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A novel way to present flood hazards using 3D-printing with transparent layers of return period isolines

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Abstract

This paper examines the 3D printed results of a floodplain analysis usually used for hydrological studies to calculate the probabilities in high water stage features. The analysis was performed using probability distributions, including Pearson type III distribution, Log-Pearson type III distribution, Gaussian (normal) distribution, Gumbel distribution, and Log-normal distribution. The maximum theoretical stages of best fitting distribution for different return periods were mapped to the Vardar and Boshava rivers in the Tikvesh Valley. Data to create the model were extracted from digital elevation models of the Vardar river target area. The extracted 3D surface model was covered with a map showing all the flooded areas in the relevant territory for different return periods as transparent layers. The data were converted into a physical model (relief map) using 3D printing methods for visualisation.

Zusammenfassung

Dieser Artikel untersucht das Ergebnis des 3D-Ausdrucks einer Naturgefahrenabschätzung, wie sie typischerweise in Flussebenen im Rahmen hydrologischer Studien durchgeführt werden, um die Wahrscheinlichkeit von Hochwasserständen abzuschätzen. Die Analyse des Hochwasserrisikos wurde anhand verschiedener bei der Abschätzung von Naturereignissen gebräuchlicher Häufigkeitsverteilungen durchgeführt: der Pearson Typ III Verteilung, der Log-Pearson Typ III Verteilung, der Normal- oder Gaußverteilung, der Gumbel-Verteilung und der Logarithmischen Normalverteilung. Die maximalen theoretischen Pegelstände der jeweiligen besten Häufigkeitsverteilungen für ausgewählte Wiederkehrintervalle wurden für die Flüsse Vardar und Boshava im Tikvesh-Tal (Nordmazedonien) berechnet und kartografisch dargestellt. Als topografische Grundlage wurde das digitale Geländemodell des Vardar Einzugsgebiets verwendet. Die daraus berechnete dreidimensionale Modelloberfläche für jedes Wiederkehrintervall wurde in eine Karte umgewandelt, welche die durch Überschwemmung gefährdeten Gebiete mit transparenten Flächen überlagert. Schliesslich wurden die Ebenen in ein physikalisches Modell (ein topografisches Relief) eingepasst und mittels 3D-Druck zur Veranschaulichung hergestellt.

Keywords 3D printing, modelling, floodplain, Vardar river, GIS

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1. Introduction

Floods are regarded as a human problem, causing enormous material damage and human casualties (*Zorn* and *Hrvatin* 2015). Prediction and modelling systems (also crisis management) should be considered closely together, as these should be the very first tools for limiting potential damage. One solution in helping to avert flood disasters might be found in predictions using Geographic information systems (GIS), since good analyses of floodplains have already been done (*Traore* et al. 2015; *Curebal* et al. 2016; *Khattak* et al. 2016; *Icaga* et al. 2016). Also, many designs to optimize anti-flood measures have been created by different authors with varying results (*Roub* et al. 2013). *Mervade* et al. (2008) presented river terrain models for hydrodynamic modelling and mapping of flood inundation. All these publications demonstrate the importance of modelling floodplain scenarios and their possible outcomes. This paper focuses on a tangible, full-colour 3D model of a real phenomenon produced by paper 3D printing technology. It introduces new options for digital relief map visualisation and the understanding of floodplain problematics.

3D printing technology is based on the gradual layering of a specific material, mainly in combination with the temperature of the apparatus. Today, many and accessible 3D printing machines are available to build models from plastic materials. These solutions can print comparatively cheaply, depending on the type of printing machine and printed model (*Brus* and *Barvíř* 2015; *Ngo* et al. 2018). These plastic techniques are limited to only a few colours, depending on the material,and in most cases it is a difficult process to change colors during or after construction of the model (*Chua* et al. 2010). However, the progress of 3D printing technology is still evolving. It should not be a surprise then that 3D printers as processing machines will develop according to the demands of the real market (*Berman* 2012). Currently, using the greatest possible variety of printing materials in only one machine to obtain different results is a great effort. Common machines with two extruders are slowly being replaced with new types that include more extruders and provide greater possibilities with materials. This is allowing new choices for multi-coloured 3D printing results. Some printers are available today that can produce full-colour models, such as the first full-colour printer ZCorporation 650, or the recent 3D paper printer Mcor IRIS HD (*von Wyss* 2015). Since its beginning, many different solutions and models have been made in the field of 3D printing. Rapid prototyping became very popular for physical 3D map production (*Rase* 2011). Not only classic map making techniques, but also 3D terrain modelling and its applications have found use in the printing of some physical maps (*Ruzínoor* et al. 2011). According to *Ghawana* and *Zlatanova* (2013), another potential for 3D printing could be in modelling cities and urban planning. LIDAR (light detection and ranging) based digital elevation models have also been applied in these areas (*Schwarzbach* et al. 2012). Finally, full-colour models have brought completely new possibilities such as relief maps and other practical aspects for geographic information systems (GIS) (*Burian* and *Brus* 2016).

The very first relief map was produced in the beginning of the twentieth century. In 1940, a process for making relief maps was devised by *Victor Perera Bamunuarchige*. Later (in 1955), some of the methods for making relief maps were both described and patented by the Reflectone Corp. Many inventors worked on the theory, and eventually Richard Mayne Meyer (in 1970) obtained a patent for relief models as a relief map comprising contour layers. To this day, many types of relief maps in various scientific disciplines have been created. *Šlangens* and *Krauklis* (2011) created a digital relief map of Latvia with a plane approximation step of 500 metres and hydrographic network included. Another approach was used in Venezuela where a digital shaded-relief map was composited from more than 20 tiles of elevation data with a 90-metre pixel resolution (*Garrity* et al. 2009). *Patterson* (2014) depicted the Hawaiian seafloor using a medium-scale relief map. Most of the solutions have only been made in digital form, as they were generated from specific digital elevation models (DEM). However, the theory of these relief maps is still being described, as DEM accuracy affects final 3D model quality (*Schoorl* et al. 2000; *Svobodová* and *Voženílek* 2010). Based on *Terribilini* (2001) and *Häberling* et al. (2008) the process of its creation should be divided into a few steps, such as (1) the process of modelling, (2) symbolization, and (3) visualisation. Using the 3D printing methods in visualisation might be very useful. The real object strengthens the data representation itself and needs less cognitive skills of the user reading it, as compared with the corresponding 2D object (*Bunch* and *Lloyd* 2006). Some other scientists have demonstrated the impact of 3D visualization, allowing users to better understand topography aspects compared to 2D maps (*Savage* et al. 2004; *Schobesberger* and *Patterson* 2008; *Popelka* and *Brychtová* 2013). The results of this paper should be helpful in contributing to the understanding of the studied area of interest as well as providing an example of the usability of 3D printing methods in GIS visualisations.

2. Area of study

This paper focuses on the process of producing a 3D model (full-colour relief map) which includes transparent layers of the floodplain analysis of the Vardar river located in the southeast (*Fig. 1*) of the Republic of North Macedonia (central part of the Balkan Peninsula). The Vardar river's total length is 237.8 km, while the interested area of analysis is 4.3 km.

Fig. 1 *Target area for 3D modelling of the floodplain analysis, 4.3 km section of the river Vardar. Source: own illustration*

3. Methodology and data

The research methodology is based on the statistical and cartographic methods calculated by *Radevski* and *Gorin* (2017). The basic, analysed parameter of the research is the maximum annual water stage for the period 1971/72-2004/05 (*Table 1*). The mathematical-statistical methods begin with a homogeneity test of the data series covering a standard period in hydrological research, calculating maximum potential high waters for different return periods (from 2 to 10,000 years) and graphic comparison and testing of concordance between empirical and theoretical distribution. The basic data were obtained from the National Hydrometeorological Service of the Republic of North Macedonia. The series must also be long enough, which means that for statistical processing of maximum discharge, a period of 30 years is necessary. The data analysis method is a flood frequency analysis using five theoretical distributions usually used in hydrological studies: (1) Pearson type III, (2) Log-Pearson, (3) Gaussian, (4) Gumbel, and (5) Log-normal distribution (*Benson* 1968; *Ahilan* et al. 2012; *Bedient* et al. 2018).

Table 1 *Maximum annual water stage for the period 1971/72–2004/05. Source: Radevski and Gorin (2017)*

Year	h (cm)	Year	h (cm)	Year	h (cm)	Year	h (cm)
1971/72	271	1981/82	362	1991/92	292	2001/02	188
1972/73	316	1982/83	327	1992/93	216	2002/03	384
1973/74	351	1983/84	306	1993/94	224	2003/04	230
1974/75	236	1984/85	248	1994/95	204	2004/05	294
1975/76	348	1985/86	350	1995/96	354		
1976/77	369	1986/87	382	1996/97	286		
1977/78	272	1987/88	168	1997/98	249		
1978/79	277	1988/89	249	1998/99	298		
1979/80	506	1989/90	200	1999/00	280		
1980/81	428	1990/91	309	2000/01	212		

The floodplain analysis at the Demir Kapija gauging station on the Vardar river was performed according to the Log-normal distribution, which was selected as the best fit for probability comparison and statistical testing (Kolmogorov-Smirnov K-S test and χ-square test). The Log-normal distribution results range between 288 cm for a return period of 5 years to 717 cm for return period of 10,000 years (*Table 2*), so it was chosen due to a good fit of maximum annual stages, especially on small probabilities, which is evident from a probability plot, as well as good results on K-S and χ-square testing. Statistical results were used to map the floodplain. Floodplain mapping was done with a combination of HEC tools (HEC RAS and HEC-GeoRAS) and ArcGIS. The following datasets were used: topographic maps (scale 1:25,000), GPS measurement data, triangulated irregular network (TIN), land use/land cover data, and statistically calculated values for different returning periods. The floodplain map created (*Fig. 2*) shows the extent of flooding areas (*Table 3*) including the 10,000-year return period covering 2.072 km^2 (*Icaga* et al. 2016; *Radevski* and *Gorin* 2017).

After floodplain visualisation, a 3D model of the Vardar river target area was created. Data for modelling were used from the digital elevation model with 5-meter resolution (data source: MAFWERM, Ministry of Agriculture, Forestry and Water Economy). The model itself was achieved using the QGIS open source multi-platform software version 2.18.6 in combination with a free DEM to 3D plugin. This library allows DEM data to be exported into the STL (Standard Triangle Language) format ready for 3D printing purposes. It is one of the first tools linking GIS and 3D printing (*Simón* 2015). The parameters of the model's properties were set to a scale of 1:25,000 and spacing detail of 0.2 mm. The 3D model output was approximately 14 × 14 cm (width × length) and included the surrounding area as part of the square format for 3D printing. The model's elevation depended on the exaggeration factor. In this study, a value of 0.5 was chosen to produce a representative example (*Fig.* 3), which means the model's elevation was 5.1 mm.

Table 2 Theoretical water stages for different return periods per five probability distributions Source: Radevski and Gorin (2017)

Return period	Gaussian (Normal)	Pearson III	Log-Pearson III	Gumbel	**Log-normal**
10,000	569	675	723	792	**717**
1,000	522	591	617	659	**613**
200	484	529	543	566	**540**
100	466	500	511	526	**507**
50	446	470	476	486	**474**
25	424	439	441	446	**440**
10	390	394	394	392	**393**
5	358	355	354	349	**353**
2	297	289	289	285	**288**

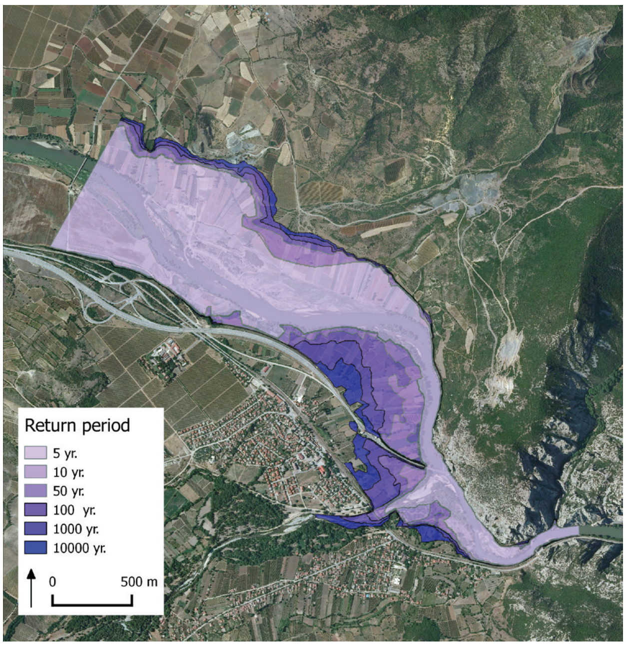

Fig. 2 Floodplain inundations for different return periods. Source: own illustration

Table 3 Flooding area for different return periods in years. Source: Radevski and Gorin (2017)

Return period	5	10	50	100	1,000	10,000
Area (km^2)	1.319	1.357	1.585	1.756	1.928	2.072

After obtaining the 3D model, the topographic underlay was created (*Fig. 4*) and comprised an aerial view of the area (*DigitalGlobe* 2009), floodplain analysis with transparent layers and some basic cartographic elements (title, legend, scale). Only a few layers were chosen for the whole floodplain visualisation to obtain better quality in the final 3D resolution. The layers show expanses of water from the flood return periods of 5 years (1.319 km^2), 100 years (1.756 km^2) and 10,000 years (2.072 km^2).

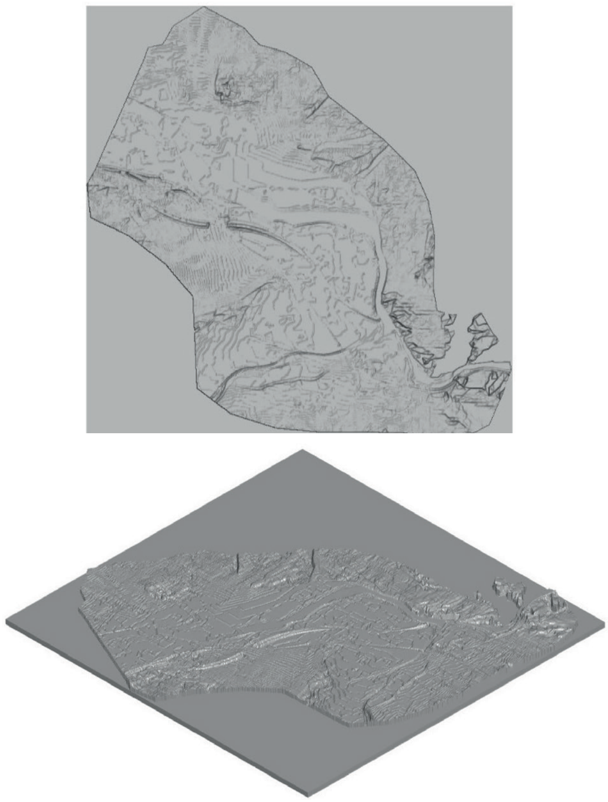

Fig. 3 Printed 3D model of the target river area (square format). Source: own illustration

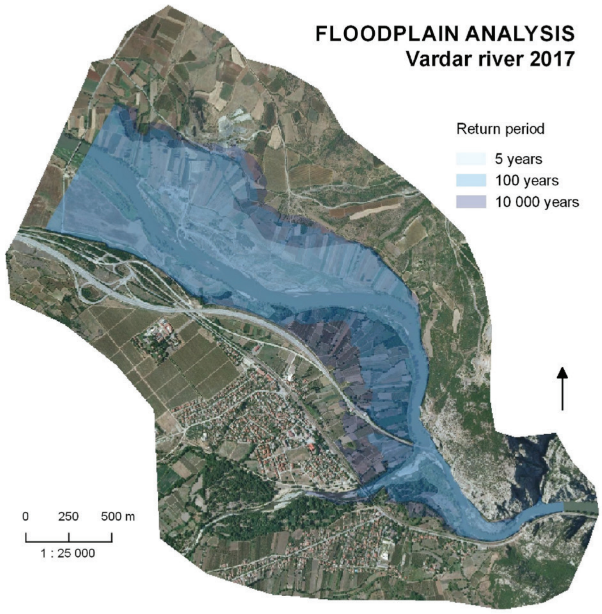

Fig. 4 *Generalization of floodplain analysis with transparent layers and orthophoto of the Vardar river. Return water period of 5 years (1.319 km2), 100 years (1.756 km2) and 10,000 years (2.072 km2). Source: own illustration*

4. Results

All collected data were spliced together. These three parts were obtained for the final result:

1. DEM data for creating the 3D model
2. Aerial image of the target area
3. Thematic (floodplain) analysis to cover the surface of the model

The topographic underlay (aerial image with floodplain analysis visualisation) was placed on the top surface of the printed 3D model using some freeware graphics software for easy texturing of objects. After these corrections, the final data were sent to an Mcor IRIS HD 3D printing machine. This 3D printer uses common office paper and provides full-colour results (*Burian* and *Brus* 2016). The model's printing process consumed only 56 paper sheets and took (approximately) two and a half hours. As a final step, the printed model was cleaned and impregnated to obtain a solid and shiny result (*Fig. 5*). The result depicted a section of the Vardar river in the Republic of North Macedonia and its floodplain scenarios. It could also be called a relief map with basic cartographic areal expression techniques (*Phillips* et al. 1975; *Patterson* 2014).

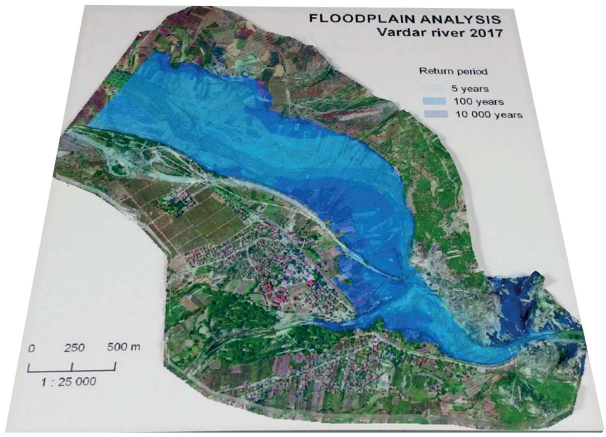

Fig. 5 *True 3D printed model of the floodplain with transparent layers of return period isolines: a case study of the Vardar river. Source: own illustration*

5. Discussion and conclusions

This type of 3D mapping brings another new approach in the field of cartography and GIS in general. The result is durable and solid with a true full-colour surface. Anyone can touch it or rotate it by himself or herself to get the desired view. This true 3D flood area model is also fully portable and can be easily presented in public. It can convey more easily understood information than using a complex computer model visualisation, with people most likely being able to appreciate a real physical model more readily at first glance. Also it is possible to present and describe more information as the additional dimension creates a new space for the data variables. It provides a new view of the relief of the country. This type of 3D map production could become very popular as the influence of rapid prototyping is increasing. Furthermore, it is much more effective to use methods with higher visualization potential.

This paper's concept introduces one of the very first ideas for further 3D printing and modelling research with full-colour results and possible practical applications in many spheres. However, as the elevation of the final model is only about 5 millimetres, displaying great detail on the top layer is limited, but for this demonstration it serves as a very good example. Other visualisations with improved detail and larger models could be 3D printed in the future, for example, as a part of a real academic scheme. It depends only on the purpose of the final result. An enormous number of possibilities for modifying the thematic information for visualisations exists, including modelling for natural disasters, hazards or urban development scenarios. It may be found highly useful for educational purposes or in crisis management. Almost any type of spatial information could be visualised using this type of 3D processing algorithm.

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References

Ahilan, S., M. O'Sullivan and *M. Bruen* 2012: Influences on flood frequency distributions in Irish river catchments. – Hydrology and Earth System Sciences **16**: 1137-1150, doi:10.5194/hess-16-1137-2012

Bedient, P.B., W.C. Huber and *B.E. Vieux* 2018: Hydrology and floodplain analysis. – London

Benson, M.A. 1968: Uniform flood-frequency estimating methods for federal agencies. – Water Resources Research **4** (5): 891-908, doi:10.1029/wr004i005p00891

Berman, B. 2012: 3-D printing: The new industrial revolution. – Business Horizons **55** (2): 155-162, doi:10.1016/j.bushor.2011.11.003

Brus, J. and *R. Barvíř* 2015: Coping with integrating low-cost 3D printing and surface models: A case study on Prusa i3. – In: *Růžičková K.* and *T. Inspektor* (eds.): Surface Models for Geosciences. – Cham: 45-59

Bunch, R.L. and *R.E. Lloyd* 2006: The cognitive load of geographic information. – The Professional Geographer **58** (2): 209-220, doi:10.1111/j.1467-9272.2006.00527.x

Burian, T. and *J. Brus* 2016: 3D printing for supporting teaching and learning in GIScience. – In: SGEM2016: Conference Proceedings: STEF92 Technology Ltd., 2016, June 28 - July 6. – Sofia: 547-552

Chua, C.K., K.F. Leong and *C.S. Lim* 2010: Rapid prototyping: principles and applications. – Singapore

Curebal, I., R. Efe, H. Ozdemir, A. Soykan and *S. Sönmez* 2016: GIS-based approach for flood analysis: case study of Keçidere flash flood event (Turkey). – Geocarto International **31** (4): 355-366, doi:10.1080/10106049.2015.1047411

Digitalglobe 2009: Google Earth V 7.1.8.3036 (June 1, 2009). Demir Kapija, Republic of North Macedonia. 41°24'39.31"N, 22°14'58.16"E. – Online vailable from within Google Earth: https://earth.google.com – accessed 1/6/2009

Garrity, C.P., P.C. Hackley and *F. Urbani* 2009: Digital shaded-relief map of Venezuela. Version 2.0. – U.S. Geological Survey Open-File Report 2004-1322, doi:10.3133/ofr20041322

Ghawana, T. and *S. Zlatanova* 2013: 3D printing for urban planning: A physical enhancement of spatial perspective. – In: *Ellul, C., S. Zlatanova, M. Rumor* and *R. Laurini* (eds.): Urban and Regional Data Management: UDMS Annual 2013. – London: 211-224

Häberling C., H. Bär, H. and *L. Hurni* 2008: Proposed cartographic design principles for 3D maps: A contribution to an extended cartographic theory. – Cartographica **43** (3): 175-188, doi:10.3138/carto.43.3.175

Icaga, Y., E. Tas and *M. Kilit* 2016: Flood inundation mapping by GIS and a hydraulic model (HEC RAS): A case study of Akarcay Bolvadin subbasin, in Turkey. – Acta Geobalcanica **2** (2): 111-118, doi:10.18509/AGB.2016.12

Khattak, M.S., F. Anwar, T.U. Saeed, M. Sharif, K. Sheraz and *A. Ahmed* 2016: Floodplain mapping using HEC-RAS and ArcGIS: a case study of Kabul River. – Arabian Journal for Science and Engineering **41** (4): 1375-1390, doi:10.1007/s13369-015-1915-3

Merwade, V., A. Cook, J. Coonrod 2008: GIS techniques for creating river terrain models for hydrodynamic modeling and flood inundation mapping. – Environmental Modelling & Software **23** (10-11): 1300-1311, doi:10.1016/j.envsoft.2008.03.005

Ngo, T.D., A. Kashani, G. Imbalzano, K.T. Nguyen and *D. Hui* 2018: Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. – Composites Part B: Engineering **143**: 172-196, doi:10.1016/j.compositesb.2018.02.012

Patterson, T. 2014: Mountains unseen: developing a relief map of the Hawaiian seafloor. – Cartographic Perspectives **76**: 5-18, doi:10.14714/CP76.859

Phillips, R.J., A. Lucia and *N. Skelton* 1975: Some objective tests of the legibility of relief maps. – The Cartographic Journal **12** (1): 39-46, doi:10.1179/caj.1975.12.1.39

Popelka, S. and *A. Brychtová* 2013: Eye-tracking study on different perception of 2D and 3D terrain visualisation. – The Cartographic Journal **50** (3): 240-246, doi:10.1179/1743277413y.0000000058

Radevski, I. and *S. Gorin* 2017: Floodplain analysis for different return periods of river Vardar in Tikvesh valley (Republic of Macedonia). – Carpathian Journal of Earth and Environmental Sciences **12** (1): 179-187

Rase, W. D. 2011: Creating physical 3D maps using rapid prototyping techniques. – In: *Buchroithner, M.* (ed.): True-3D in Cartography. – Berlin/Heidelberg: 119-134

Roub, R., P. Novák and *T. Hejduk* 2013: Optimization of flood protection by semi-natural means and retention in the catchment area: a case study of Litavka River (Czech Republic). – Moravian Geographical Reports **21** (1): 51-66, doi:10.2478/mgr-2013-0005

Ruzínoor, C.M., A.R. Shariff, A.R. Mahmud and *B. Pradhan* 2011: 3D terrain visualisation for GIS: A comparison of different techniques. – In: *Buchroithner, M.* (ed.): True-3D in Cartography. – Berlin/Heidelberg, 265-277

Savage, D.M., E.N. Wiebe and *H.A. Devine* 2004: Performance of 2D versus 3D topographic representations for different task types. – Proceedings of the Human Factors and Ergonomics Society Annual Meeting **48** (16): 1793-1797, doi:10.1177/154193120404801601

Schobesberger, D. and *T. Patterson* 2008: Exploring of effectiveness of 2D vs. 3D trailhead maps, Proceedings of 6th ICA Mountain Cartography Workshop, Lenk, Switzerland, Feb 11-15. – Online available at: http://www.mountaincartography.org/publications/papers/papers_lenk_08/schobesberger.pdf – accessed 2/1/2020

Schoorl, J.M., M.P. Sonneveld and *A. Veldkamp* 2000: Three-dimensional landscape process modelling: the effect of DEM resolution. – Earth Surface Processes and Landforms **25** (9): 1025-1034, doi:10.1002/1096-9837(200008)25:9<1025::AID-ESP116>3.3.CO;2-Q

Schwarzbach, F., T. Sarjakoski, J. Oksanen, L. T. Sarjakoski and *S. Weckman* 2012: Physical 3D models from LIDAR data as tactile maps for visually impaired persons. – In: *Buchroithner, M.* (ed.): True-3D in Cartography. – Berlin/Heidelberg: 169-183

Simón, F.J. 2015: DEMto3D. – Online available at: http://demto3d.com/en/demto3d-disponible-qgis – accessed 24/2/2019

Svobodová, J. and *V. Voženílek* 2010: Relief for models of natural phenomena. – In: *Anděl, J.* and *V. Voženilek* (eds.): Landscape Modelling. – Dordrecht: 183-196

Šlangens, J. and K. *Krauklis* 2011*:* Creating of digital relief map for regional hydrogeological model of Latvia. – Boundary Field Problems and Computer Simulation **50**: 21-25

Terribilini, A. 2001: Entwicklung von Arbeitsabläufen zur automatischen Erstellung von interaktiven, vektorbasierten topographischen 3D-Karten, Ph.D. dissertation, ETH Zurich. – Zurich, doi:10.3929/ethz-a-004229058

Traore, V.B., M. Bop, M. Faye, G. Malomar, H. Sambou, A.N. Dione and *A.C. Beye* 2015: Using of Hec-ras model for hydraulic analysis of a river with agricultural vocation: A case study of the Kayanga river basin, Senegal. – American Journal of Water Resources **3** (5): 147-154, doi:10.12691/ajwr-3-5-2

von Wyss, M. 2015: 3D-printed landform models. – Cartographic Perspectives **79**: 61-67, doi:10.14714/CP79.1297

Zorn, M. and *M. Hrvatin* 2015: Damage caused by natural disasters in Slovenia between 1991 and 2008. – Acta Geobalcanica **1** (1): 33-43, doi:10.18509/AGB.2015.04