Hrvatski meteorološki časopis, 31, 95-102, 1996.

UDK: 551.586
Izvorni znanstveni rad

APPLICATION OF SPATIAL MODELLING IN THE KARST BIOCLIMATOLOGY

Primjena prostornog modeliranja u bioklimatologiji krša

OLEG ANTONIĆ

Ruđer Bošković Institute
Bijenička 54, 10000 Zagreb, Croatia

Primljeno 11. studenog 1996. u konačnom obliku 25. veljače 1997.

Abstract — The possibilities of the raster-GIS topoclimatic modelling and its applicability in the Karst bioclimatology have been generally presented. The short descriptions of the particular models derived from the digital elevation model include: terrain slope, relative terrain orientation, terrain curvature, direct and diffuse insolation, altitude in the sinkhole, flow accumulation and exposure to wind. These models are spatially exact and also spatially intensive, and they do not have a practical alternative in precise studies of spatial distribution of ecosystem types, particular species or biodiversity. The other contribution in the same volume summarizes the results of such a study on the Croatian Karst.

Key words : digital elevation model, geographic information system, topoclimate

Sažetak — Mogućnosti rasterskog GIS topoklimatskog modeliranja i njegova primjena u bioklimatologiji krša prikazani su općenito. Kratki opisi pojedinih modela izvedenih iz digitalnog modela reljefa uključuju: nagib terena, relativnu orijentaciju terena, zakrivljenost terena, direktnu i difuznu insolaciju, visinu u ponikvi, akumulaciju tečenja i izloženost vjetru. Ti su modeli prostorno egzaktni i istovremeno prostorno intenzivni, te nemaju praktične alternative u preciznim studijama prostornih razdioba tipova ekosustava, pojedinih vrsta ili biološke raznolikosti. Poseban prilog u istom broju sažima rezultate takve studije na hrvatskom kršu.

Ključne riječi: digitalni model reljefa, geoinformacijski sustav, topoklima

1. INTRODUCTION

Many ecological problems (e.g. exact spatial prediction of ecosystem types or species abundance) request spatially intensive and at the same time very precise climatic data. Available data from meteorological stations are usually not satisfactory for a local climatic field description, especially in the Karst regions where the relief strongly modifies the global climatic field.

In these cases, information about local climatic variability (topoclimatic field) are very important for clearly understanding and predicting the spatial phenomena which are affected by the topoclimate. These correlations are often obvious even on the qualitative level (see e.g. Horvat 1953).

Additional field measurements (e.g. Bertović 1975a) are often also unsatisfactory data source, because they cannot provide a sufficiently dense sample on larger areas. The vegetational study of

Bertović (1975a) for Zavižan (Mount Velebit, Croatia) is an instructive example: one main and six additional climatological stations on less than 24 km^2 of a 'leopard skin' of almost thirty vegetation types (different forests, shrublands, grasslands, screes and cliffs) under the same geological conditions, is probably spatially the richest climatological sample for the entire Croatian Karst.

Spatial modelling is a possible approach for the solution of these problems. It is a group of algorithms that can be applied to simulate and estimate the spatial distribution of hardly measurable variables. This paper gives a short review of these methods.

2. SPATIAL MODELLING BASED ON DIGITAL ELEVATION MODEL

The digital elevation model (DEM) is a cluster of geographical points, with coordinates arranged in a suitable way for computer processing, that represents one part of the Earth's surface. There are several possible types of data arrangement in the DEM (see e.g. Fritsch and Pfannenstein, 1992), the regular square grid being the most suitable type for application in spatial modelling. This type of DEM has usually been produced by the digitalization and rasterization of topographic maps.

The spatial modelling described here comprises functions that include the DEM as the basic argument. The results of these functions are also grids that represent distributions of modelled values in the same geographical space. A spatial model representing one topoclimatic field could be named topoclimatic model. Theoretically, such model simulates a topoclimatic field and approximates results of spatially intensive climatological measurements. Practically, many of these models do not have a methodological alternative, especially on the dissected relief of the Karst areas, with strong local topoclimatic contrasts that require a spatially dense sample of measurements.

Examples of topoclimatic models

1. Digital elevation model

The DEM could be considered as a separate topoclimatic estimator in the sense of it indirectly representing the altitudinal temperature and/or precipitation gradient, but only if it is approximatively linear (e.g. as in Penzar 1959). In other cases, the DEM could be an independent variable in the functions that describe mentioned gradient (e.g. Pache et al 1996). An example of a DEM (central part of NP Risnjak, Croatia) is shown on Figure 1a. This DEM is also a basis for the following models. All these models have a resolution (pixel dimensions) of 10 x 10 m.

2. Terrain slope

Terrain slope can also be considered as an indirect topoclimatic variable, because steeper areas are locally dryer, due to shallower soils with more rocks on the surface. The terrain slope (see Figure 1b) is usually calculated as the maximal slope of the regression plane through a 3 x 3 neigbourhood for each pixel in the DEM.

3. Relative terrain orientation

Terrain orientation can represent an additional indirect estimator of the precipitation quantity in the sense of declination of the dominant incoming precipitation direction (e.g. as in Penzar 1959). This declination can be calculated as the angle distance between the terrain slope azimuth and the incoming precipitation azimuth. Figure 1c represents a relative terrain orientation toward the west.

4. Terrain curvature

Terrain curvature shows the rate of change of the surface slope in a given direction. A curvature in the direction of maximal terrain slope (profile curvature, see Figure 1d) affects the acceleration and deceleration of flow, and therefore influences erosion and deposition. A curvature in the direction perpendicular to the direction of the maximal terrain slope (planform curvature, Figure 1e) influences the convergence and divergence of flow.

5. Flow accumulation

The number of pixels that gravitate to the given pixel (the relative basin area for that pixel) can be a potential estimator of soil moisture, together with the different hydraulic characteristics of the soils (Beven 1978, Beven and Kirkby 1979, Burt and Butcher 1985, O'Loughlin 1986, Wolock et al. 1989). Application to the Karst areas requires inclusion of geological porosity as an additional estimator that hardly affects the surface flow (see Figure 1f, based on the geological data by Božičević et al. 1994).

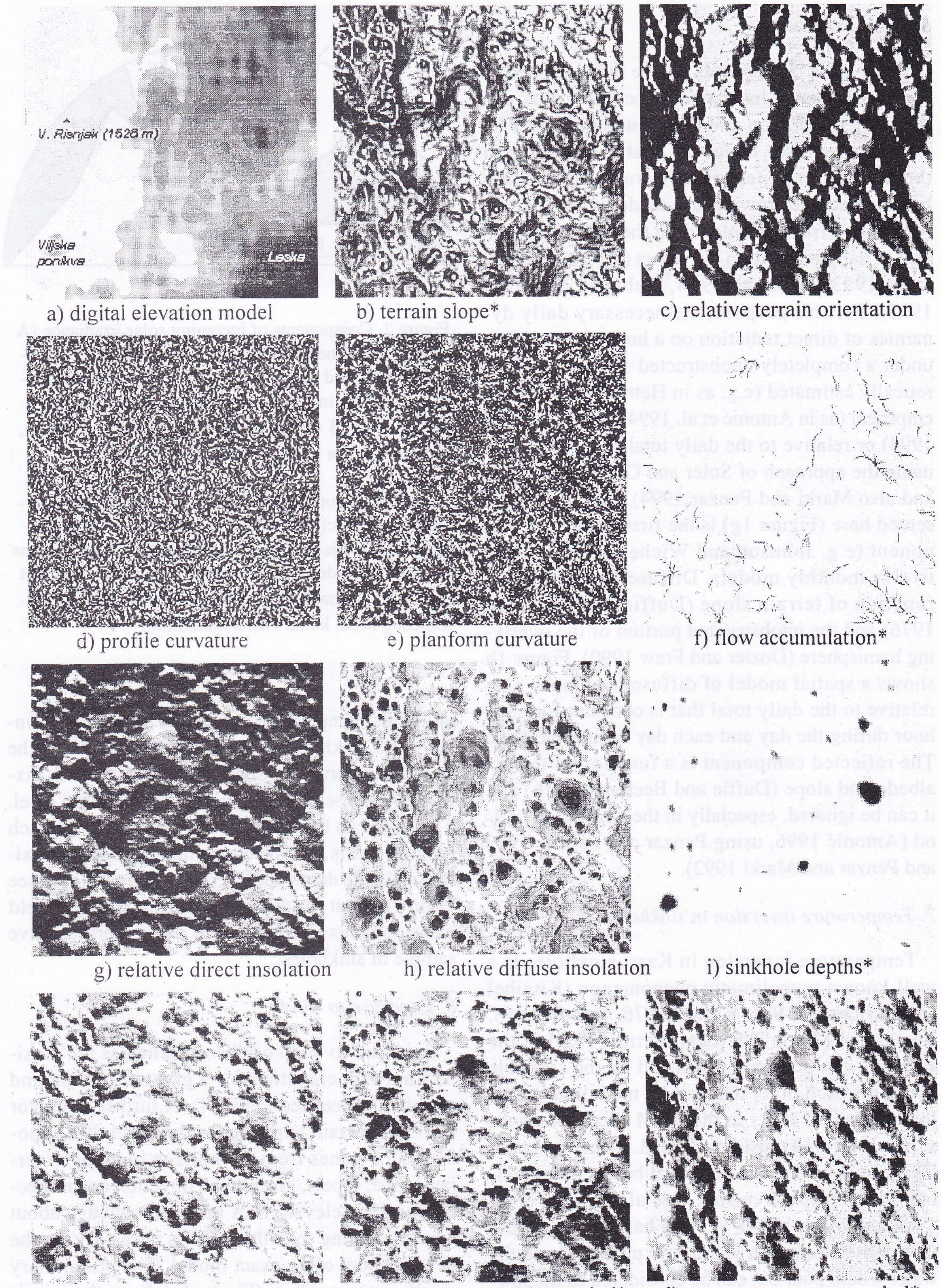

Figure 1. Examples of topoclimatic models for the central part of NP Risnjak (Croatia). Model values in the gray scale: black = minimum, white = maximum (* reversely).

Slika 1. Primjeri topoklimatskih modela za središnji dio NP Risnjak (Hrvatska). Vrijednosti modela u skali sivih tonova: crno = najmanje, bijelo = najveće (* obrnuto).

6. Solar irradiance

Three basic components can be distinguished in the total incoming insolation: direct irradiance, diffuse sky irradiance and irradiance reflected by nearby terrain (see Figure 2). Spatial modelling of the direct component is an iterative procedure based on self-shadowing and shadows cast by surrounding terrain calculated on the DEM for each unit of daily integration e.g. hours (see also Hetrick et al. 1993, Dubayah 1994, Dubayah and Rich 1995). For this purpose, the necessary daily dynamics of direct radiation on a horizontal surface under a completely unobstructed sky can be theoretically estimated (e.g. as in Hetrick et al. 1993), empirical (as in Antonić et al. 1994 and in Dubayah 1994) or relative to the daily total (Antonić 1996, using the approach of Soler and Gopinathan 1994 and also Marki and Penzar 1994). The result presented here (Figure 1g) is the first principal component (e.g. Johnson and Wichern 1988) of the twelve monthly models. Diffuse irradiance is a function of terrain slope (Duffie and Beckman 1976) and the unobstructed portion of the overlying hemisphere (Dozier and Frew 1990). Figure 1h shows a spatial model of diffuse irradiance also relative to the daily total that is constant for each hour during the day and each day during the year. The reflected component is a function of terrain albedo and slope (Duffie and Beckman 1976) and it can be ignored, especially in the vegetation period (Antonić 1996, using Penzar and Penzar 1989 and Penzar and Marki 1992).

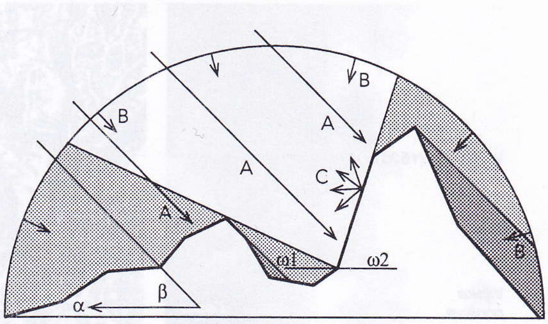

Figure 2. Components of incoming solar irradiance (A - direct irradiance, B - diffuse sky irradiance, C - irradiance reflected by nearby terrain) and some independent variables in the solar irradiance modelling (α - Sun azimuth, β - Sun elevation, ω - horizon elevation, elevation of the unobstructed part of the sky).

Slika 2. Komponente dozračene Sunčeve energije (A - direktna radijacija, B - difuzna radijacija od neba, C - radijacija odbijena od okolnog terena) i neke nezavisne varijable u modeliranju Sunčeve radijacije (α - azimut Sunca, β - kutna visina Sunca, ω - kutna visina nezaklonjenog neba, kutna visina horizonta).

7. Temperature inversion in sinkholes

Temperature inversion in Karst sinkholes is a well-known topoclimatic phenomenon (Kitaibel 1802 in Degen 1936, Kerner 1876, Horvat 1953, Bertović 1975a). The local thermic field in the sinkhole can be easily estimated by the sinkhole depth for each pixel that can be modelled as follows. First, all sinks in the DEM (pixels without surface outflow) must be selected. Then, the entire DEM must be divided into local basins that gravitate to the respective sink (see also Marks et al. 1984 and Mark 1988). If these basins were hypothetically filled with water, the points where the water would pour out can be considered as the lowest point of each sinkhole edge. Finally, the sinkhole depths (Figure 1i) are calculated for each pixel in the basin that is lower than the respective sinkhole edge as an altitudinal difference from the edge. The higher pixels are set to zero as open slopes without temperature inversion. The inverse altitudinal temperature gradient is probably not linear in the sinkhole but inversely proportional to the area of the horizontal sinkhole section for each pixel, in the sense of a temperature equalization level. This area can be approximately modelled for each pixel in terms of respective sinkhole depth, maximal sinkhole depth and average sinkhole slope (see Figure 3), but the final application requires field measurements of temperature at the representative sample of sinkholes.

8. Exposure to wind

Exposure to wind can be modelled as the maximal horizon elevation for a given direction and search distance (see Figure 4). A further estimator could be terrain exposure to the wind that hypothetically comes from the horizon in terms of terrain slope, aspect, given wind direction and respective horizon elevation. A better knowledge about wind streaming over the relief is necessary for the development of an exact model. The preliminary results presented here (Figure 1j,k,l) are the principal components (e.g. Johnson and Wichern 1988) of the separate horizon angle models (search distance 30 and 300 m) and the respective models of terrain exposure, each for eight cardinal directions.

New topoclimatic models can be developed as

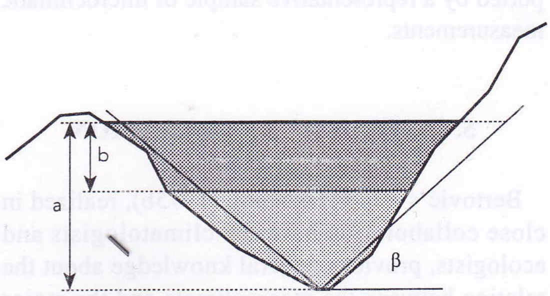

Figure 3. Independent variables in the modelling of the area of a horizontal sinkhole section (a - maximal sinkhole depth, b - depth of the particular pixel, β - approximate average slope in the sinkhole).

Slika 3. Nezavisne varijable pri modeliranju površine horizontalnog presjeka ponikve (a - najveća dubina ponikve, b - dubina određenog piksela, β - aproksimativni srednji nagib u ponikvi).

functions of the models presented (e.g. Brown 1994 calculates snow accumulation potential in terms of altitude, relative orientation to the predominant winter winds and terrain curvature).

Used software and possible further processing

Most of the models presented, or their components, are avaliable as standard functions in the new PC raster-GIS software package *Model for Windows 1.1* (Antonić et al. 1994, Bušelić 1996, contact the author for further information), excluding the calculation in the basin, which will be available in the next version. The flow accumulation and temperature inversion models presented have been developed in the *ArcInfo GRID* software package for UNIX workstations.

All these models can be included in the geographic information systems (GIS) together with other relevant layers, e.g. spatial distribution of ecosystem types, biodiversity or species abundance (see also Bridgewater 1993, Haines-Young et al. 1993, Stow 1993, Goodchild 1994). Virtual sampling (systematic or random) of different GIS layers provides data matrices that are a suitable input for statistical and numerical analyses (e.g. correlation, discrimination, clustering etc.).

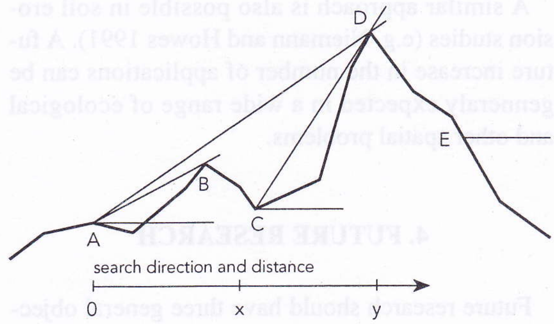

Figure 4. Some possible relations between search distance and horizon elevation: for point A - under distance 'x', the critical point is B, under distance 'y', the critical point is D; for point C - the critical point is D under both distances; for point E - the horizon elevation is set to zero.

Slika 4. Neki mogući odnosi između udaljenosti pretraživanja i kutne visine horizonta: za točku A - uz udaljenost 'x' kritična točka je B, uz udaljenost 'y' kritična točka je D; za točku C - kritična točka je D uz obje udaljenosti; za točku E - kutna visina horizonta je nula.

3. APPLICATIONS IN ECOLOGY

The application of these models is strongly affected by the computer computational resources. Consequently, these methods are relatively new and the existing number of respective ecological studies is relatively small.

A relatively large number of applications have tried to solve the problem of the spatial distribution of ecosystems types (e.g. Burke et al. 1989, Saving et al. 1993, Brown 1994, Walsh et al. 1994., Antonić 1996).

Topoclimatic models can also be applied as spatial estimators of species abundance, biodiversity, dendrometric parameters (standardized tree height, crown height, radial increment and its variability) and ecosystem pollution (Antonić 1996). The other contribution in this volume summarizes the results of Antonić's (1996) study, which is the first application of the models presented to the Karst ecology.

Spatially exact simulations under different conditions, e.g. presumed climatic changes (e.g. Brzeziecki et al. 1995), could be probably improved by using these models.

A similar approach is also possible in soil erosion studies (e.g. Niemann and Howes 1991). A future increase in the number of applications can be genneraly expected in a wide range of ecological and other spatial problems.

4. FUTURE RESEARCH

Future research should have three general objectives:

1. A more adequate definition of topoclimatic estimators

The model of incoming solar irradiance seems to be more complex than the other models presented. In fact, the other models are only possible components of basic stochastical processes that are much more complex and insufficiently known, as opposed to the well-known and deterministic key components of the irradiance model. A more adequate definition of other important topoclimatic estimators (e.g. development of an integral model of soil moisture in terms of solar irradiance, precipitation quantity, wind evaporation, flow accumulation, terrain curvature, including the relevant pedological and geological parameters) is probably achievable by using a representative sample of field measurements and by building stochastical models based on collected data in terms of the models presented.

2. A macroclimatic calibration of topoclimatic models

The models described are only local or maybe regional topoclimatic estimators, because the macroclimatic field cannot be neglected on larger areas. The main meteorological stations could probably provide suitable data for the modelling of the macroclimatic field. A general approach could follow e.g. Pandžić (1989), but some of the models presented, e.g. the DEM, and exposure to maritime winds could probably provide better results (see also Antonić and Lovrić, 1996).

3. The building of models of microclimate impact

In spatially complex ecosystems (e.g. forests), the microclimatic field could be locally very contrasting under the same topoclimatic conditions. Suitable data sources for a spatially intensive modelling of the microclimatic field could probably be terrestrial and/or air photogrammetric records, supported by a representative sample of microclimatic measurements.

5. INSTEAD OF A CONCLUSION

Bertović's important study (1975b), realized in close collaboration between climatologists and ecologists, provides general knowledge about the relation between the macroclimate and the major vegetation types in Croatia. More than twenty years later, we need a better and spatially exact understanding of this relation, as a basis for the optimal management of natural resources, especially on the Karst areas. The approach presented here could be a suitable frame for this kind of ecoclimatological studies.

REFERENCES

Antonić O., R. Belušić, M. Ananić and V. Kušan, 1994: GRID 1.0: development of landscape ecology GIS-functions. Proc. 16th Int. Conf. "Information technology interfaces", Pula, Croatia, June 1994, 467-470.

Antonić O., I. Penzar and R. Belušić, 1994: Modeliranje Sunčeve radijacije na reljefnoj površini. Zbornik radova "Energija i zaštita okoliša". Opatija, listopad 1994, 277-282.

Antonić O. and A.Ž. Lovrić, 1996: Numerical analysis of vegetation complexes and community diversity of major coastal Dinaric mountains. *J. Veg. Sci.* **7**, 73-80.

Antonić O., 1996: Modeli utjecaja topoklime na vegetaciju krša (doktorska disertacija). Sveučilište u Zagrebu, Prirodoslovno-matematički fakultet. 156 p.

Bertović S., 1975a: Ecological - vegetational characteristics of the environs of Zavižan in the northern ranges of the Velebit mountain (Croatia). *Glasnik za šumske pokuse* **18**, 5-75 + 1 map.

Bertović S., 1975b: Contribution to knowledge of relation between climate and vegetation in Croatia. *Acta Biol.* **VII/2**. 189-196.

Beven K.J., 1978: The hydrological response of headwater and sideslopes areas. *Hidrol. Sci. Bull.* **23**, 419-437.

Beven K.J., M.J. Kirkby, 1979: A physically-based variable contributing area model of basin hydrology. *Hidrol. Sci. Bull.* **24**, 43-69.

Božičević S., D. Ivičić, B. Biondić, Ž. Viljevac i D. Singer, 1994: Hidrogeološke karakteristike risnjačkog područja i problematika zaštite njegovih voda. Zbornik radova "40 godina NP Risnjak", Crni Lug, rujan 1993, 121-123.

Bridgewater P.B., 1993: Landscape ecology, GIS and nature conservation. in Landscape ecology and GIS, ed. by Haines-Young, R., Green, D.R. and Cousins, S., Taylor and Francis, London, 23-36.

Brown D.G., 1994: Predicting vegetation types at tree-line using topography and biophysical disturbance variables. *J. Veg. Sci.* **5**, 641-656.

Brzeziecki B., F. Kienast and O. Wildi, 1995: Modelling potential impacts of climate change on the spatial distribution of zonal forest communities in Switzerland. *J. Veg. Sci.* **6**, 257-268.

Burke I.C., W.A. Reiners and R.K. Olson, 1989: Topographic control of vegetation in a mountain big sagebrush steppe. *Vegetatio* **84**, 77-86.

Burt T.P. and D.P. Butcher, 1985: Topographic controls of soil moisture distributions. *J. Soil Sci.* **36**, 469-486.

Bušelić V., 1996: *Model* - softver za raster-GIS modeliranje. *BYTE,* 4/1996.

Degen A., 1936: Flora velebitica. I. 389. Budapest.

Dozier J. and J. Frew, 1990: Rapid calculation of terrain parameters for radiation modeling from digital terrain data. *IEEE Transactions on Geoscience and Remote Sensing* **28**, 963-969.

Dubayah R.C., 1994: Modelling a solar radiation topoclimatology for the Rio Grande River Basin. *J. Veg. Sci.* **5**, 627-640.

Dubayah R. C. and P.M. Rich, 1995: Topographic solar radiation models for GIS. *Int. J. Geographical information systems* **9-4**, 405-419.

Duffie J.A. and W.A. Beckman, 1976: Sonnen energie, thermische processe. Udo Pfriemer Verlag, München, p. 75.

Fritsch D. and A. Pfannenstein, 1992: Conceptual Models for Efficient DTM Integration into GIS, Proc. Conf. EGIS'92, Munich, **1**. 702-710.

Goodchild M.F., 1994: Integrating GIS and remote sensing for vegetation analysis and modeling: methodological issues. *J. Veg. Sci.* **5**, 615-626.

Haines-Young R., D.R. Green and S. Cousins, 1993: Landscape ecology and GIS. in Landscape ecology and GIS, ed. by Haines-Young, R., Green, D.R. and Cousins, S., Taylor and Francis, London, 3-8.

Hetrick W.A., P.M. Rich, F.J. Barnes and S.B. Weiss, 1993: GIS-based solar radiation flux models. *American Society for Photogrammetry and Remote Sensing Technical Papers,* **3**, GIS, Photogrammetry and Modelling, 132-143.

Horvat I., 1952-53: Vegetacija ponikava - prilog biljnoj geografiji krša. *Geografski glasnik* **14-15**, 1-25.

Johnson R.A., D.W. Wichern, 1988: Applied multivariate statistical analysis. Prentice Hall Int., New Jersey.

Kerner A., 1876: Die Entstehung relativ hoher Lufttemperaturen in der Mittelhöhe der Talbecken der Alpen. *Zeit. Öster. Gesell. Meteor.* **XI.**

Mark D.M., 1988: Network models in geomorphology. Modelling in geomorphological systems. J. Wiley, Chicester.

Marki, A. and I. Penzar, 1994: Proračun dnevnog hoda Sunčevog zračenja iz dnevnog srednjaka. Zbornik radova "Energija i zaštita okoliša", Opatija, rujan 1994, 373-380.

Marks D., J. Dozier and J. Frew, 1984: Automated basin delineation from digital elevation data. *Geo-Processing* **2**, 299-311.

Niemann K.O., D.E. Howes, 1991: Applicability of digital terrain models for slope stability assessment. *ITC J.* 1991-3, 127-137.

O'Loughlin E.M., 1986: Prediction of surface saturation zones in natural catchments by topographic analysis. *Water Resour. Res.* **22**, 794-804.

Pache G., S. Aime and R. Michalet, 1996: A simple model for the study of the altitudinal rainfall gradient, applied in the Tyrolian orographic complex. *Rev. Ecol. Alp.* III, 13-20.

Pandžić K., 1989: Faktorska analiza lokalnih klimatskih polja unutar globalnog strujanja. (doktorska disertacija). Sveučilište u Zagrebu, Prirodoslovno-matematički fakultet.

Penzar B., 1959: Razdioba godišnjih količina oborine u Gorskom Kotaru. Zbornik radova "II. savjetovanje meteorologa FNRJ za planinsku meteorologiju", Senj, rujan 1957. HMZH Zagreb.

Penzar I. and A. Marki, 1992: Mathematical simulation of diurnal variation of natural illumination. Proc. Conf. "Meteorology for Agriculture", Ljubljana, April 1992, ed. by A. Hočevar and J. Rakovec, University of Ljubljana.

Penzar I. and B. Penzar, 1989: Agroklimatologija. II izdanje. Školska knjiga, Zagreb.

Saving S.C., P.M. Rich, J.T. Smiley and S.B. Weiss, 1993: GIS-based microclimate models for assessment of habitat quality in natural reserves. *American Society for Photogrammetry and Remote Sensing Technical Papers,* **3**, GIS, Photogrammetry and Modelling, 319-330.

Soler, A. and K.K. Gopinathan, 1994: Estimation of monthly mean hourly global radiation for latitudes in the 1°N-81°N range. *Solar Energy* **52-3**, 233-239.

Stow D.A., 1993: The role of geographic information system for landscape ecological studies. in Landscape ecology and GIS, ed. by Haines-Young, R., Green, D.R. and Cousins, S., Taylor and Francis, London, 11-21.

Walsh S.J., D.R. Butler, T.R. Allen and G.P. Malanson, 1994: Influence of snow patterns and snow avalanches on the alpine treeline ecotone. *J. Veg. Sci.* 5, 657-672.

Wolock D.M., G.M. Hornberger, K.J. Beven and W.G. Campbell, 1989: The relationship of catchment topography and soil hydraulic characteristics to lake alkalinity in the North-eastern United States. *Water Resourc. Res.* **25**. 829-837.