

## Scripting cartographic techniques of R and GMT for geomorphological and topographic mapping of Peru

### *Scripting de técnicas cartográficas de R y GMT para el mapeo geomorfológico y topográfico del Perú*

### *Scripting de técnicas cartográficas de R e GMT para o mapeamento geomorfológico e topográfico do Peru*

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#### Abstract

The paper presents the use of scripting cartographic techniques for the visualization of topographic and geomorphological maps by R and GMT. The thematic maps intend to analyze the region of Peru with specific focus on its geomorphology: slope, aspect, elevation and hillshade performed in R libraries 'raster' and 'tmap'. The integrated free materials include several datasets embedded in R library 'OpenStreetMap': Stamen, ESRI World Imagery, Bing Maps, National Park Service. The research shows a particular example of the use of open source datasets and free tools available for distance-based online education and research, which becomes an actual tendency in modern geographic research.

**Keywords:** cartography, GMT, R language, programming, Peru, geomorphology, topography

#### Resumen

El artículo presenta el uso de técnicas cartográficas de scripting para la visualización de mapas topográficos y geomorfológicos por R y GMT. Los mapas temáticos pretenden analizar la región del Perú con un enfoque específico en su geomorfología: pendiente, aspecto, elevación y sombreado realizado en las bibliotecas R «raster» y «tmap». Los materiales integrados incluyen varios conjuntos de datos integrados en la biblioteca R "OpenStreetMap": Stamen, ESRI World Imagery, Bing Maps, National Park Service. La



investigación muestra un ejemplo particular del uso de conjuntos de datos de código abierto y herramientas gratuitas disponibles para la educación e investigación en línea a distancia, que se convierte en una tendencia real en la investigación geográfica moderna.

**Palabras clave:** cartografía, GMT, lenguaje R, programación, Perú, geomorfología y topografía

## Resumo

O artigo apresenta o uso de técnicas cartográficas de scripting para a visualização de mapas topográficos e geomorfológicos por meio do R e do GMT. Os mapas temáticos têm como objetivo analisar a região do Peru com um enfoque específico em sua geomorfologia: declividade, exposição, elevação e sombreamento, realizados nas bibliotecas R «raster» e «tmap». Os materiais integrados incluem vários conjuntos de dados incorporados na biblioteca R "OpenStreetMap": Stamen, ESRI World Imagery, Bing Maps, National Park Service. A pesquisa apresenta um exemplo particular do uso de conjuntos de dados de código aberto e ferramentas gratuitas disponíveis para o ensino e a pesquisa a distância, o que se torna uma tendência real na investigação geográfica moderna.

**Palavras-chave:** cartografia, GMT, linguagem R, programação, Peru, geomorfologia e topografia

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## 1. Introduction

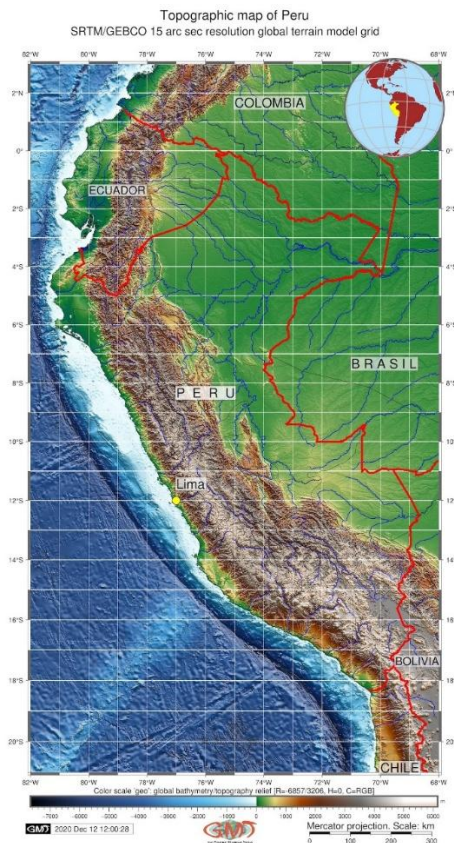
Scripting techniques is a new approach in cartography with promising perspectives for data visualization and mapping in Earth science applications such as geography, geomorphology and topography. Since the first introduction of the concept of GIS in the early 1960s, it has been a subject of constant development and methodological progress. For many years since then, and especially after the rapid computerization and development of personal computers in 1990s, technical evolution in methods and approaches of digital cartography has been a topic of concern in scientific community.

The advantages of various GIS in geomorphological mapping are diverse, since they provide various approaches to accurately model, map, visualize, depict and spatially

quantify the geographic phenomena on the Earth's surface. Various GIS have been utilized for geomorphological mapping, which differ in methodological functionality of geospatial data processing used to visualize spatial datasets.

The organization of the present study is as follows. The first Section (Introduction) includes several sub-sections introducing the study aim, scope and research problem and briefly discussing the need and actuality of scripting methods in modern cartography. The second Section (Study Area) presents a brief overview of the physical geography of Peru. The third Section (Materials and Methods) includes two subsections. The '3.1. Mapping in GMT' which discusses the scripting techniques in GMT and presents the code used for (Figure 1). and also demonstrates the effects of scripting for automatization in cartography. The subsection '3.2.

**Figure 1.** Map of Peru. Dataset: SRTM/GEBCO. Mapping: GMT



Source: Elaborated for author

Plotting in R' presents methods of R programming languages used for cartographic plotting: the packages 'tmap', 'raster', and 'OpenStreetMap' with several examples of

codes accompanied by technical explanations. This section covers the non-trivial application of R programming language for mapping and the significance of scripting automatization and integrating open datasets to topographic mapping which is achieved by the repeatability of codes using syntax of R language.

Section 4 (Results and Discussion) shows and discusses the findings of this study concerning the topographic and geomorphological settings of Peru. The remainder of the section follows both a brief discussion of the datasets availability (ESRI, Bing, Stamen, OpenStreetMap) for a thematic mapping using R libraries, and general discussion of the geomorphology of Peru. Section 5 ‘Conclusions’ finalizes and summarizes the manuscript by giving conclusions, final notes and recommendations for future studies.

### **1.1. Research Focus**

The study is presented at the level of multi-disciplinary applied research combining technical cartographic scripting and geomorphological analysis. In such a way, this paper explores how the concept of scripting cartography can be used to support geomorphological and topographic mapping in a geographical context. A case study of this research is Peru, South America (Figure 1). The theoretical concept and practical development of the cartographic shell scripting places contemporary mapping in the context of high-level automatization of data visualization, which effectively presents the data-driven research. Although the traditional GIS are still widely used in research community (Alcalá-Reygosa et al. 2016; Suetova et al. 2005a, 2005b; Bromley et al. 2011; Klaučo et al. 2013, 2017; Lemenkova et al. 2012; Gohl et al. 2006a), this involves the shift of mapping paradigm to the process of coding in cartographic techniques.

A high-quality machine-based mapping offers large potential benefits not only to cartographers and map-makers, but also to a variety of Earth science disciplines, such as geomorphology, glaciology, geology and landscape studies. In this manner, the use of scripting in cartography recognizes the importance of automatization in data visualization and mapping (Schenke & Lemenkova, 2008; Lemenkova, 2019a, 2019b, 2020g; Lemenkov & Lemenkova, 2021). Another important focus of this study is the use of the open-source data. Hence, in light of the rapidly increasing amount of researchers (students,, employees) working on a distance-based manner (‘from home’ or in ‘online-

mode'), the availability of the open source data and free programs become crucial factors for research process.

## **1.2. Innovation and Originality**

Innovation of the scripting approach in cartography consists in the link between the two disciplines presenting the multi-disciplinary research approach: programming and geography. Thus, applying scripting techniques in cartography enables technically more accurate mapping which in turn provides a better understanding of the morphological structure in the Peruvian Andes. This is critical, given their prominent role in several aspects of the physical geography of the country: hydrology and glaciology (water supply and mountain glaciers), environment (unique ecosystems and mountain habitats for rare species), social and cultural values (development of the tourism in mountain areas), natural hazards (impacts of slope steepness on the landslides occurrence).

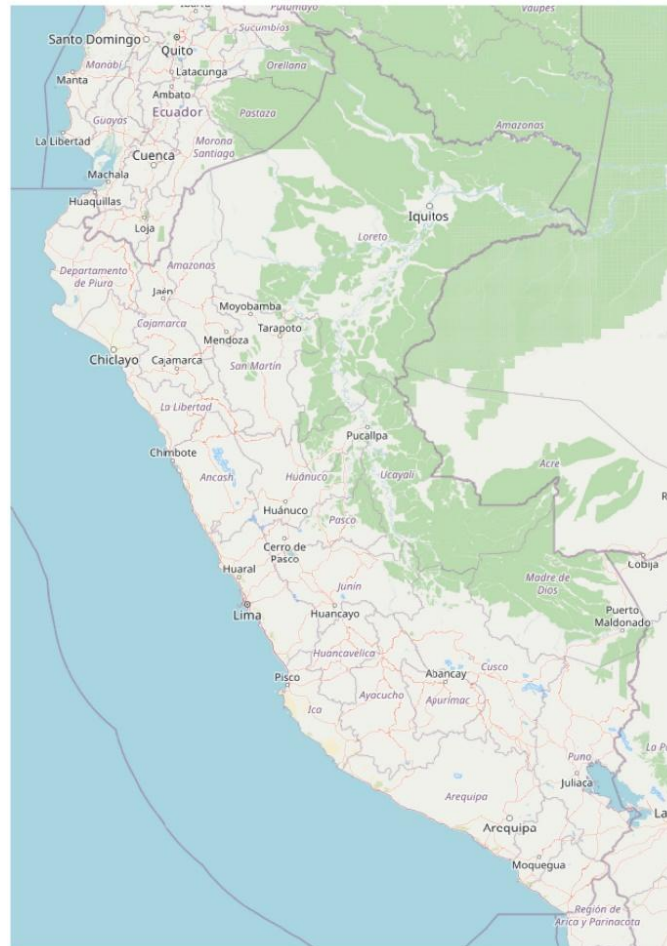
The new paradigm of scripting-based cartographic methods presents a novel approach of geographic knowledge generation which is based on 2 fundamental aspects: 1) open source data; 2) free scripting programs for visualization of these data. The programs can include scripting tools such as Generic Mapping Tools (GMT), programming languages, such as R and Python or scripting-friendly GIS, (e.g. GRASS GIS). (Lemenkova, 2020f). The innovations of this research consist in the comparative mapping of the several datasets using R programming language for the study area of Peru. The wider use of the open source data and presented programming methods will eventually trigger a gradual decline of the commercial expensive GIS software and the onset of the open data research.

## **1.3. Research Goal**

Hence, the goal of this study is to determine how efficient the application of the scripting methods in cartography really are, and to what extent the geomorphology of Peru reflects the geological and geographic setting of Andes. The document also considers various approaches of graphical data processing from the open sources on the visualization and mapping outputs, by comparing several datasets (OpenStreetMap, ESRI Topo, GEBCO, aerial imagery from Bing, National Park Service (NPS), SRTM) using an empirical scripting models of R and GMT that reads the raster formats for mapping. Of these, the

free wiki world map OpenStreetMap (Figure 2) is widely used in the web-mapping and its application for academic studies is also advisable.

**Figure 2.** Map of Peru. Dataset OpenStreetMap. Mapping: R.

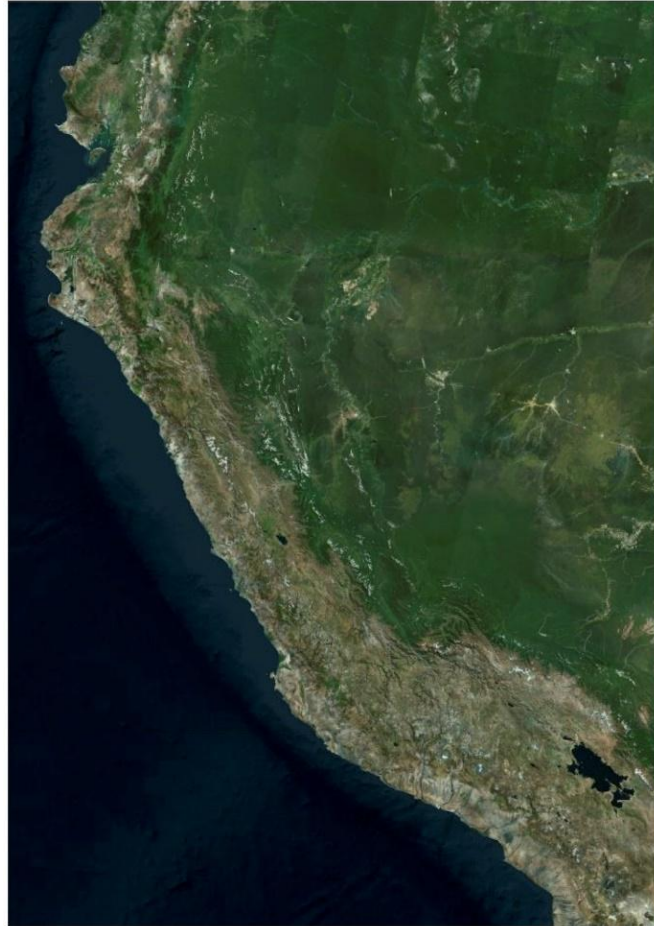


Source: Elaborated for author

In contrast to the traditional GIS software in geographical research, cartographic shell scripting and open geographic datasets are publicly available for students and researchers searching for tools and materials for practical usage. Although applications of programming languages (R or Python), statistical libraries or scripting GIS has been adopted in a variety of research papers (see Lemenkova, 2019c, 2019d, 2019e), there is little publications with special focus on application of specific cartographic packages (libraries) of R ('tmap', 'raster', 'OpenStreetMap') and visualization of the open datasets,

such as Open Street Maps (Figure 2) or aerial imagery (Figure 3) by R language in topographic mapping and geomorphological analysis using RStudio environment.

**Figure 3.** Map of Peru. Dataset: aerial imagery from Bing. Mapping: R.



Source: Elaborated for author

#### **1.4. Research Objectives**

Therefore, the objectives in this paper are twofold:

- i. First to introduce an approach of two specific scripting tools – GMT and R – to cartographic workflow in general and in particular how the selected packages of R ('tmap', 'raster' and 'OpenStreetMap') and a set of GMT modules might assist with the cartographic data plotting.

- ii. Second to explore the topographic settings and geomorphology of Peru (Figure 1), a unique place in Latin America with complex elevation range of geomorphology.

### **1.5. Research Aims**

The aim of this research is to demonstrate that the developing concepts of scripting cartography, such as those by R libraries designed specially for geoinformation mapping, or module of GMT, can assist in classifying the units of the geomorphometric variables (slope, aspect, hillshade, elevation mapping and processing DEM) and, in turn, assist in the discipline of physical geography. Hence, in order to achieve this aim, this manuscript present the following methodological steps:

- a. Review the geographical and geomorphological background of Peru to present the key setting in physical geography of the Peruvian Andes, their structure and special features.
- b. Discuss the interplay between the geomorphology and physical geography of Peru.
- c. Visualize several maps made using scripting techniques to prove that programming algorithms are acceptable for physical geographic studies in data visualization.
- d. Demonstrate scripting snippets to show the technical use of the programming which assists in geomorphological mapping.

### **1.6. Research Questions**

This study raises questions aimed to characterize variations in the geomorphology of Peru and perform mapping using various open source datasets using advanced methods of data analysis (GMT and R). Thus, to systematically visualize several geomorphometric variables and assess their values settings, as well as to visualize different open raster data on the topography of Peru, a combination of the GMT modules and R programming were applied.

Hence, research questions are as follows: 1) How does the slope steepness vary according to the DEM analysis of the geomorphology of Peru according to varying in-situ geological



and geographic setting? 2) What factors affect the geomorphology of the Peruvian Andes and which of them are the most influencing regarding the relief of the country? 3) What libraries and algorithms of the R and GMT scripting toolsets can be suggested for similar geomorphological studies in other regions of Andes? The solutions to these questions are proposed using cartographic modeling for geomorphological data using DEM.

## **2. Study Area**

Quaternary tectonics of Peru as a northern part of the South American continent largely affected its physical geographical setting. Specifically, the morphology of the river slopes and the steepness of the valleys, distribution of the glaciers, and coastlines are all the variables of the regional geomorphology of Peru which is the subject of strong tectonic and seismic processes sculpturing the face of the relief in the Peruvian Andes (Clapperton, 1993).

Physical geographic, geologic and environmental factors in Peru are highly correlated which is discussed in the existing papers (Cobbing, 1982; Weibel et al. 1978). For example, geophysical processes (seismic activity in the tectonically active Andes, repetitive volcanism and earthquakes) together with climate factors (e.g., intense precipitation) and geomorphology (strong to extreme slopes) generate major debris flows and landslides in the mountain rivers draining the Andes. According to Dornbusch (1998), most of the high-mountain area in the southern Peru (> 4000 m altitude) receive precipitation over 600 mm/yr, with many areas receiving even more than 800mm/yr. Together with extreme to steep gradient of the mountain slopes this points the question of the risk of landslides hazards.

The geomorphology of Peru is largely influenced by the extent of Andes that run parallel to the Pacific Ocean and determine the three major physical geographical regions of Peru: i) western coastal zone, a narrow plain, mostly arid excluding the valleys formed by seasonal rivers; ii) the highlands (sierra) which is the major region of the Andes including the Altiplano plateau and the highest peak of the country Huascarán (6,768 m); iii) the eastern region of jungles (selva) covered by the Amazon rainforests where several National Parks are situated (Figure 4). The geomorphology here is presented by flat wide terrain.

**Figure 4.** Map of Peru. Dataset: ESRI Topo. Mapping: R.



Source: Elaborated for author

Climate setting of Peru controls the distribution and the extent of glacial sediments in the cold areas of the Peruvian Andes. Thus, glacial sediments here reach relatively low values (3650 m) in the surroundings of Pampa Galeras. Well developed glacial moraines can be found as close as 60km from the coast at only 4240m (Dornbusch, 2002, 2005). Active geomorphological processes control the distribution of habitats and vegetation in Peru that contribute to the soil properties. This illustrates the importance of considering a variety of processes, landscape elements and factors for physical geographic analysis.

Quaternary geology of Peru is significantly affected by the processes of Andean volcanism that changed both rock and soil properties and the geomorphological shape of the landscapes. The geomorphology of Peru includes a vast variety of complex landforms (plateaus, high mountains, hills, depressions, highs, moraines) with distribution regulated by the situation in the Andes. General geomorphological division of the Peruvian

landscapes includes the Andean high mountainous region, the alluvial basins, the Pacific coastal regions and the shield highlands with dominating plateau. Specific settings on geomorphology and mountain glaciers are further reviewed and described in a variety of papers (Rose, 1996; Ubeda, 2013; Schulz, 1994; Lemenkova, 2019f; Kull & Grosjean, 2000) to mention some of them for further reading.

### **3. Materials and Methods**

#### **3.1. Mapping in GMT**

The proposed methodology of R and GMT based cartographic scripting demonstrated application of machine learning in visualization of geospatial data derived as open datasets. The topographic map (Fig. 1) has been plotted using GMT cartographic scripting toolset (Wessel & Smith, 1995) which is used in some papers focused on geophysical, geological and geomorphological research (Gauger et al. 2007; Lemenkova, 2020a, 2020b).

The plotting was based on using the sequence of codes calling various modules of GMT for mapping cartographic elements. The mapping uses the following sequence of commands:

1. In order to visualize the map extent in the given coordinates the raster file has been clipped. This was done by means of 'grdcut' using the coordinates determined by West-East-South-North convention. Thus, subsetting of the study area was done using the command: `gmt grdcut GEBCO_2019.nc -R278/292/-21/3 -Gperu_relief.nc`
2. The extent of the topographic data of the applied study area and the variations in its topography have to be known. Therefore, the utility of Geospatial Data Abstraction Library (GDAL) has been applied to check up the elevation range for Peru: `gdalinfo peru_relief.nc -stats`
3. A map has to be presented using appropriate color table. Therefore, a more accurate way is to use previously obtained elevation range and apply this actual extent for the raster image for the color palette as follows: `gmt makecpt -Cgeo.cpt -V -T-7668/6151 > myocean.cpt`

4. After the areas was clipped and color defined, the PostScript file has been generated as follows: `ps=Topography_Peru.ps`
5. Visualizing raster image has been done by 'grdimage' module: `gmt grdimage peru_relief.nc -Cmyocean.cpt -R278/292/-21/3 -JM6i -P -I+a15+ne0.75 -Xc -K > $ps`
6. The grid and ticks are then adjusted for the map individually and applied by the 'psbasemap' module as follows: `gmt psbasemap -R -J -Bpx1fla2 -Bpyg1fla2 -Bsxg1 -Bsyg -B+t"Topographic map of Peru" -O -K >> $ps`
7. Adding isolines: `gmt grdcontour peru_relief.nc -R -J -C1000 -W0.1p -O -K >> $ps`
8. Adding scale and directional rose has been carried out automatically: `gmt psbasemap -R -J -Lx12.7c/-2.3c+c50+w300k+l"Mercator projection. Scale: km"+f -UBL/-5p/-65p -O -K >> $ps`
9. From GSHHS (Global Self-consistent, Hierarchical, High-resolution Shoreline database) developed by Wessel and Smith (1996) vector data on coasts, borders, rivers have been derived and added on the map using the following code: `gmt pscoast -R -J -P -Ia/thinner,blue -Na -N1/thickest,red -W0.1p -Df -O -K >> $ps`
10. The use of the 'psscale' was a solution for automatic adding a legend: `gmt psscale -Dg278/-22.1+w15.2c/0.4c+h+o0.0/0i+ml -R -J -Cmyocean.cpt -Baf+l"Color scale 'geo': global bathymetry/topography relief [R=-6857/3206, H=0, C=RGB]" -I0.2 -By+lm -O -K >> $ps`
11. Adding texts (example for the country name, others are added using the same logic): `gmt pstext -R -J -N -O -K -F+jTL+f14p,Helvetica,black+jLB -Gwhite@20 -Wthinnest >> $ps`  
`<< EOF 283 -8.5 P E R U EOF`
12. The process of adding cities is semi-automatic. Thus, adding a point for a capital city (Lima) with coordinates in 360° convention which has following meaning: '283' means

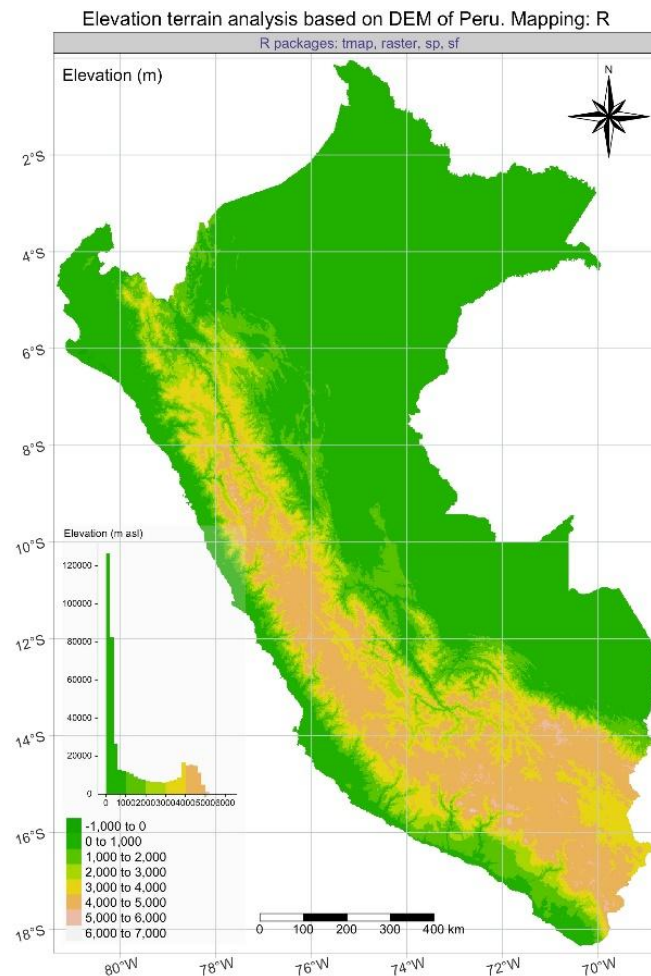
```
77°W, and '-12.0' means 12°S: gmt psxy -R -J -Sc -W0.5p -Gyellow -O -K << EOF >>  
$ps 283 -12.0 0.3c EOF
```

13. Inserting a global map has been done using a combination of modules 'psbasemap', 'pscoast' and 'psxy', as well as countries codes by a convention ISO 3166-1 alpha-2.

The reader can notice from the given above example that each line of the code has been written using a standard GMT syntax and has been added to the once generated PostScript file. The initial command is written using single quotes "> \$ps" followed by the next commands added by double quotes: '>> \$ps' Each line also corresponds to a specific cartographic element on a map (legend, grid ticks, visualization raster image grid, adding texts, etc). Each flag with detailed explanation can be found in the technical reference of GMT either online or in software standard help. The resulting map is presented in Fig. 1.

### **3.2. Plotting in R**

The application of R libraries for cartographic purposes has to be based on programming principles of R syntax. An independent libraries (packages) have to be installed and uploaded as a pre-requisite of the workflow. The mapping has been performed in RStudio environment (RStudio Team, 2017) in R version 4.0.3 (R Core Team, 2020). Mapping in R had two major parts: 1) topographic visualization of Peru using 'OpenStreetMap' package of R (Figure 5 and 2) geomorphological modelling using 'raster' package of R followed by the 'tmap' package for finer cartographic visualization. The depending packages ('sp', 'ncdf4', 'RColorBrewer', 'sf') have been used for geomorphological modelling. Packages 'ggplot2', 'maps' were used during topographic plotting. Specifically, package 'maps' has been used for data capture.

**Figure 5.** Elevation terrain analysis based on DEM of Peru. Mapping: R.

Source: Elaborated for authors

Topographic plotting has been done by the ‘OpenStreetMap’ package of R which accesses high-resolution raster cartographic datasets using the OpenStreetMap protocol. These includes data on road, satellite, and topographic map servers including Apple, ESRI-topo, Bing, and stamen, as visualized in (Figures 2, 3, 4, 9, 10 and 11.) These raster maps were constructed using the direct coordinate input by the provided tile servers via the internet on-the-fly. The maps were hence plotted using either base graphics or ‘OpenStreetMap’ package.

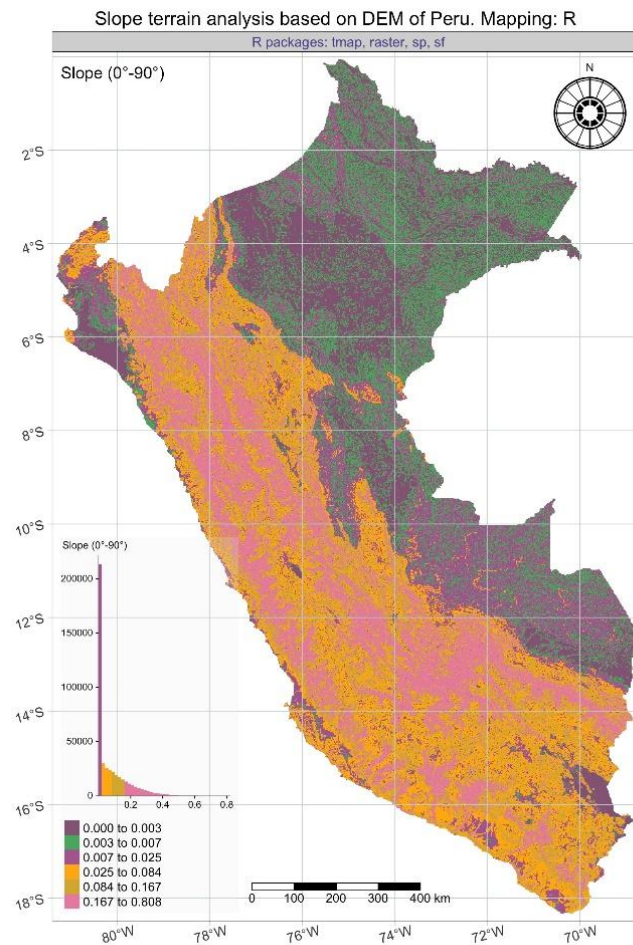
Specifically, the topographic plotting was performed using the following sequence of codes. First, the coordinates for the upper left and lower right corners were read in as follows: `upper_left <- c(3, -82.0)`, `lower_right <- c(-22.0, -68)`. Then the map was

visualized using the 'openmap' function of OpenStreetMap package as follows (here the example for the ESRI topo dataset visualized in (Figure 4): `map_osm <- openmap(upper_left, lower_right, type = c('esri-topo'))`). The plotting has been done using the straightforward function: `plot(map_osm)`. Besides the OpenStreetMap and ESRI topo, other datasets used in this study include the following ones: "stamen-terrain", "esri" and "nps" and visualized in (Figures 9, 10 and 11).

The next stage of the methodology included data processing for geomorphological terrain modelling. The data capture was made by defining input spatial data using 'getData' function of 'raster' package of R: `alt = getData("alt", country = "Peru", path = tempdir())`. Afterwards, the data were pre-processed before they were used as an input materials in RStudio. After the data were loaded, the dimensions of the table was checked up, and the column content.

The visualization of the maps in (Figures 5, 6, 7 and 8) was performed using 'tmap' library of R which defines the shape objects plotted on a map (Tennekes, 2018). Mapping DEM (Figure 5) was done using main function of R 'tmap' package 'tm\_raster' with the following set up parameters: `tm_raster(title = "Elevation (m asl)", palette = terrain.colors(256), legend.show = T, legend.hist = T, legend.hist.z=0)`. The scale bar (Figure 6) was added as an additional cartographic element using 'tm\_scale\_bar' function of 'tmap' by the following code snippet: `tm_scale_bar(width = 0.25, text.size = 0.9, text.color = "black", color.dark = "black", color.light = "white", position=c("left", "bottom"), lwd = 1)`.

**Figure 6:** Slope terrain analysis based on DEM of Peru. Mapping: R



Source: Elaborated for author

Here the flags and their parameters are self-explaining and the reader can understand their meaning easily. The compass has been added for orientation on all the maps using the 'tm\_compass' function by the following code: `tm_compass(type = "8star", position=c("right", "top"), size = 6.0)`. Other options used on the maps include the following ones: "arrow", "4star", "8star", "radar", "rose". The calculation of the slope and aspect maps was done using the following codes: `slope = terrain(alt, opt = "slope")` and `aspect = terrain(alt, opt = "aspect")`, respectively (Figures 6 and 7).

Finally, the cartographic elements should always include the grid which was added on the maps (Figures 5, 6, 7 and 8) by the 'tm\_graticules' option using this code:



`tm_graticules(ticks = TRUE, lines = TRUE, labels.rot = c(15, 15), col = "azure3", lwd = 1, labels.size = 1.0)`. Since the syntax of R demonstrated here is logical, it does not require additional notations.

The rest of the cartographic elements were added using the `tm_layout()` function of 'tmap' where the following elements were defined: the title and the sub-title of the maps, legend, its position and text fonts, panel legends, added histograms of data distribution. Finally, the maps have been plotted and saved using the 'tmap\_save' function of 'tmap' package by the following code snippet: `tmap_save(map4, "Peru_Elevation.jpg", dpi = 300, height = 10)`, where 'height = 10' stands for the physical dimensions of map (a cartographic layout) in inches.

### **3.3. Trends in Data Analysis**

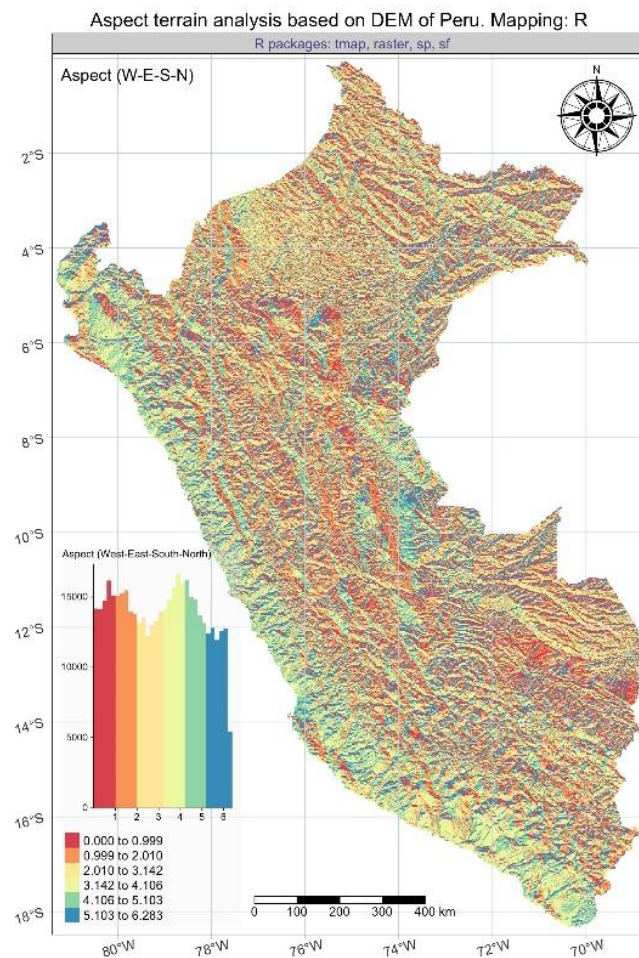
General trends in contemporary data analysis and data science should be briefly mentioned in context with their applications in geographic data modeling. The development of the programming languages gradually evolved from the low level assembly languages where the code is often cryptic and not human-readable to the high-level scripting languages with more straightforward syntax and meaningful semantics (e.g. Python or R). This naturally included rapid development of data analysis, visualization and modeling through the sophisticated approaches and algorithms of graphical manipulation with data. Further advantages of this progress presented the extension of the programming to a wider range of disciplines, including Earth sciences and development of such special scripting toolsets as GMT that combines geographic analysis and scripting philosophy.

Comparing to the standard programming languages, the specifics of the GMT code techniques creates the possibility of data modeling and visualization in Earth science rather than general data analysis. Here syntax enables automated cartographic plotting, mapping and graphical data visualization of the readable formats which depicts geographic objects according to the selected modules (to a certain extent, the equivalent to the libraries of R).

The cartographic attributes can be derived from the raster or vector geodata formats and / or be converted using GDAL which is compatible with GMT. The connection of spatial data with tabular data is another important feature of GMT that enables to read in data

from tables and visualize them as objects using coordinates and attribute values. The specific properties of R libraries enable to perform selected actions using data that facilitates the workflow of the data analysis. Hence, rather than using the GIS, R enables to upload the selected libraries directly for the concrete needs which is a significant advantage of R.

**Figure 7:** Aspect terrain map of Peru. Mapping: R.



Source: Elaborated for author

**Figure 8:** Hillshade map of Peru. Mapping: R.



Source: Elaborated for author

#### 4. Results and Discussion

The R and GMT scripting algorithms were applied to study the variations in geomorphology and physical geographic setting over the region of Peru, assessing values of slope steepness, aspect and altitude and how these variables relate to the topography of the country in its three major physical-geographic zones: i) narrow arid plains of the Pacific coastal zone in the west, ii) highlands (sierra) of the Andes, iii) eastern region of jungles (selva) with the Amazon rainforests. The geomorphological mapping include complex computation of relief indices, for instance, sinuosity, asymmetry, basin elongation, ratio, hypsometry, raw and normalized slope steepness, concavity and others. Within the scope of this study, the most relevant geomorphic features have been included

in this research. These refer to the geomorphometric variables embedded in R 'raster' package algorithm used for computation and mapping of the four parameters: 1) slope steepness, 2) aspect orientation, 3) visualization hillshade, 4) elevation based on the DEM of Peru.

The importance of the geomorphic computations consists in visualization of the terrain (slope, aspect, hillshade and elevation) which can be used as new data and added to the thematic research. In particular, new data and maps on geomorphological setting are applicable in geological and geographic studies. Other fields of application concerns natural risks analysis of hazardous events, such as landslides, computed using major geomorphometric variables: slope stability and instability, steepness and orientation among the other factors. Thorough analysis of the relief features enables to explain the vegetation distribution for landscape habitat analysis, since biogeographic studies need computations of the geomorphological parameters and terrain altitude as a core information on landscapes. The information on slope steepness, orientation, aspect and DEM based terrain is used in hydrological and glaciological study.

Elevation based on DEM varies considerably between various regions of Peru (Figure 5), ranging from plains on the north-east of Peru including a vast area of Amazonian jungles in the Reserve Nacional Pacaya-Samiria, tropical rainforests in Park Nacional Alto Purús, a mix of Andean highlands, cloud forest and lowland jungle in the biosphere Park Nacional del Manú in south-west of Peru to the central highlands of Peru (Huancay, Cusco) and the highest mountain regions in the Peruvian Andes along the coasts of the Pacific Ocean.

Slope terrain analysis (Figure 6) includes the geomorphometric map showing variation of slope steepness ranging from gentle, moderate, strong, very strong, extreme and steep slopes of the country. The ranging of slopes (Figure 6) demonstrates automatic subdivision of the slope types according to the number of pixels in each group: over 200,000 pixels on a raster grid belongs to the 1st category with 0 to 3% (purple color), followed by 35,000 in a group of 2,5 to 8,4% (orange color), followed by a group of 8,4% to 16,7% not exceeding 25,000 (beige color) and a dominating group between 16,7 to 80,8% with not exceeding 20,000 (magenta color). The remaining two groups show clusters of 3,0 to 7,0% (green color) and 0,7 to 2,5% (dark eggplant color), (Figure 6).

The map of the slope aspect (Figure 7) shows the distribution of various aspect of slopes in terms of compass orientation to the West-North-East-South over the country. The distribution of data is shown in the histogram of the map. Accordingly, the map of hillshade (Figure 8) shows a visualization of the relief via the hypothetical illumination of the surface by the determined light source values for each cell in a raster. This has been achieved using the algorithms of R ‘raster’ package data processing.

The terrain map of Peru (Figure 9) was visualized based on the Stamen dataset of OpenStreetMap package. The ‘stamen-terrain’ was selected among the available types ‘toner’, ‘terrain’ and ‘watercolor’. It shows the standard terrain with added labels, lines and a background represented in traditional elevation color palette. The map features hill shading in natural topographic colors (Figure 10), yet lacks some advanced labeling and representing major generalization of the roads and country borders. It well suits as a base for the thematic maps.

**Figure 9:** Map of Peru. Dataset: stamen-terrain from the OpenStreetMap package.

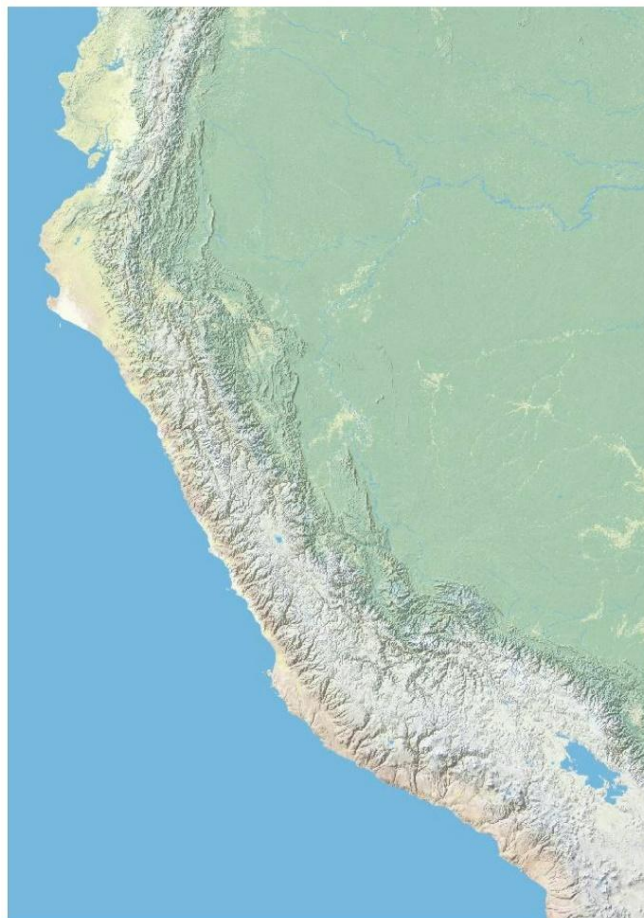
Mapping: R.



Source: Elaborated for author

The ESRI (Environmental Systems Research Institute) dataset visualized from the OpenStreetMap package of R (Figure 11) shows the publicly available ESRI World Imagery. Among the other features, it visualizes major topographic features, national boundaries, text annotations for major cities and hill-shaded topographic relief. The hosted vector feature layers of ESRI as a replica of the OSM dataset which is available in the OpenStreetMaps package or R. The OSM suits various types of features (such as buildings in large-scaled maps, highways) based on the ESRI World Imagery which includes the 15-m resolution TerraColor imagery for mapping at small and mid-scales. The OpenStreetMap (Figure 2) shows the geocoded crowdsourced data, embedded in R, originally sourcing from the collaborative OSM project based on surveys, GPS devices, aerial photographs, built-in map data.

**Figure 10:** Map of Peru. Dataset: nps (National Park Service), OpenStreetMap.  
Mapping: R.



Source: Elaborated for author

The visualized Bing map (Figure 3) is based on the Bing Maps (earlier: Microsoft Virtual Earth), an online cartographic platform, the Bing division of Microsoft. This platform is embedded in R and includes map tiles, map APIs and routing among the most important cartographic features. The Bing aerial imagery is available for purpose of contributing content to OpenStreetMap, that is to use the aerial imagery layer as background for OSM cartographic drawing, thematic mapping aimed for own study and research.

Questions of using machine learning in physical geographic studies are important due to the extended variety of the methodological approaches. Besides GIS, rapid development of the programming languages and data science algorithms brings along new automated methods in cartography. Speedy and more accurate machine plotting places cartography at the principally new level in technical sense. This includes the two major branches of geographic data analysis: cartographic visualization of maps (both raster and vector data) and modeling data according to attribute values using methods of statistical analysis.

In recent years, methods of cartographic data handling have reached a high level due to many innovations in field of machine learning and data science. These included the developed algorithms of data processing, elaborated GIS plugins and special packages of scripting languages, web tools of internet cartography and combined data analysis (e.g. integrating image processing with traditional maps).



**Figure 11:** Map of Peru. Dataset: ESRI from the OpenStreetMap package.



Source: Elaborated for author

The era of expanding computerization of Earth sciences has been extended significantly over the recent two decades in large part by the progress in programming algorithms of data analysis and modeling. Machine learning approaches made significant contributions as a branch of mathematical advances in the development of artificial intelligence and algorithms of data analysis. Selected parts of these efforts have involved the studies in Earth sciences, where the phenomena and processes are studied from analysis of the maps and models used for visualization. In view of this, new methods in cartography became of crucial importance.

Scripting as a paradigm of contemporary cartography involves the machine learning methods that can also be more sophisticated for the advanced cartographic tasks. Scripting is particularly suitable for the needs of topographic and geomorphological mapping closing the gap between the applied programming languages in data analysis and geographic studies. Its relatively flexible approach in data handling and abundant set of



algorithms results in a wide variety of modules and packages adjusted and tuned for different cartographic tasks.

## **5. Conclusion**

Cartographic methodology for automatic geomorphological and topographic mapping of Peru by open source datasets using scripting algorithms of GMR and R has been successfully tested and presented in this study. The actuality of this study is explained by unique local geomorphic and environmental settings of Peru, which is a part of the South American Andes.

The selected studied area is located in the tectonically active Andes. Natural hazards such as seismic activity and intense precipitation generate major debris flows and landslides in the steep slopes. The geomorphology of the landforms is formed as a result of complex interaction of the geologic, glacial, geophysical, geodynamic and tectonic settings, climate and sedimentation factors as discussed in various papers (Hall, 2009; Lemenkova, 2020c, 2020d, 2020e; Kelly et al. 2012; Gohl et al. 2006b; Kuhn et al. 2006; Alcalá et al. 2015).

Therefore, visualization of the geomorphologic maps, such as slope, aspect and relief is actual for the thematic geomorphological and topographic mapping of Peru. At the same time, mapping techniques are increasing and require higher degree of automatization along with the progress in scripting and integration of the programming language libraries in mapping. However, comparing to GIS, less examples has been given so far in demonstrating in detail and application of programming languages in cartography with respect to the physical geographic studies, except in GMT-based research papers.

The results obtained in this study for thematic mapping of Peru shown both imagery and raster maps processed by scripting cartographic techniques. The demonstrated approaches are promising due to the cartographic quality and speed of data processing received through the automated scripting. With regard to the general trends in the development of contemporary cartography in Earth sciences, it is possible that the tendency of applied programming and scripting in geographic studies as also demonstrated in this research will continue to contribute to similar multi-disciplinary studies.

The paradigm of the open source data application in cartographic studies is explained by the recently shifted nature of research. Indeed, many researchers nowadays moved to the

home- or distance-based work. As a consequence, the demand for the open source geographic data and free tools for the processing of these data is considerably increased. This paper demonstrated the use and applicability of such datasets and instruments that can be applied for solving these needs, which can be used in similar research. Among others, several packages of R and available free datasets are reviewed and demonstrated. The examples of GMT and R code scripting are presented for repeatability in similar works. Specifically, the demonstrated advantage of the open source geospatial data consists in availability for mapping which facilitates distance-based education and research.

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