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

Keywords
3D printing, modelling, floodplain, Vardar river, GIS
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; Carebal 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 problematic.

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 (Ruzinoor et al. 2011). According to Ghawana and Zlatanov (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 Håberling 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 visualisation, 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.

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>
<thead>
<tr>
<th>Year</th>
<th>h (cm)</th>
<th>Year</th>
<th>h (cm)</th>
<th>Year</th>
<th>h (cm)</th>
<th>Year</th>
<th>h (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974/75</td>
<td>236</td>
<td>1984/85</td>
<td>248</td>
<td>1994/95</td>
<td>204</td>
<td>2004/05</td>
<td>294</td>
</tr>
<tr>
<td>1976/77</td>
<td>369</td>
<td>1986/87</td>
<td>382</td>
<td>1996/97</td>
<td>286</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1979/80</td>
<td>506</td>
<td>1989/90</td>
<td>200</td>
<td>1999/00</td>
<td>280</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1980/81</td>
<td>428</td>
<td>1990/91</td>
<td>309</td>
<td>2000/01</td>
<td>212</td>
<td></td>
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</tr>
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</table>

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 km² (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 combina-
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itation 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)

<table>
<thead>
<tr>
<th>Return period (years)</th>
<th>Gaussian (Normal)</th>
<th>Pearson III</th>
<th>Log-Pearson III</th>
<th>Gumbel</th>
<th>Log-normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,000</td>
<td>569</td>
<td>675</td>
<td>723</td>
<td>792</td>
<td>717</td>
</tr>
<tr>
<td>1,000</td>
<td>522</td>
<td>591</td>
<td>617</td>
<td>659</td>
<td>613</td>
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<tr>
<td>200</td>
<td>484</td>
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<tr>
<td>2</td>
<td>297</td>
<td>289</td>
<td>289</td>
<td>285</td>
<td>288</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Return period (years)</th>
<th>5</th>
<th>10</th>
<th>50</th>
<th>100</th>
<th>1,000</th>
<th>10,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (km²)</td>
<td>1.319</td>
<td>1.357</td>
<td>1.585</td>
<td>1.756</td>
<td>1.928</td>
<td>2.072</td>
</tr>
</tbody>
</table>

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 km²), 100 years (1.756 km²) and 10,000 years (2.072 km²).

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

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

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
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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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