to the gradient of road segments while Y axis to the number of road segments. The gradient value for the majority of road segments is less than 10°, while few segments have gradient more than 20°. The maximum calculated gradient value is 38.73°.

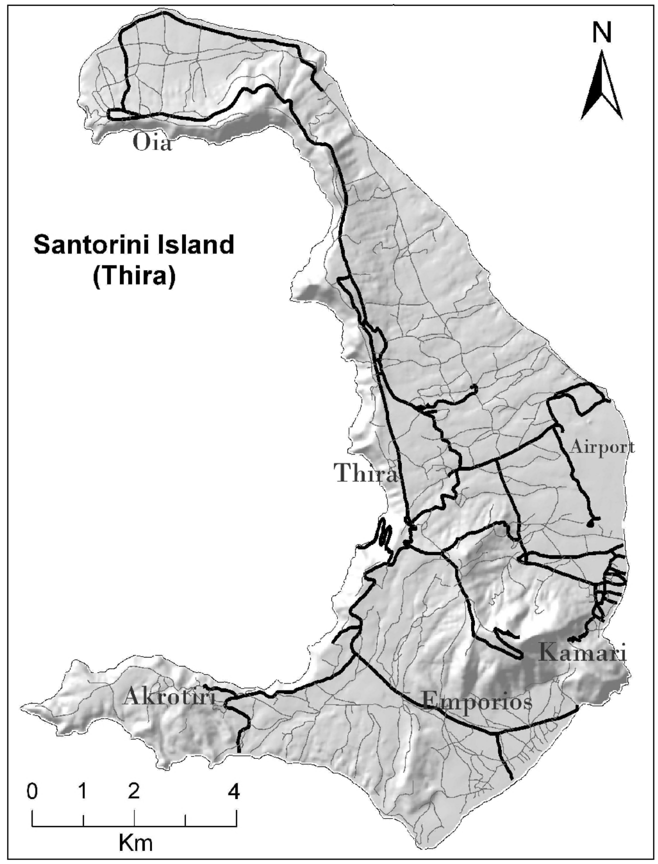

Fig.4 Santorini isl.: Road Network. (Bold lines: primary network, gray lines: secondary network).

Moreover, the statistical analysis for the road network of Santorini isl. shows a more or less uniform distribution, with local peaks at N-S and E-W direction.

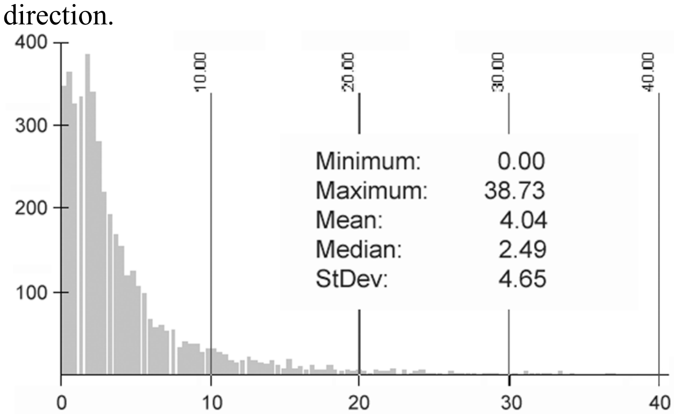

Fig. 5: Distribution of road gradient values for the road network of Santorini Isl.

5. Results - Discussion

The methodology described previously was applied in the study area (Santorini Isl.) in order to analyze the exposure of the road network to direct sun-light. Although the proposed system permits on-demand analysis for every time period, the results for the summertime (May – September 2008) are presented here (fig. 6). This time period was chosen in order to interpret the results of the proposed analysis for a cloud free season. Notice that one of the basic assumptions of the method is the absence of atmospheric effects (e.g. cloud cover, precipitation etc). Moreover, during the selected time period more drivers are exposed to the risk under investigation due to the significant touristic activity and increased road traffic in the study area.

After the creation of the database - both spatial background and sun position data - the road network of Santorini Isl. was divided into straight-line road segments. This segmentation provides as output 4447 straight-line road segments with 296.4 km of total length.

The next step was the creation of hillshade layers (as DEM output layers) for every time snapshot with the use of corresponding sun altitude and azimuth.

Table 2: Overview of sun position data (sun altitude, sun azimuth) during the period May – Sep 2008.

date\hour		*06:00*	*12:00*	*19:00*
May 10th 2008	*Alt*	7.7	71.1	2.1
	Azm	73.5	169.2	291.0
Jun 10th 2008	*Alt*	10.2	76.1	5.7
	Azm	68.7	162.8	294.7
Jul 10th 2008	*Alt*	8.6	74.9	6.2
	Azm	68.6	158.6	293.1
Aug 10th 2008	*Alt*	4.7	68.4	2.2
	Azm	74.1	164.5	287.7
Sep 10th 2008	*Alt*	0.3	58.1	-6.3
	Azm	83.9	172.9	280.4

Sun position data for the summer of 2008 (Table2) shows that from ~ 09:00 am to ~15:00 pm the altitude of sun was more than 30^o, so these hours do not affect the road network with direct sun-light. Based on these values, hillshade layers were created for every hour during 06:00 - 09:00 am and 15:00 - 19:00 pm.

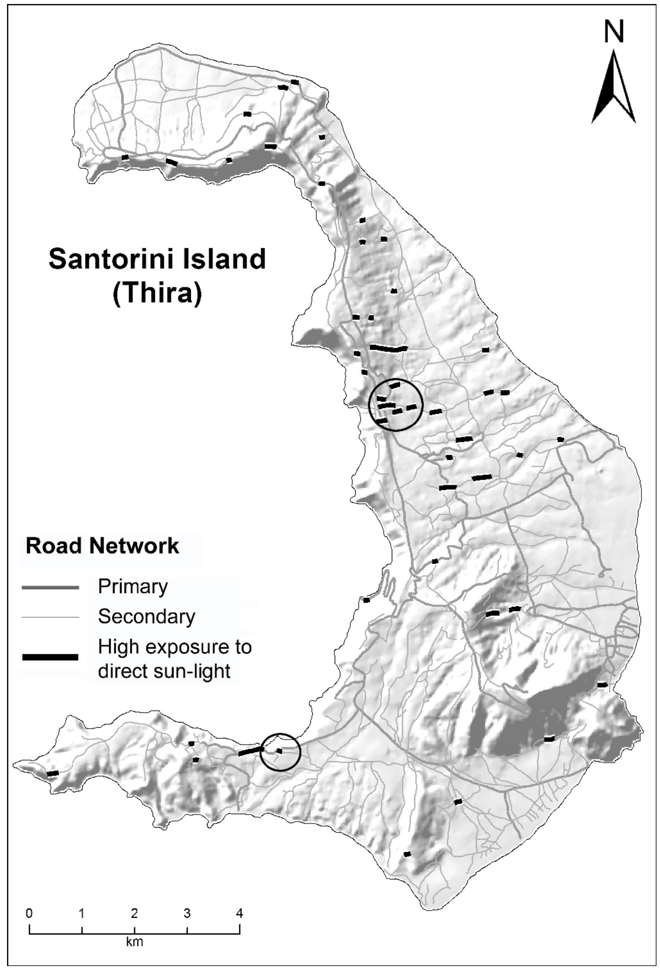

Fig.6: Santorini Isl.: Road segments with high exposure to direct sun-light. Summer period (May – Sep. 2008). Circles indicate segments with extremely high exposure.

According to the proposed methodology, road network segments in shadowed areas were excluded from the analysis. After this primary filtering, the azimuth for the remaining road segments under sun-light was calculated. As the direction of each road segment is known, it can be compared to the azimuth of the sun in order to identify if it is affected by direct sun-light. Thus, road direction was compared with solar azimuth for every time snapshot. All road segments that have the same azimuth (± 5^o) with azimuth of sun were selected for the next step (the slope test). 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. Next, the gradient for each road segment was calculated and compared with the altitude of sun. According to this comparison, every road segment with direction towards the sun position was marked as road at risk. Fig. 6 presents road segments located at regions with high exposure to direct sun-light. Notice that in this map we present only the road segments in this category with length more than 100m. We define here as "high exposure" the exposure to direct sun-light for more than 30 hours during the summer time. As "extremely high exposure" we define the exposure to direct sun-light for more than 100 hours during the period of modeling. A first reading of the map with the road segments at risk shows up that some major risk zones occur mainly in the central part of the island. Inside these zones - in many cases - the length of the road segments under risk reaches up to 300 meters. For these road segments – with more or less E-W direction – further investigation is needed as they are located in high risk areas. In these parts of the road network the exposure to direct sun-light during a travel may last almost a minute (average velocity: 40km/h).

Table 3: Summarized data for road segments highly exposed to direct sun-lights for summer 2008.

Length (m)	*Mean Length (m)*	*Total Length (m)*	*Std Length*
0-100	65.7	6044	17.7
100-300	150.4	6467	46.6
> 300	427.5	2565	158.8

The statistical analysis of the results (table 3) shows that 15,1 km (about 5.1% of the total length of road network) of the road network is exposed to direct sun-light for more than 30 hours during the period of modeling. It should also be mentioned that all segments are considered as bidirectional rural roads. Due to this assumption a significant part of the road network is exposed to direct sun-light both during the first sunrise hours and the last sunset hours.

6. Conclusions

In this study a GIS based spatiotemporal model for the evaluation of the exposure to direct sun radiation in rural road network is proposed. The major elements of the method are: a) background spatial data (road network, elevation model and derivables: slope, aspect, hillshade) b) data concerning sun position for a specific time period and c) advanced GIS functionality for spatial analysis. The integrated use of these elements is the basis for the dynamic modeling and mapping of the exposure to direct sun light for the road segment in the rural network under investigation. 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 and acts to prevent road 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 more than 5% of the total length of the road network is exposed to high risk conditions for more than 30h/month during the summer season. Moreover, in the central and Southern part of the island, the analysis identified road segments with extreme exposure to direct sun light (more than 100 hours during the period of the modeling).

Whether increased exposure entails increased risk of road accidents is a question related to the assumptions and limitations of the study. These assumptions are: a) the time snapshot (1 hour) approach, b) the adoption of threshold (± 5°) for azimuth and slope filtering, c) the absence of atmospheric effects (clouds, rainfall etc) and c) absence of special on site conditions affecting the direct sun-light (line of tree, buildings/constructions etc). These are the main subjects of the future extension and update of the proposed methodology.

The study illustrated the use of GIS technology as a spatiotemporal modeling tool, able to support decision making process. Future work should focus on the development of an automated real time warning system for the identification of high risk conditions in terms of extreme exposure to direct sun light. The use of GIS in co-operation with GPS seems to be the ideal technologies for the development of this system.

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