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Original paper

Mapping Ghana by GMT and R scripting: advanced cartographic approaches to visualize correlations between the topography, climate and environmental setting

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Abstract: The applications of the machine learning and programming approaches in cartography has been increasing in recent years. This paper presents a case study of the scripting techniques used for cartographic mapping using Generic Mapping Tools (GMT) and R language (raster and tmaps packages). The aim of the study is environmental mapping of Ghana. The materials include high-resolution raster grids: topography by the General Bathymetric Chart of the Oceans (GEBCO), climate and environmental datasets (TerraClimate) and Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) for geomorphometric analysis (slope, aspect, hillshade and elevations). The methodology includes code snippets commented and explained with details of scripts. It is argued that using console-based scripting tools for mapping is effective for cartographic workflow due to the logical structure and repeatability of scripts. The results include eight new thematic maps of Ghana performed using scripting approach in GMT scripting toolset and R language for quantitative and qualitative environmental assessment. Maps show correlations between the landforms of Ghana and certain environmental variables (drought index and soil moisture) showing the effects of the topographic relief on the distribution of the continuous geographic fields. These varied in several geographically distinct regions of Ghana: Ashanti (Kumasi), Volta, Savannah, coastal and northern regions. Demonstrated maps show that scripting method works effectively on a wide range of geosciences including environmental, topographic and climate studies. In such a way, this paper contributes both to the regional studies of Ghana and development of cartographic techniques.

Keywords: geophysics, mapping, cartography, R language, GMT

1. Introduction

This paper considers the problem of automated cartographic data handling using scripting techniques. Over the last few years this topic has received a growing amount of attention in the cartographic community. We argue that using scripts improves the quality and speed of mapping process which results in more accurately plotted and aesthetically visualized maps. Such assumptions are reflected in the characteristics of the most powerful scripting geospatial tools, the Generic Mapping Tools (GMT) and the GRASS GIS, which improve the cartographic workflow in terms of accuracy of data processing and without consideration of the commercial costs of the proprietary GIS.

The paper provides a case study of mapping Ghana (Fig. 1) with a special focus on geomorphometric modeling for topographic and environmental analysis of the country. The aim is to visualize and highlight the existing correlations between the variability of the topographic landforms and environmental setting, thus showing the effects of the relief on the distribution of the continuous geographic fields (soil moisture, climate water deficit and Palmer Drought Severity Index (PDSI) in Ghana). A special aim of the research is to demonstrate the application of scripting techniques combining GMT scripting toolset and R programming language (packages 'raster' and 'tmap') for mapping and modeling using high-resolution geospatial datasets on Ghana using both quantitative and qualitative approaches for the environmental assessment.

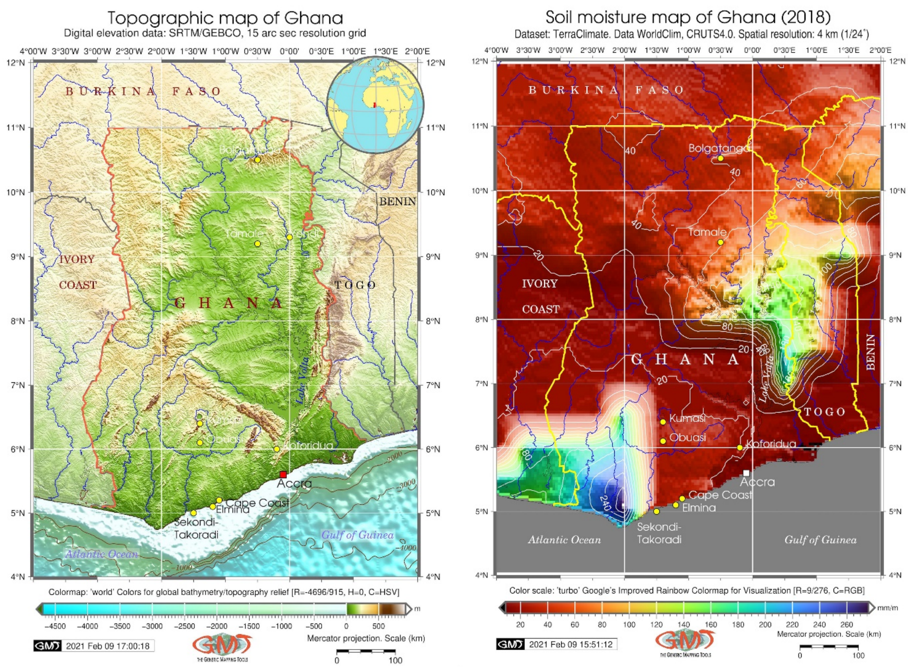

Fig. 1. Topographic and soil moisture maps of Ghana. Mapping: GMT

The novelty of this research is explained by the innovative application of the state-of-the-art approaches in geospatial scripting. Existing GIS-based methods often handle only limited challenges of modern cartography leaving apart automation and accuracy of data processing. This paper addresses these needs in a unified framework which integrates R and GMT for geospatial scripting. Thus, although traditional GIS is widely used in the geographic analysis and environmental mapping (Burrough and McDonnell, 1998; Suetova et al., 2005; Klaučo et al., 2017; Mensah et al., 2019; Worqlul et al., 2019; Lemenkova, 2020d, 2021a, 2021d; Larbi et al., 2022), this paper argues that applying scripting by integration of GMT and R is beneficial for effective geomorphological, environmental and topographic mapping of Ghana. Thus, the major contribution of this paper lies in automatic visualizing of the selected region of west Africa via a scripting technique. The advantages of scripting in modern cartography are discussed in the existing publications and used in this study as reference (Lemenkova, 2021b). The geomorphometric analysis allows to perform ranking of the terrain using its derivatives: slope and aspect, hillshade and elevation, aimed at the visualizing and assessment of factors affecting local climate and environmental setting of the selected region of west Africa.

The application of the geomorphometric analysis by R was used for land surface analysis by the embedded numerical data processing of 'raster' package designed for geospatial data processing. Besides being a general programming language widely used for statistical analysis (Lemenkova, 2019a), R language also has powerful possibilities of scripting in geospatial data modeling and visualization using cartographic approaches. Therefore, ranking land slope and aspect was visualized by R and demonstrated for correlation analysis with topography of Ghana. The terrain morphometry is characterized by quantitative land surface analysis computed based on the quantification of geomorphological, hydrological, and environmental aspects of the land surface (Jarvis and Clifford, 1990; Bishop et al., 2003; Alvioli et al., 2016; Lemenkova, 2019a, 2020a).

Geomorphometry extracts Earth's surface parameters, such as morphometric and hydrological objects (geomorphic landforms, river networks, structured ecosystem analysis) using input Digital Elevation Model (DEM), statistical analysis and data processing (Hobson, 1972; Horn, 1981; Ritter, 1987; Holling, 1992; Jones, 1998; Peckham and Gupta, 1999; Lemenkova et al., 2012; Klaučo et al., 2013; Alvioli et al., 2018). The results of the geomorphometry can be used for analysis of correlation between the topography and climate variations in different parts of the country.

Ghana has a contrasting topography which can be illustrated by a brief description of its geographic setting. Ghanaian Coastal Plain is characterized by low and sandy coastline with dominating plains and shrubs situated beyond the coast. Central areas are notable for dense network of rivers and streams: Ashanti and Brong-Ahafo. The Eastern and Volta regions are located to the north of the coast and east of the country and notable for the Volta Lake with tributaries. The typical vegetation types are presented by tropical and forests and hilly areas, numerous streams and rivers.

Northern regions of the country (Northern, Upper East and Upper West) have land heights varying from 90 m to 400 m above sea level (a.s. l.) with area generally covered by low shrubs, savannah, grasslands and plains. Volta is the largest river in Ghana together with Volta Lake. Its basin forms the largest drainage area of the country, originating in the north and discharging into the Atlantic Ocean in the east of the country. In the western regions, the Pra and Tano rivers also form significant drainage areas and special regions of Ghana (Atta-Peters and Achaegakwo, 2016; Awotwi et al., 2017, 2018).

Current environmental and social issues of Ghana are reported in the existing publications and include the ongoing issues of deforestation (Dwomoh et al., 2019; Amankwah et al., 2021), land use/cover change and agricultural land loss in the Sekondi-Takoradi (Acheampong et al., 2018), limited healthcare and poverty (Agbenyo et al., 2017; Tansley et al., 2017; Ashiagbor et al., 2020b), droughts and agriculture sustainability (Kasei et al., 2010, 2014; Antwi-Agyei et al., 2012), climate change, rainfall variability and water supply affecting ecological vulnerability and resilience in Ghana (Leemhuis et al., 2009; Logah et al., 2013; Adzawla et al., 2020). Environmental analysis and monitoring of such a sensitive region requires complex mapping approach based on the multi-source high-resolution data using advanced cartographic techniques.

Application of GIS for environmental mapping involves differences in the approaches to data processing, which are specific for each program. For instance, those include interfaces and functionality of software for geographic data processing. Some GIS rely on the menu with Graphical User's Interface (GUI) for data import, processing and output layouts (ILWIS, Erdas Imagine), while other programs offer the console-based command-line interface (GRASS GIS) or scripting language (GMT), or the combination of both (Python-compatible ArcGIS and QGIS).

One of the reasons that make scripting cartography an important issue in contemporary mapping is automation of the cartographic workflow (Lemenkova, 2019b, 2019c). Scripting technique stands apart from the existing approaches of machine learning in GIS (Schenke and Lemenkova, 2008; Jebamalai et al., 2019; Lemenkova and Lemenkova, 2021a, 2021b). The special features of scripting is the repeatability of scripts which enables the significant increase of mapping process and data processing. The second reason consists in the open access which enables data processing for all categories of study and way of work, including distance (home-) based research.

2. Materials and methods

The methodology is realized at the three different stages of this study: i) data capture; ii) mapping in GMT; iii) mapping in R. The details are described in relevant sub-sections below.

2.1. Data

The data applied for topographic mapping (Fig. 1, left) include openly available General Bathymetric Chart of the Oceans (GEBCO) (Schenke, 2016; GEBCO Compilation Group 2020, 2020), https://www.gebco.net/. It contains the most comprehensive dataset for the topography and bathymetry of the Earth with 15 arc second resolution. Due to its unprecedentedly high resolution and precision, GEBCO is widely used in topographic and geological studies (Kuhn et al., 2006; Gauger et al., 2007; Nock et al., 2019; Lemenkova, 2020c, 2021e). The data for geomorphometric analysis (Fig. 2 and Fig. 3) were derived from the installed dataset of SRTM-90 m integrated in the 'raster' package of R and received using the getData() function. The data used for environmental and climate maps (Fig. 1, right and Fig. 4) were received from the TerraClimate dataset (Abatzoglou et al., 2018).

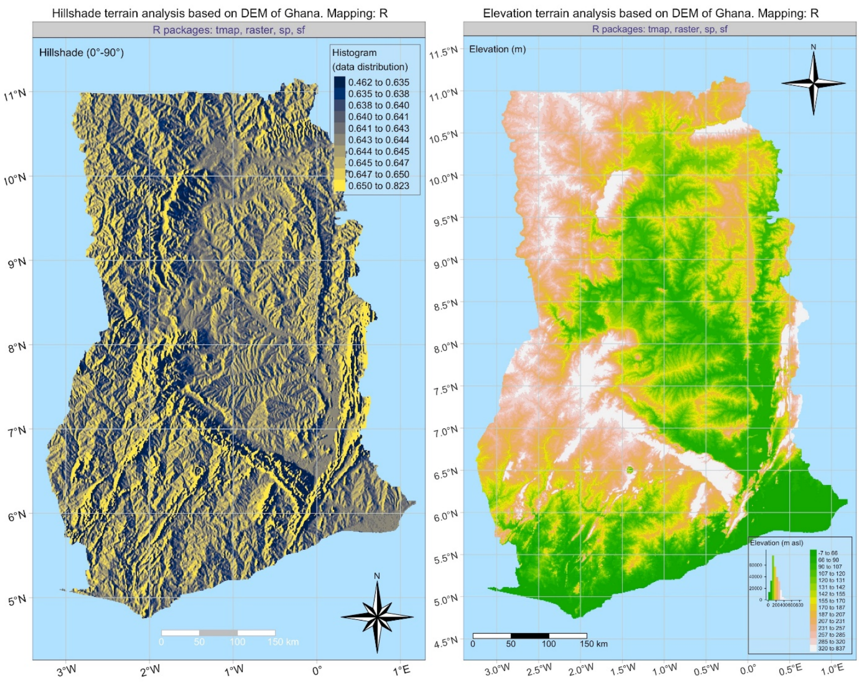

Fig. 2. DEM and hillshade of Ghana. Mapping: R ('raster' and 'tmap')

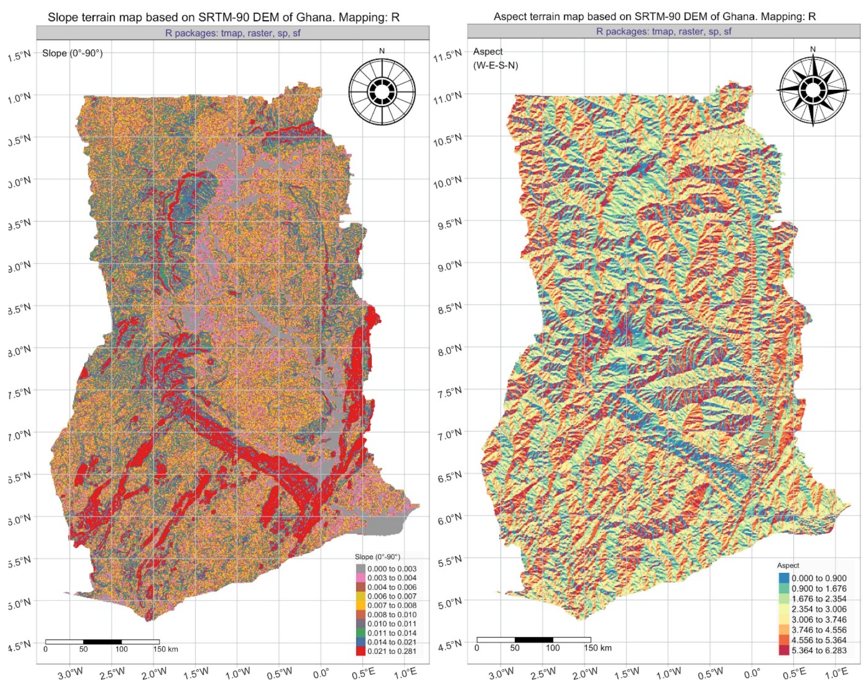

Fig. 3. Slope and aspect modeled based on DEM SRTM-90 of Ghana.
Mapping: R ('raster' and 'tmap' packages)

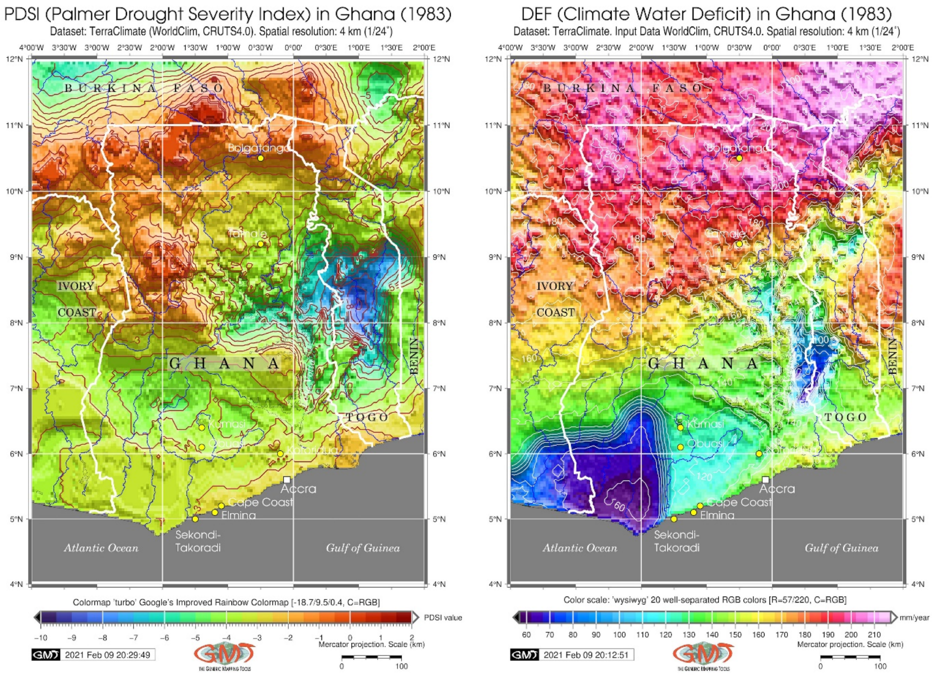

Fig. 4. Climate models based on TerraClimate dataset showing distribution of drought hazards in 1983 in Ghana. Mapping: GMT

2.2. GMT based mapping

Based The topographic, environmental and climate mapping (Fig. 1 and Fig. 4) has been performed using the GMT cartographic scripting toolset (Wessel et al., 2019). From a methodological point of view, this part of research consisted of the individual modules of GMT and shell scripting techniques. The most important code snippets that illustrate the scripting cartographic technique are as follows:

– extracting a subset of GEBCO for Ghana region: 'gmt grdcut ETOPO1_Ice_g_gmt4.grd -R-4/2/4/12 -Ggh_relief1.nc';
– making color palette using the topographic extent (elevations from −4696 m to 915 m): 'gmt makecpt -Cworld.cpt -V -T-4696/915 > pauline.cpt';
– adding a legend: 'gmt psscale -Dg-4/3.4+w12.0c/0.15i+h+o0.3/0i+ml+e -R -J -Cpauline.cpt -Bg500f50a500+l"Colormap: 'world' Colors for global... [R=-4696/915, H=0, C=HSV]" -I0.2 -By+lm -O -K >> $ps';
– adding a grid: 'gmt psbasemap -R -J -Bpxg2f1a0.5 -Bpyg2f1a1 -Bsxg2 -Bsyg1 -B+t"Topographic map of Ghana" -O -K >> $ps';
– adding annotations: 'gmt pstext -R -J -N -O -K-F+jTL+f10p,26,slateblue1+jLB -Gwhite@70 >> $ps << EOF 0.5 4.6 Gulf of Guinea EOF';
– adding isolines for a climate map (PDSI): 'gmt grdcontour gh_pdsi.nc -R -J -C0.5 -A1 -Wthin,brown -O -K >> $ps';

– making a soil moisture map using NetCDF image: ‘gmt grdimage gh_soil.nc -Cpauline.cpt -R-4/2/4/12 -JM5.0i -I+a15+ne0.75 -Xc -P -K > $ps’;
– adding scale bar, and a time stamp: ‘gmt psbasemap on the Water Climate Deficit map: -R -J -Lx11.0c/-2.4c+c10+w100k+l"Mercator projection. Scale (km)"+f -UBL/0p/-70p -O -K >> $ps’.

The given above code snippets illustrate general conceptual principles of the GMT scripting approach that are discussed in more details in earlier works (Lemenkova, 2019d, 2020b). The measurement of the degree of PDSI and spatial changes in the values of Climate Water Deficit (Fig. 4) values are provided by 1983, because year 1983 was the time of the severe climate disaster in West Africa in general and Ghana in particular, which resulted in the most intense drought recorded in Ghana (Incoom et al., 2020).

2.3. R based mapping

The geomorphometric analysis (Fig. 2 and Fig. 3) has been performed using R programming language (R Core Team, 2020) in RStudio environment (RStudio Team, 2017). The R language is a high-level programming language with powerful functionality, structured syntax and flexible semantics. It is widely used in semi-automated quantitative data analysis and visualization (Ferraro and Giordani, 2015; Lemenkova, 2020e). Specifically, the two packages of R have been used in this study: ‘raster’ and ‘tmap’. The R package ‘raster’ (Hijmans and van Etten, 2012) was used to plot topographic features of quantitative geomorphometric techniques used for DEM. The data processed by the ‘raster’ package were then handled using ‘tmap’ package for a better cartographic visualization and adjustments (Tennekes, 2012).

The techniques of ‘raster’ library used modeling of hillshade, slope, aspect and elevation of Ghanian topography to demonstrate the slope steepness (Fig. 3, left) and general compass relief orientation of the landforms using W-E-S-N convention (Fig. 3, right) and curvature/roughness of the terrain (Fig. 2, left), aimed to visualize the distinct topographic regions of Ghana by DEM (Fig. 2, right) through a scripting cartographic data processing. The geomorphometric mapping was used in combination with R programming techniques generally applied in statistical data analysis (Lemenkova, 2018a, 2018b). Each map in Figures 2 and 3 is derived as a variable DEM SRTM-90 dataset for Ghana using the following code: alt = getData("alt", country = "Ghana", path = tempdir()).

The values for slope, aspect and elevation have been identified using ‘terrain’ function of package as follows (example for slope): ‘slope = terrain(alt, opt = "slope")’ and then visualized using ‘plot’. A hillshade of DEM values is defined as follows: ‘hill = hillShade(slope, aspect, angle = 40, direction = 270)’, that is, calculated using previously defined slope and aspect as their derivative. The next stage of data processing has been performed using ‘tmap’ package using following structure of the code: map1 <– tmap_style("watercolor") + tm_shape(slope, name = "Slope", title = "Slope") + tm_raster() + tm_scale_bar() + tm_compass() + tm_layout() + tm_graticules().

The parameters in brackets were defined for each function using technical manuals of the 'raster' package. For instance, the compass was plotted using following commands: tm_compass(type = "radar", position=c("right", "top"), size = 8.0).

To better visualize the variation performance on all derivative layers from DEM of Ghana (slope, aspect and hillshade) and to study differences in the topography of the relief in various parts of the country, this study used the 'tmap_style' functions of 'tmap' for adjusting the background of maps to highlight the clearest contrast and geomorphological structure of Ghana. The two styles were applied: 'watercolor' with blue background and 'natural' with white background.

3. Results

The Figure 1 (left) shows the topographic and soil moisture maps of Ghana. The topography visualizes general relief structures of the country: mountain ridges, hills, lowlands and river valleys, coastal areas and savannah plains (Fig. 1, left). The results of the cartographic of DEM analysis (Fig. 1, left) show that there are distinct variations in the topographic relief of Ghana: i) Volta Lake basin and its tributaries with clearly visible lowlands and local depressions in the relief; ii) the Ashanti-Kumasi region that is notable for the most diverse topography with mountain hills and lowlands, local streams and forests; iii) the coastal regions of Cape Coast, western coastal region of Sekondi-Takoradi and Greater Accra. These variations in the topographic landforms of Ghana explains the variability of the environmental and climate parameters affected by the local and regional relief. The visualization of DEMs demonstrated the extensive areas of Ghana with highly-rugged mountainous terrain in the selected regions of Ashanti known for a highly contrasting topography, lowland areas of the Volta Lake basin and plain regions with smoothed topography in the coastal region of the Atlantic Ocean and the Gulf of Guinea.

Figures 2 and 3 show geomorphometric functions visualized by R: hillshade and elevation (Fig. 2), slope and aspect (Fig. 3), showing variability and general curvature of the relief. The DEM was based on the import of the Shuttle Radar Topography Mission (SRTM) DEM with 90 m resolution for the region of Ghana (Fig. 2, right), which was performed in the 'raster' package of R. The map of aspect (Fig. 3, right) enables better understanding the hydrologic flow directions in Ghana, a country with well-developed river network showing the distribution of data by orientation of eight types of slopes (W-E-S-N-SW-SE-NW-NE). Flow direction shows general hydrological parameter of the orientation of river streams. It forms the basis for the hydrogeological assessment using high-resolution data. A hillshade model well represents the distribution of hilly and mountainous landscapes contrasting with plains and lowlands of Ghana as well as regions with a smooth ground surface (Fig. 2, left). The hillshade of the Ghanian relief presents the results of the operation of working with DEM for calculation of an analytical hill shading of 'raster' package of R, which is specially designed for terrain visualizations based on DEM (Fig. 2, right) and well correlates with other geomorphometric layers: slope, aspect and elevation (Fig. 2, left and right, Fig. 3, right, respectively).

The hillshade for azimuth direction 270° and altitude angle 40° presents a visibility analysis for a single simulated artificial light source presenting the modeled lookout point above the surroundings of Ghana derived from DEM (Fig. 2, right). The aim of hillshade mapping was to improve the geomorphometric applicability of DEM SRTM-90 by visualizing an image of Ghanian topography for precise mapping of the relief with simulated artificial lighting. The 'cividis' colormap was applied, generated by optimizing the 'viridis' color table and effectively adjusted for the hillshade illumination of Ghana (Fig. 2, left). The cartographic solution of R achieves an informative aspect map of Ghana (Fig. 3, right) derived from the geomorphometric analysis based on the SRTM-90 data of 'raster' package which have been both generalized (i.e., reclassified into 8 classes according to the compass orientation) and colored-enhanced through the application of 'Spectral' color palette of RColorBrewer package. The map of slope steepness (Fig. 3, left) derived from the relief of Ghana using SRTM-90 DEM produced at the same resolution as DEM (90 m) with enhanced class edges through the inverted 'Set1' color palette of RColorBrewer.

Figure 4 shows examples of climate mapping presented in GMT: the PDSI visualization (Fig. 4, left), and the Climate Deficit (Fig. 4, right), which are both derived for the year 1983, since the 1983 is the most representative period of drought in Ghana. The evaluation of the results of climate analysis in Ghana is performed using the integrated approach by visualized grids and complementary literature analysis. The Climate Water Deficit shown the least affected regions along the coasts of the Gulf of Guinea, while the suffered areas are located predominantly in the north. The PDSI shown the most affected regions of drought in the east border regions close to Togo and in the Volta Lake, while the least affected ones are in savannah. The PDSI values are varying from the most severe drought areas (up to –10) in the east of the country and in Togo to a lesser extent (no more than +2) in the northern regions in savannah as a result of the hydrological dynamics caused by the effects of the topography. The Water Climate Deficit shows the least effected regions in the western coastal areas of Ghana in Sekondi-Takoradi and Cape Coast regions (less than –60 mm/year) while the considerable values in the north-eastern areas (over 210 mm/year). The map of Water Climate Deficit shows annual evaporative demand that exceeds available water in Ghana.

4. Discussion and recommendations

Using numeric analysis of correlation among the data visualized on present maps using open geospatial sources may assist in environmental understanding of the phenomena and support decision making in modelling scenarios of the environmental and landscape change contributing to the existing studies on Ghana (Amisigo et al., 2015; Awotwi et al., 2015). Specifically, using thematic maps enables autonomous decisions for the environmental missions aimed at the sustainable development of the country through illustrating land cover types of Ghana, which can be extended to contribute and continue existing works (Braimoh, 2004). Besides, DEM-based geomorphometric analysis presented as maps of slope/aspect and topographic variables can support high-precision agricultural mapping through illustrating the terrain patterns.

As an extended further application of this study, the presented series of maps could be used in combination with the remote sensing data, such as satellite images of Ghana or drone-based data, providing large-scale information for crop mapping in agricultural regions of the country. In such a way, this study may be applied for regional agricultural forecasting purposes as cartographic illustrations of the country, especially in the Upper West Region of Ghana. This includes, in particular, numerical analysis of crop area assessed for dominating crop types in the country, predictive analysis for yield forecasting and drought risk quantification using crop mapping based on the high-resolution remote sensing data and using presented topographic and environmental maps.

The scenarios of possible land cover changes and risk assessment can be assessed using presented maps as a contribution for existing agricultural ecosystem mapping, forest and biodiversity monitoring of Ghana (Cobbinah et al., 2015; Gyamfi et al., 2021; Appiah-Badu et al., 2022). This is ensured by heterogeneous geospatial data used for visualizing topographic units, geomorphology, climate setting and agricultural landscapes of the country, as made similarly in earlier integrating studies on the environmental monitoring of Ghana (Glover et al., 2005; Obiri et al., 2021). Flexibility of scripting approaches can be used for comparative analysis using visualized maps made by scripting cartographic methods.

The heterogeneous landscapes of Ghana are characterized by the mixed crop types (maize, millet, rice, sorghum, yam, groundnut, and soya beans) as well as very diverse ecosystems (plains, low hills, riverine landscapes, coastal areas, savannah, Volta Lake landscapes, tropical moist broadleaf forests, mangroves). Such landscape diversity of Ghana makes cartographic discrimination of the agricultural crop types more complicated and requires advanced methods of precise topographic and environmental mapping. In this way, this study contributed to this goal by presenting a series of maps plotted by the advanced mapping methods of GMT for an in-depth topographic analysis of the unique and diverse system of the west African landscapes.

The analysis of the multi-source geospatial raster grids and DEM data for cartographic visualization aimed to detect and identify topographic and geomorphological types in Ghana. The comparison of the topography with climate and environmental setting revealed that soil moisture, climate water deficit and PDSI index of droughts have a correlation with geomorphological landforms of the country. Furthermore, this study visualized regions of Ghana prone to droughts with low level soil moisture. Such information can be used for climate and environmental susceptibility assessment and monitoring crops in Ghana.

Using present maps may contribute to the agricultural decision making through a DEM-based modelling. For example, DEM-based maps may be used for decisions on planting crop with seasonally varying phenology or rotation of crops according to the aspect of slopes, in order to improve soil health and optimize nutrients and moisture in soil. The series of maps presented in this study illustrate the topographic variability of landscapes and climate units of Ghana. Specifically, it demonstrated the distinct areas prone to droughts (PDSI) and soil dryness as well as regions of water climate deficit in Ghana. The analysis of regional diversity in topography and landscapes of Ghana is necessary for understanding factors affecting farming systems in various regions of the country. Yet another challenge is to highlight the environmental dynamics (e.g., forest canopy health) affected by climate changes and topographic variables, such as aspect and slope. A better understanding of regional inequality of topographic patterns detected from DEM can be seen using the analysis of the hill shade with relief visualization effect which contributes to a more detailed analysis of topography of the country with a final goal of supporting effective landscape monitoring for farming agricultural ecosystems in Ghana.

To overcome the challenges of modern cartographic techniques, the present work was intended to use the synthesis of the high-resolution raster grids (e.g. GEBCO and TerraClimate data) for terrain and climate mapping of Ghana by scripting algorithms of GMT. Several modules of GMT and its specific syntax were applied to identify continuous fields of changing variables on a raster-based basis and cartographically visualize variations in topographic and climate setting in various regions of the country, including both natural landscapes and irrigated soils. The visualized data on environmental parameters are useful for assessment of the soil moisture and topographic variables (heights, slope steepness, roughness and aspect), which directly affects vegetation.

As a recommendation for future studies, an extended environmental and agricultural analysis of Ghana can be performed through by adding extra datasets: data obtained from the in situ observations and fieldwork, drone-borne aerial data and satellite remote sensing (RS) data. The RS data may include, for instance, multi-temporal Sentinel-2A or Landsat TM/ETM+ data for time series analysis aimed at land cover changes (Ashiagbora et al., 2020a; Lemenkova, 2020f, Asare et al., 2021). The aerial data covering the same field perimeter as the RS data may enable multi-scale mapping in both local and regional contexts. The LiDAR can be used for estimating slope steepness and generating high-resolution models of the ground elevation with high vertical accuracy.

Moreover, acquiring reference training data for species canopies, crops and plant communities in agricultural regions of Ghana can be performed during the fieldwork and added to the database. Defining geometric polygons of the crop field and boundaries for target plants, crop types and canopies can further be used for visual interpretation of the crops fields in agricultural mapping of Ghana. Overlay of such data with topographic and climate maps presented in this study can further extend this research towards a more detailed land cover types analysis of Ghana.

Generating the environmental database with new datasets on Ghana requires processing them in an effective and robust way. The statistical processing of such data can be performed using libraries of Python and R for implementation of the machine learning methods. In this way, scripting continues workflow automation, which enables smooth and rapid processing of the large datasets in case of using multiple sets of satellite images (billions of pixels on the images, and a large number of points in the remote sensing point clouds). The statistical analysis of tabular data obtained from the geospatial data can be done by R. Robust statistical techniques for LiDAR point clouds processing can be used for feature extraction, outlier detection, image segmentation and pattern modelling of landscape polygons in Ghana.

Other methods that could be recommended include the Object Based Image Analysis (OBIA) for automated object recognition on the object-based level rather than pixel-based classification. Finally, the GMT mapping can be integrated with the GIS for data integration with vector layers in '.shp' formats (native format of the ArcGIS). Thus, combination of multi-source data and methods can assist in highlighting connections between the climate, hydrological, environmental and topographic phenomena that change the face of the landscapes in Ghana.

5. Conclusions

The demonstrated scripting approach of GMT and R shown a concept of the machine learning applied to cartographic data processing and mapping. It proved that different morphologies along the topography of Ghana can be quantitatively assessed and classified based on the geomorphometric metrics and consistently visualized in comparison with the multi-source environmental and climate datasets. Although not as straightforward as in the GUI-based GIS, it is argued that using console-based scripting tools for mapping is effective for cartographic workflow due to the logical structure and repeatability of scripts.

The use of automation improves technical mapping process and increases cartographic quality of maps. Human-induced errors and imperfectness of workflow, occasional mistakes and misprints negatively affects mapping production. For instance, handmade drawing of lines may lead to a reduced accuracy and imprecise geometry of visualized objects; using layer-based GIS environment can be a tedious and not straightforward process and involve a time-consuming workflow; aesthetic features for objects and their properties are often limited in the existing GIS. However, using scripting requires extra explanation and might be not as straightforward as traditional GIS, which could be mentioned as a disadvantage compared to GIS.

Another issue concerns open availability of GIS with technical notes regarding algorithms of computing methods. The commercial cost of the proprietary GIS restrict access and possibility to use them. Temporary licenses (e.g. academic access) may limit the functionality of the selected plugins. Therefore, using commercial GIS might be strictly regulated and controlled, which is the opposite for the open source tools, such as GMT and R. Using freely available tools ensures unlimited processing of data and enables unrestricted access to software. Another important issue concerns data quality control with publicly available information on metadata, precision (resolution) and actuality (production date) of geoinformation.

Accurate and actual information on topography, climate setting, DEM-based geomorphology, soil moisture and climate water deficit is necessary for targeted use in the environmental monitoring of African countries. Such data can be obtained from the public sources (TerraClimate or GEBCO, SRTM and ETOPO). Using a dataset covering arable areas of Ghana containing information on soil and topography obtained from the open source high-resolution data can be applied and used in further studies and interpreted for the extended environmental analysis of west Africa. In this way, the use of the advanced scripting cartographic methods may help to reproduce codes for plotting additional maps in the extended project, which well illustrates the advantages of the repeatability of scripting. Thus, positive effects of scripting concept in geographic studies include the following issues:

i) automation provided by scripting methodology increased the speed and precision of cartographic workflow through the repeatability and machine learning algorithms;
ii) improved aesthetics and design of maps through the refined adjustments of the cartographic elements: selection of color palettes, fonts, line/symbol styles;
iii) free open source availability of both GMT and R programming packages available in the remote access mode including home- and distance-based studies, which is actual nowadays.

The results of the present study consist in an applied integrated scripting methodology for accurate, rapid and aesthetic mapping using R and GMT methods used for open datasets. These methods help to effectively, rapidly and accurately perform cartographic data processing and mapping and demonstrate the aesthetics of the outcome products made by means of R and GMT, in terms of the improved color balance of the selected palettes, cartographic visualization of objects, general map layout, selection of font types, ornamentation, scale, direction and refine plotting of ticks, and visual appearance, to mention a few. The GMT-based maps can be used as auxiliary illustrations in geosciences (Peirce et al., 1996; Lindh and Lemenkova, 2021a), besides cartographic research.

Color and geometric shapes of the objects on the maps refine their appearance and effectiveness of the layout. Both GMT and R include a wide variety of fine adjustments techniques in the functionality, as demonstrated in this paper. The presented results included eight new maps of Ghana aim to visualize its environmental setting and complex topographic terrain (high ruggedness and variability of slope steepness). The geographic complexity of the country requires refined methods of geospatial data visualization, which was enabled by scripting cartographic techniques, as demonstrated in this paper.

In a regional context of the topographically diverse landscapes of Ghana, using open source datasets with various thematic coverage processed by GMT and R enabled to characterize environmental variables from the multiple hierarchical perspectives (local, regional and national levels) through the improved representation of the print-quality maps. This includes the processing of the data on geomorphometry and climate, topography and coastal bathymetry of Ghana.

Since heretofore there is no empirical study on the application of scripting mapping for mapping PDSI, climate water deficit and geomorphometric analysis at national and regional level in Ghana, this paper contributed to fill in this gap. It continues both regional environmental studies of Ghana and applied geophysical studies (Dzikunoo et al., 2021; Forson et al., 2021; Lemenkova, 2021c; Lindh and Lemenkova, 2021b) to the cartographic technical development through the presentation of the new methods and machine learning approaches. From this point of view, this study aims to visualize correlations between the geomorphological structure of Ghana and climate datasets on 1983 and 2018 at the national and regional levels aimed to examine the variations in geographic continuous fields using graphical solutions of scripting approach by GMT cartographic toolset and R programming language.

Topographic modelling of Ghana based on the SRTM DEM and GEBCO-derived data enables to estimate variables of heights and slopes showing where the water would run off, which can be applied for agricultural mapping and analysis. The geomorphological analysis of the valleys demonstrated as geomorphometric maps (side slope steepness, aspect and terrain ruggedness) and soil moisture can contribute to estimate the strength of water drainage. Therefore, present series of maps can be applied and extended for sustainable development studies of Ghana where geospatial modelling and advanced methods of spatial analysis are required.

The presented comparative scripting approach by GMT and R is an excellent technical cartographic solution for making use of the high-resolution spatial data on Ghana at the regional country scale. A set of the multi-source datasets is chosen for the series of the thematic maps visualizing environmental, climate and topographic parameters of the country. The outputs visualize general distribution of the continuous fields (PDSI, water climate deficit, topography, geomorphometric variables) over the country. The paper applied scripting means of GMT and R for cartographic visualization of the topography of the country, modeling climate datasets and regional geomorphometric variables. This work furthermore demonstrated the application of the terrain surface modeling by algorithms of R and scripting solutions of GMT for delineation of the geomorphometric parameters. It shown structural details of the Ghanian topography (slope steepness, aspect orientation and hillshade model) reflected in the data distribution of soil moisture and climate data.

According to the obtained results, scripting cartographic techniques demonstrated to be effective and applicable for topographic visualization and geomorphometric modeling. The study focused on the consequent structural interpretation of the relief and environmental parameters of Ghana based on the high-resolution input data (GEBCO, SRTM DEM, TerraClimate). Furthermore, the paper proved the importance of the correct, precise and reliable input raw datasets, crucial for geospatial modeling. The disposition of the geomorphometric variables and correlation between the variables (slope and aspect, hillshade and elevation) is highlighted using visualized topographic heights and surface roughness. Slope steepness (angles) and gradient of the vertical dissection of the terrain of Ghana is mirrored by the climate data, which proved deep structural connectivity between the relief, hydrology (density and flow direction of the rivers), climate and environment of the country. Mapping slope, aspect, hillshade and elevation of the topography of Ghana shown differences in heights which highlighted the altitudinal effects of the geomorphological structures.

The geomorphometric parameters demonstrated to be the most applicable markers for the delimitation of the morphological structures of the geologic and tectonic forms mirrored in the surface topography of the Earth. By integrated mapping of the slope steepness and aspect orientation of the geomorphometric structures, the terrain surface blocks separating elevated hills from lowland depressions in the geomorphology of the Ghana were visualized. Adding climate and environmental data enabled to demonstrate variations in local geomorphology correlated with landforms, since it mirrors the intensity of complex environmental processes of Ghana. The discontinuities in the PDSI and climate water deficit correlate with the distribution of water areas (coastal areas, river network, Volta Lake and its tributaries) represented by the cartographic techniques of GMT.

The presented new eight cartographic images provided a visualized representation of the topographic, geomorphometric, environmental and climate parameters of the terrain of Ghana. The importance of the presented research consists in the innovativeness of the methods. Thence, the presented scripting cartographic techniques can be re-applied and re-used in other similar works on topographic and environmental modeling of Ghana using other datasets (e.g., ETOPO1, GLOBE) or other territorial extents for neighbor countries. The cartographic visualization presented by the GMT scripting and R programming approaches applied for Ghana has been interpolated according to the precision of the input datasets (GEBCO with 15 arc second resolution, SRTM with 90 m resolution, TerraClimate data with 4 km resolution). The presented cartographic methodology and new eight maps can be applied in further studies, such as mapping land cover types and ecosystems analysis of Ghana.

Data availability statement

Full codes of the GMT and R, used for mapping, are provided in the GitHub: https://github.com/paulinelemenkova/GMT-and-R-scripts-for-GaC.

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