Revista GEOGRÁFICA VENEZOLANA
Volumen 63(2)2022 julio-diciembre
ISSNe 2244-8853 ISSNp 1012-1617
RECIBIDO: septiembre, 2021. ACEPTADO: febrero, 2022
pp. 110-127
https://doi.org/10.53766/RGV/2022.63.02.05

Analysis of the precision of different digital models of global and local elevations in continental Ecuador

Análisis de la precisión de distintos modelos digitales de elevaciones globales y locales en el ecuador continental

Iván Fernando Palacios Orejuela

Theofilos Toulkeridis

Universidad de las Fuerzas Armadas ESPE
Sangolquí, Ecuador
ivan199632@hotmail.com; ifpalacios@espe.edu.ec; ttoulkeridis@espe.edu.ec
Palacios: https://orcid.org/0000-0003-3209-9810
Toulkeridis: https://orcid.org/0000-0003-1903-7914

Abstract

Currently, DEMs are inputs in multiple geoscience applications. Ecuador presents three regions with topographic characteristics that influence the performance of the DEM on altimetric precision. The main objective has been to analyze the precision of five global models and the official local model of the country, using GPS points to determine the level of adjustment of the DEM in the regions of Ecuador. The cities of Macas (Amazonian basin), Quito (Highlands) and Guayaquil (Coastal lowlands) were considered as study areas for each region. Statistics and spatial correlation / dispersion graphs were obtained with the R software, also with QGIS longitudinal profiles of the models were performed. According to the statistics calculated, the local SIGTIERRAS model presents more auspicious results in the Highlands and Coast of the country, with an RMSE of 2,498, 1,556 meters, while in the Amazon the ALOS model is slightly better than the local DEM, with 5,792 meters of RMSE.

KEYWORDS: GPS points/leveling; altimetric precision; R software; DEM; ALOS; SIGTIERRAS.

Resumen

Actualmente, los DEM son insumos en múltiples aplicaciones de las geociencias. Ecuador presenta tres regiones con características topográficas que influyen el desempeño de los DEM sobre la precisión altimétrica. El objetivo fue analizar la precisión de cinco modelos globales y el modelo local oficial del país, usando puntos GPS para determinar el nivel de ajuste de los DEM en las regiones del Ecuador. Las ciudades de Macas (Amazonía), Quito (Sierra) y Guayaquil (Costa) se consideraron como zonas de estudio de cada región. Estadísticos y gráficos de dispersión/correlación espacial se obtuvieron con el software R; además con QGIS se realizaron perfiles longitudinales de los modelos. Según los estadísticos calculados, el modelo local SIGTIERRAS presenta resultados más auspiciosos en la Sierra y Costa del país, con un RMSE de 2.498, 1.556 metros, mientras que en la Amazonía el modelo ALOS es ligeramente mejor que el DEM local, con 5.792 metros de RMSE.

PALABRAS CLAVES: puntos GPS/nivelación; precisión altimétrica; software R; DEM; ALOS; SIGTIERRAS.

1. Introduction

Currently, a widely used way to represent variables in geographic space is through a raster, in which each pixel contains the value of the parameter under analysis (Goodchild, 1992; DeMers, 2001; Jasiewicz *et al.*, 2018). The relief of the terrain is a variable of great importance for studies of civil, environmental, hydraulic works, and geosciences in general (Massonnet & Elachi, 2006; Sharma *et al.*, 2009; Wacha *et al.*, 2018). Height values are usually presented as digital elevation models (DEM) referred to a reference surface or vertical datum, which are obtained from different techniques such as radar interferometry, photogrammetry, LIDAR, or remote sensing satellite data (Li *et al.*, 2018; Abdulhassan *et al.*, 2021).

Nowadays it is also possible to generate DEM through drones (Santise *et al.*, 2014; Pardo *et al.*, 2017; Viera-Torres *et al.*, 2020). However, the economic benefit / time is not feasible for large areas of land, so global models are used that have been made and made available by different space agencies, such as the United States Geological Survey (USGS), Japan Aerospace Exploration Agency (JAXA), National Aeronautics and Space Administration (NASA) besides others (Oyoshi *et al.*, 2019; Azizian & Brocca, 2020). Among the most popular digital elevation models are the Shuttle Radar Topography Mission (SRTM), Global 30-Arc-Second DEM (GTOPO30), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Advanced Land Observation Satellite – Phased Array type L-band Synthetic Aperture Radar (ALOS PALSAR), Global Multi-Resolution Topography (GMRT), Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010), to name a few (Mukul *et al.*, 2017; Pakoksung & Takagi, 2021; Abrams *et al.*, 2020; Bouvet *et al.*, 2018; Gupta *et al.*, 2017). In addition, there are government institutions, such as the National Information System on Rural Lands and Technological Infrastructure (or simply SIGTIERRAS) in the case of Ecuador, which was the institution in charge of preparing the DEM at the local level for the entire country (Muhlenkort, 2011; Corral & Olea, 2020).

Each digital elevation model has specific characteristics; therefore, it is fundamental to consider the type of study to be performed or its scale in order to select one of them. The latter is directly related to the determination of the errors or precisions of the DEM and their influence on the quality of the derived products (Felicísimo, 1994). Among the main factors that reduce the quality of a model are raster spatial resolution (Hengl, 2007), technique used for interpolation (Pérez & François, 2009), terrain topography (Su & Bork, 2006), vertical and horizontal spacing (Fisher & Tate, 2006) among others, which are responsible for systematic and gross errors, and therefore, in the relative precision of them.

The evaluation of the vertical precision of DEM has been studied globally from various points of view, with applications in hydrological models (Munoth & Goyal, 2019; Wu *et al.*, 2008), archaeological works (Palacios & Leiva, 2018; 2019), natural hazards (Jaboyedoff *et al.*, 2012; Palacios & Toulkeridis, 2020), coastal altimetry (Du *et al.*, 2016; Wang *et al.*, 2018), to name a few. However, at the country level there is very little research that analyzes the degree of precision of digital models for engineering applications (Mancero *et al.*, 2015), and even more so if the topographic variability of continental Ecuador is considered, including the Coastal lowlands, Highlands and Amazonian basin, with mountainous areas, coastal and jungle plains.

Therefore, the predominant objective of the current study has been to analyze the precision of the most used digital models of global elevations such as SRTM, ASTER, ALOS PALSAR, GMRT, GMTED2010, and the national model of SIGTIERRAS, in cities of each region of continental Ecuador, by comparing with scattered vertical control points and the calculation of descriptive statistics, in order to demonstrate which of the models best fits the topography of the most diverse regions of continental Ecuador with the Coastal lowlands, Highlands and Amazonian basin.

2. Materials and methods

2.1 DEM Features

The SRTM model belonging to NASA is obtained by radar interferometry (Michalak, 2004; Yang *et al.*, 2011; Alganci *et al.*, 2018). As of September 23, 2014, data at 1 arc-sec (≈30 meters) were released globally, which is a considerable improvement since previously this resolution existed only for the United States and 3 arc-sec (≈ 90 meters) in the rest of the world (Rabus *et al.*, 2003). Version 3 of the SRTM is used in the current study, the same that fills in empty spaces with the DEM of the ASTER GDEM2, and presents an absolute error of geolocation of 9 meters, and an absolute error in height of 6.2 meters in South America (Rodríguez *et al.*, 2019). Its vertical and horizontal datum is EGM96 and WGS84, respectively.

For its part, the GMRT is a global multiple resolution model developed by the Marine Geoscience Data System in collaboration with the United States Academic Research Fleet (GMRT, 2020). This DEM also provides high resolution bathymetric data (≈100 meters), while its resolution for the earth's surface is similar to that of the SRTM, with 30 pixel meters (Ryan *et al.*, 2009). Like the SRTM, it uses the same datums, both vertical and horizontal.

The ASTER digital elevation model was generated by two institutions that are NASA of the United States and the Ministry of Economy, Trade, and Industry (METI) of Japan. In August 2019 they launched the new version of the DEM known as GDEM version 3, which also has a dataset for the study of bodies of water (ASTWBD), whose products are referred to the WGS84 datum (Abrams *et al.*, 2020). The first version of the ASTER model was made using satellite stereoscopy of images collected by the ASTER sensor on board the Terra satellite, now the GDEM v3, as used in the present study, which incorporates more stereo pairs to reduce gaps and improve its coverage, keeping the resolution at 30 meters (NASA, 2019).

As for the ALOS PALSAR model, it has been developed by JAXA since 2008. In October 2014, products with radiometric terrain correction (RTC) were created within the Alaska Satellite Facility (ASF) project using information from the synthetic aperture radar (SAR), being geometrically and radiometrically corrected on thin beam and polarimetric scenes, with models of 12.5 and 30 meters of resolution and almost global coverage (ASF, 2021). However, unlike the rest of DEM, the ALOS model is referred to the WGS84 ellipsoid. In this case, the raster with the best spatial resolution was used.

Another global elevation model is proposed by the USGS and the National Geospatial Intelligence Agency (NGA) of the same country, which developed the GMTED2010 model, and which replaces the GTOPO30 with better data on a world scale (Poppenga and Worstell, 2016). This DEM provides rasters of 30, 15 and 7.5 arc-sec, with precisions expressed in mean square error values, between 25 - 42 m, 29 - 32 m, and 26 - 30 m, respectively (USGS, 2018), which uses the EGM96 model as a reference for its heights. This study worked with the highest resolution.

The DEM SIGTIERRAS is a raster model developed within the program that bears the same name and which was coordinated by two State portfolios of Ecuador, being the Ministry of Agriculture and Livestock (MAG) and the Ecuadorian Space Institute (IEE) in 2012. It presents a variable spatial resolution of 3, 4 and 5 meters for the Highlands, Coastal lowlands and Amazonian region respectively. Its horizontal datum is SIRGAS 95 and the vertical one EGM96. It was constructed by combining LIDAR data and photogrammetric techniques, with altimetric precision between 1.5 to 3 meters, depending on the region (SIGTIERRAS, 2016).

2.2 Study area

The cities of Quito, Guayaquil and Macas were chosen as case studies for the analysis of the precision of the different digital elevation models. These three cities represent the three different and mentioned natural regions of continental Ecuador, being the Coastal lowlands (Guayaquil), Highlands (Quito) and Amazon (Macas). The idea of selecting areas of each region is aimed at verifying the behavior of the DEM in different terrain conditions, both in coastal plains with gentle slopes of the Coast, the central mountain range with mountains and steep slopes of the Highlands, and foothills mixed with alluvial plains of the Amazon basin (FIGURE 1A).

Macas is a city, which belongs to the Morona Santiago province, and is located on the eastern bank of the Upano River, ≈40 km from the Sangay volcano, towards the south of the Amazon region. The city has 28035 inhabitants according to the projection to 2021, and it is located spatially at 2° 17'54.94" of South Latitude and 78 ° 09'59.03" of West Longitude, with an average height of 1010 masl (FIGURE 1B).

The city of Guayaquil is located on an alluvial plain within the mouth of the Guayas River, within the province of Guayas. It is the second most populous city in the country with about two and a half million inhabitants. It is located at 2°10'05" South Latitude and 79 ° 54'14" West Longitude and with an average of 27 masl, located in the central-south part of the Coast region (FIGURE 1C).

Finally, the city of Quito is the capital of Ecuador, it is located in the province of Pichincha to the north of the Sierra region. Its city sits on the western flanks of the Pichincha stratovolcano along the Guayllabamba basin, very close to the equator. Geographically it is located at 0°11'29" South Latitude and 78°29'45" West Longitude, and at 2.850 meters above sea level. It is one of the most populated cities in the country with approximately three million inhabitants throughout its metropolitan area (FIGURE 1D).

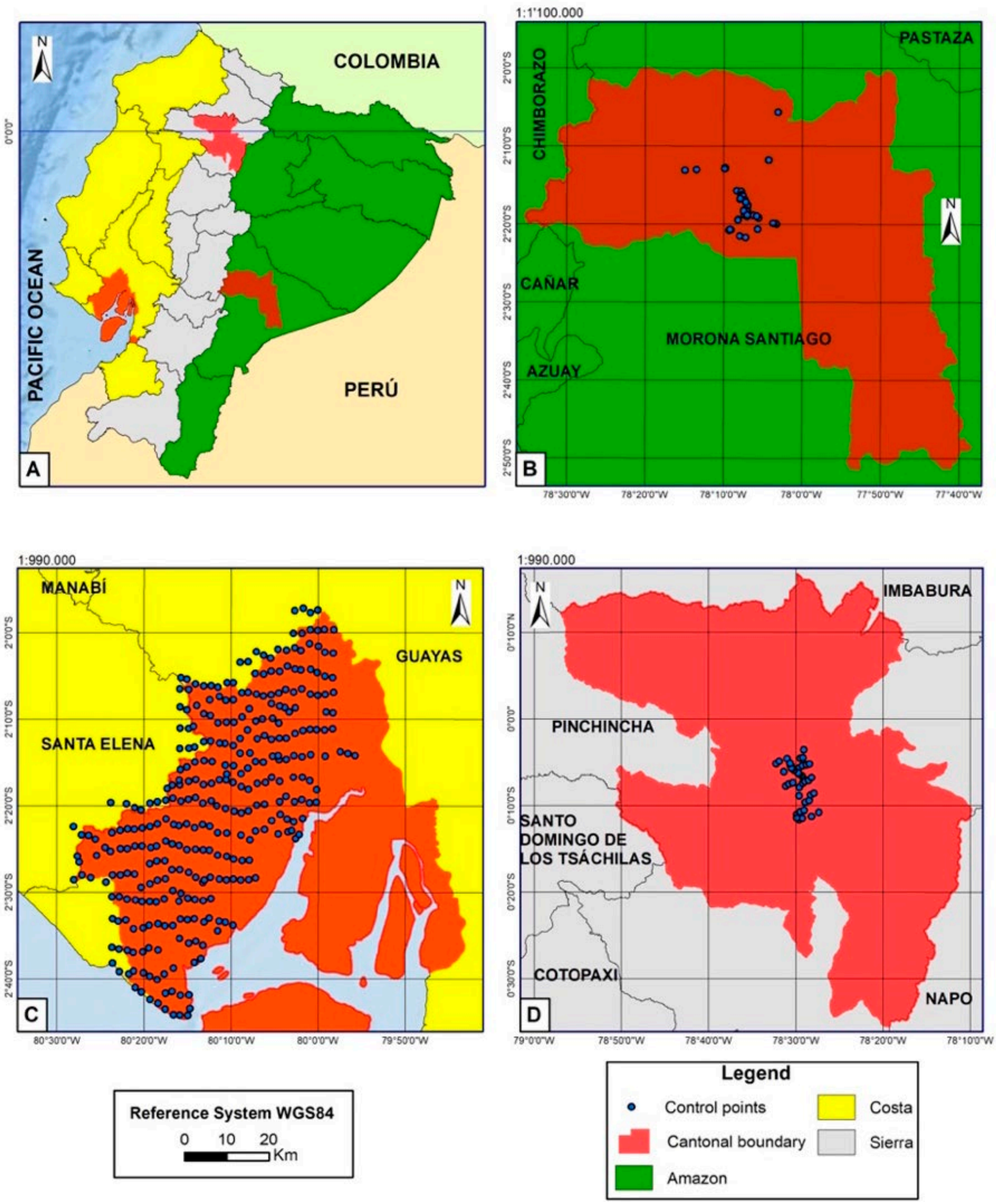
2.3 Obtaining control points

In order to control the altimetric precision of the different DEMs, data belonging to GPS control points were used with their respective height value referred to the official vertical datum of Ecuador (La Libertad tide gauge - Santa Elena province), (Palacios, 2019). In the case of Guayaquil, the data were collected by the Military Geographical Institute of Ecuador (IGM) as inputs for photogrammetric work, using double frequency GNSS antennas with the differential static method and linked to the GNSS Continuous Monitoring Network of Ecuador (REGME). The height value was obtained through second-order geometric leveling campaigns, with a total of 290 points that served to compare its value with the elevation models analyzed.

The control points for Quito also respond to data collected by the IGM for photogrammetric purposes and which are distributed throughout the metropolitan urban area of the city. The values in the horizontal component were obtained with a double frequency GNSS antenna and linked to the REGME, while the height value was obtained through second and third order geometric leveling campaigns, with a total of 48 vertices.

Finally, the control points for Macas derived from the 20 vertices of the geodesic network of Morona canton, which were surveyed with dual frequency GNSS antennas through differential static positioning and linked to the REGME, while the height value was obtained with leveling geometric of the first order. In addition to these data, 28 more points were used which are densifications of

FIGURE 1. A: Location map of Ecuador and position of the three different study areas. B: Distribution of studied points in Macas (Province of Morona-Santiago), within the Amazonian region. C: Distribution of studied points in Guayaquil (Province of Guayas), within the Coastal lowlands. D: Distribution of studied points in Quito (Province of Pichincha), within the Highlands



the geodetic network, whose value in the vertical component was calculated by GPS leveling, with the following equation (Banerjee *et al.*, 1999):

$$\Delta N = (h_2 - h_1) - (H_2 - H_1)$$

Where ΔN is the geoid undulation or separation between the geoid and ellipsoid at the unknown point; h_2 and h_1 are the ellipsoidal heights of the unknown and known point respectively, H_2 and H_1 represent the orthometric heights of the unknown and known point respectively. In this case, since the objective is to obtain H_2, the previous equation may be expressed as follows:

$$H_2 = H_1 + (h_2 - h_1) - (n_2 - n_1)$$

Where n_2 and n_1 are the geoidal undulation values for the unknown and known points respectively. From the EGM08 gravimetric model, the undulation values were taken for both points, thus eliminating the systematic errors of the GPS leveling method (Fotopoulos *et al.*, 2003), and the height value for each vertex was obtained.

2.4 Calculation of height differences and statistics

The height values were extracted from each DEM using the Point Sampling Tool plugin of the free software QGIS, based on the shapefile of the control vertices for each city. In addition, a graph of the longitudinal profiles of each digital model was made in order to observe their behavior in the different topographic conditions of the regions of Ecuador, through the QGIS Terrain Profile plugin. The statistics to evaluate the precision of the DEM analyzed in the present study were the mean error (ME), mean square error (RMSE) and the standard deviation (σ). Pearson's coefficient and scatter plots and spatial correlation were also calculated in order to observe the underlying spatial dependence between the elevation values of each DEM and the heights leveled with the control points. All these calculations were conducted with the free software R.

3. Results and discussion

Based on the aforementioned methods used in the current study, the resulting values of the statistics calculated in order to analyze the quality of the DEM in each of the cities were summarized in TABLE 1. Among the three statistics used to evaluate the altimetric quality of the different DEMs, it is necessary to differentiate them and know their limitations. The EM is an indicator to determine the presence of bias or bias in the model (the higher the value, the greater the bias), but it is not an adequate criterion to validate the precision of a model. On the other hand, the standard deviation is contextualized as the dispersion of the data with respect to an exact value. This statistic is better interpreted to determine a value interval at a certain percentage of confidence (Palacios, 2020). The RMSE is presented with a more robust indicator in order to evaluate precision, whose value should be as low as possible, since it minimizes the underlying errors of the analyzed data set (Palacios, 2019). Therefore, in this work the result of the RMSE was considered as an indicator to determine the most accurate digital model in the regions of Ecuador. Additionally, Shapiro-Wilk and Kolmogorov-Smirnov normality tests of height values were performed, whose results were all less than p value 0.05, so they are normal (Palacios *et al.*, 2021). This agrees with the scatter plot and frequency histogram (FIGURE 4). In addition, in the R software, the residuals of the heights were analyzed, which follow a normal distribution, so it complies with the statistical assumption for the calculation of the RMSE (Carrera *et al.*, 2021).

According to the results listed in table 1, in the three study areas that represent the regions of continental Ecuador, the GMRT2010 model presented the highest RMSE in all cases, therefore, it is the DEM that least adjusts to the values real height. In the city of Quito, the SIGTIERRAS digital model obtained the lowest RMSE with 2.498 m, as

TABLE 1. Statistics calculated to analyze the precision of the DEM

Quito			
DEM	**EM (m)**	**RMSE (m)**	**σ (m)**
ALOS PALSAR	0.210	3.725	3.758
SRTM	1.421	3.604	3.347
ASTER	-2.204	6.228	5.887
GMRT2010	0.077	21.336	21.561
GMTED	3.026	10.949	10.634
SIGTIERRAS	-0.891	2.498	2.359
Guayaquil			
DEM	**EM (m)**	**RMSE (m)**	**σ (m)**
ALOS PALSAR	2.145	4.117	3.521
SRTM	1.905	4.314	3.877
ASTER	-8.088	12.309	9.294
GMRT2010	-6.440	13.723	12.139
GMTED	2.146	8.246	7.976
SIGTIERRAS	-0.642	1.556	1.420
Macas			
DEM	**EM (m)**	**RMSE (m)**	**σ (m)**
ALOS PALSAR	3.599	5.792	4.586
SRTM	0.919	6.249	6.247
ASTER	-4.206	11.123	10.407
GMRT2010	-9.337	15.200	12.121
GMTED	-0.372	12.468	12.594
SIGTIERRAS	-4.568	7.428	5.919

well as its standard deviation with 2.359 m, which translates into a confidence interval of ± 4.623 m at 95% confidence. The DEM SRTM and ALOS PALSAR reached an RMSE of 3.604 and 3.725 m, respectively. Therefore, they can also be considered as elevation models with auspicious performance in topographic conditions of the Sierra region, after the SIGTIERRAS model.

Regarding the city of Guayaquil, the results are similar to those found in the northern region of Ecuador, with the SIGTIERRAS model as the DEM that reached the lowest values in the three statistics analyzed (mean error -0.642 m; RMSE 1.556 m; deviation standard 1.420 m), compared to the rest of the digital models studied. The confidence interval calculated with the SIGTIERRAS values is ± 2.783 m at 95% confidence, that is, half of that determined in Quito. Also, the ALOS PALSAR and SRTM models are again presented as DEM with good performances, where the ALOS is being slightly better than the SRTM in this case, according to the RMSE values, with promising values for use in almost flat reliefs of the Coastal region.

In the city of Macas, unlike the two previous cases, the DEM that achieved the best performance was the ALOS PALSAR model with an RMSE of 5.792 meters, which corresponds to an interval of ± 8.988 m at 95% confidence, being the highest for the three cases analyzed. The SRTM model is presented as the second DEM with the lowest RMSE (6.249 meters), followed by the SIGTIERRAS DEM with an RMSE of 7.428 meters. The results achieved with the ALOS PALSAR model may be related to the way of obtaining this DEM, since the SAR information by its wavelength can penetrate the forest cover and collect the real surface of the land, which is necessary for extensive forest areas in the Amazon region.

As mentioned above, most digital elevation models are referred to a vertical datum (EGM96), so their height values can be used directly. However, the DEM ALOS PALSAR is referred to the WGS84 ellipsoid, so before using such information, it is necessary to convert to heights above sea level. In order to conduct this, the conventional formula of geoidal undulation is used, which allows the heights of the ellipsoid to be passed to the geoid (considered in practical terms close to mean sea level):

$$N = H - h$$

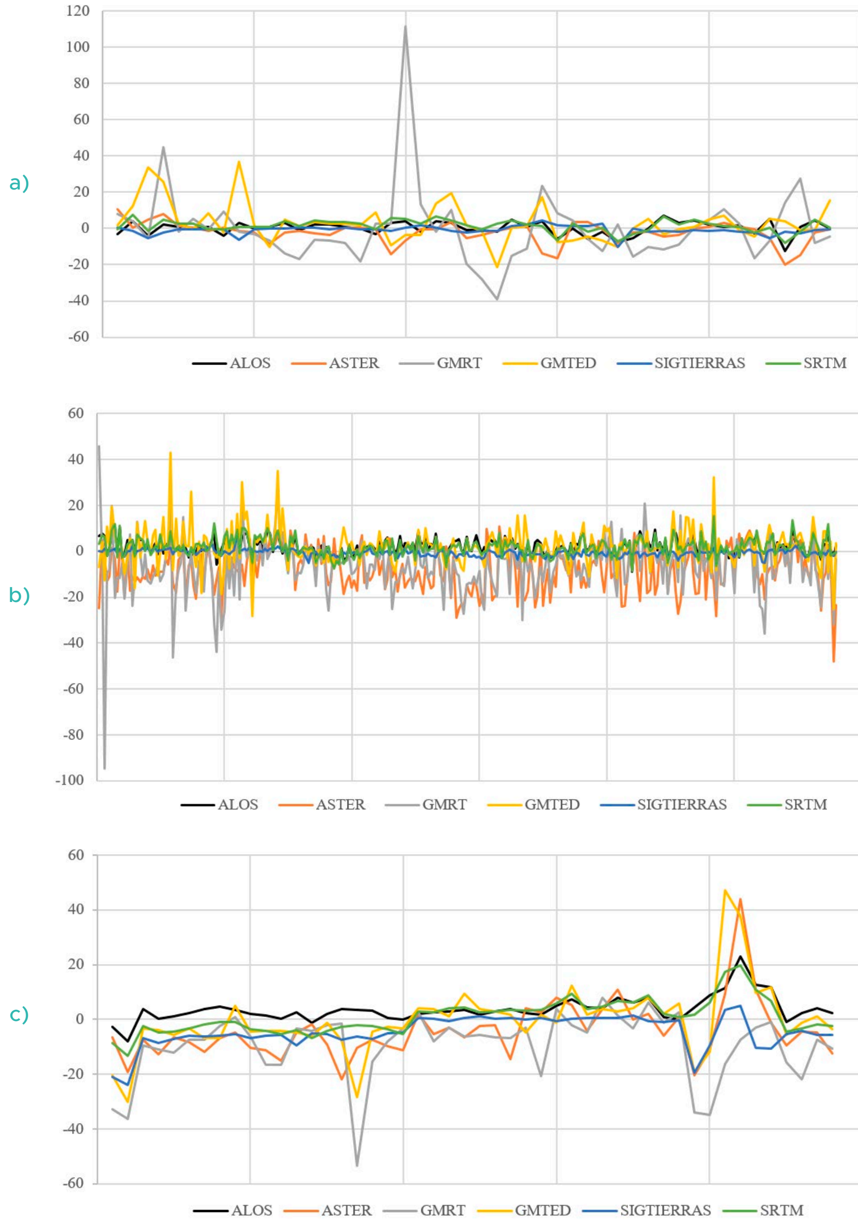
Where N is the geoidal undulation, H is the orthometric height ≈ mean sea level, and h is the ellipsoidal height. From the ALOS model itself, the ellipsoidal height values are extracted, while the geoidal undulation values were extracted from the EGM08 geopotential model. This digital model works on a mathematical surface (ellipsoid) to apply radiometric terrain correction to PALSAR data. By means of a graph of the height errors found, the behavior of the digital models can be better observed by analyzing them, as demonstrated in FIGURE 2.

In all cases, it is denoted that the DEM GMRT2010 and GMTED present the largest errors, in accordance with the statistical results listed in table 1, which may be due to several factors such as spatial resolution, probably mainly in the case of GMTED (Saksena & Merwade, 2015; Shi *et al.*, 2014), which is the largest of all the digital models analyzed, while in GMRT2010 it can be attributed to the control points used for its processing, the same ones that are found to a lesser extent in South America, compared to North America and Europe (Ryan *et al.*, 2009). On the other hand, it is observed that the error graphs of the three models that obtained the best performances (SIGTIERRAS, SRTM and ALOS PALSAR). Their behavior is similar in all the cases analyzed, as illustrated in the longitudinal profiles of each DEM for the study regions (FIGURE 3).

When making longitudinal transects on the relief of the study areas in each region of Ecuador, it is observed that the behavior of the DEM in the Highlands, present divergence in the peaks or mountainous areas, with peaks and separations between them, which is consistent with several studies that have found similar conditions (Mancero *et al.*, 2015; Yao *et al.*, 2020). Regarding the performance of digital elevation models in the Coastal region, it is encountered that in flat areas, elevation models perform best (Zhao *et al.*, 2011), being the DEM SRTM, ALOS PALSAR and SIGTIERRAS those that are juxtaposed almost in their entirety, agreeing with the calculated statistics and, therefore, better represent the reality of the terrain.

The longitudinal profile performed in the Amazonian city of Macas, demonstrates the variability of the terrain in this region of the country, in which part of steep areas, river plains and dense forest cover are combined. In this case, it can be observed again that in mountain or foothill areas, the behavior of the DEM is uneven, with protruding peaks, as well as in the flatter areas they converge again with more notoriety. Due to the spatial heterogeneity that the relief of Ecuador presents, it is important to know the performance of each model to opt for the DEM that allows achieving a better performance for the required work. Mainly in steep areas or mountain tops that could lead to some underlying error for the determination of characteristics of the model and the products

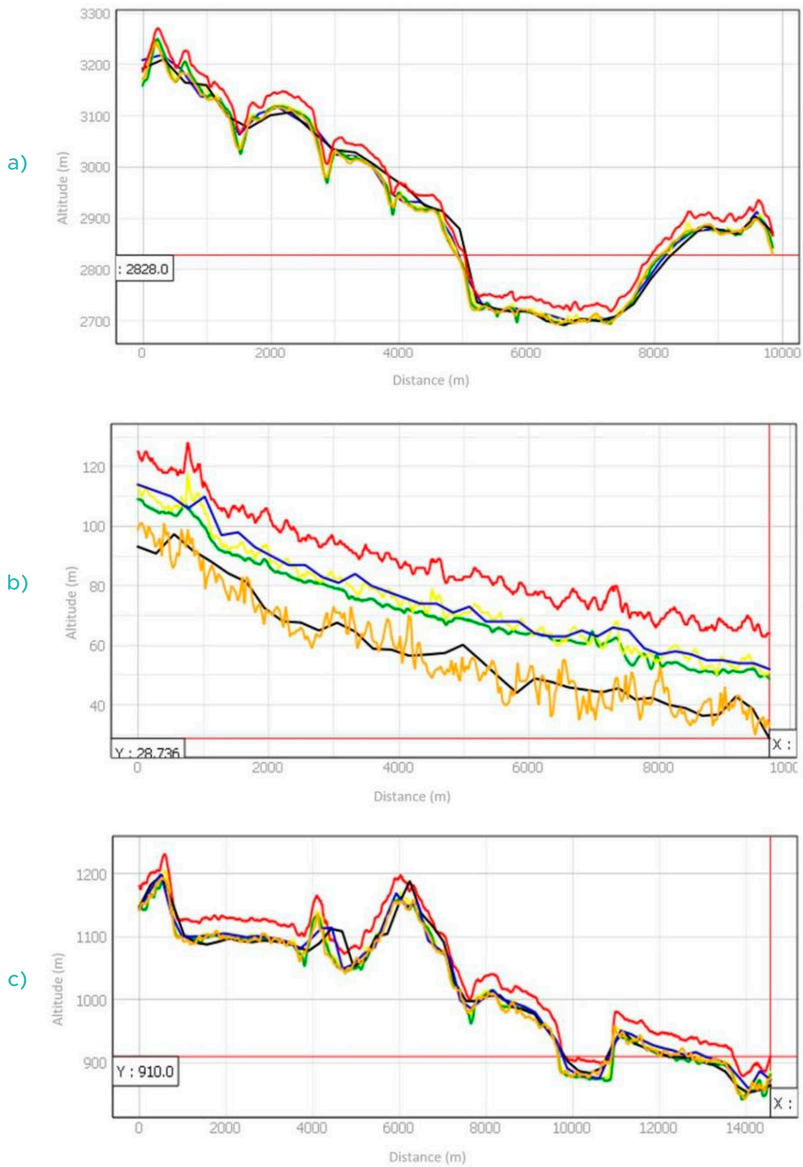
FIGURE 2. Graph of errors in height of each DEM analyzed in the cities of: **a)** Quito; **b)** Guayaquil; **c)** Macas



derived from it, or alternatively in areas with dense vegetation cover as an additional variable to the relief of the land where, according to the method of obtaining the DEM, it will better represent the reality of the territory.

Although it is true the surface of the regions of Ecuador is much more extensive than the analyzed territory in the three cities mentioned, however, the topographic conditions of each region do not differ in themselves throughout its extension, so

FIGURE 3. Longitudinal profile generated with the DEMs analyzed, in the three case studies: **a)** Quito, **b)** Guayaquil, **c)** Macas. The color palette represents a digital model, as follows: red - ALOS, yellow - SRTM, green - SIGTIERRAS, black - GMRT2010, blue - GMTED, orange - ASTER



the results obtained on the study areas may be extrapolated to the rest of the areas of continental Ecuador, respectively. It should be noted that it is not a unique condition, since the values of the statistics will depend, among other factors, on the number of control points used, the method of obtaining the value of the height of the vertices, and therefore the precision of them.

By having GPS control points, there is a more precise value for the comparison and validation of the different DEMs. The scattered and random distribution avoids a possible bias in the calculation of the error statistics. In the current study, GPS points combined with first order geometric leveling (in Macas), as well as second and third order (in Quito and Guayaquil) were used, that is, the precision of the sampled points guarantees greater accuracy in the selection of one or other DEM.

In addition, a dispersion and correlation graph was performed using Pearson in which two determinations are mainly evidenced. The first is that regardless of the spatial resolution of the raster model, the height values present a normal distribution. In the second, all the Pearson coefficient values are above 0.96 in relation to the scattered data of height of the control points used, and that could have caused the sample correlation (Cumming, 2014; FIGURE 4).

One of the most used applications with DEMs is the extraction of natural drains. Although the resolution of the elevation model in principle provides a greater detail of the terrain, its resolution does not unequivocally guarantee that the data is free of noise and errors that were generated by the technique of obtaining the raster, which could affect the correct extraction of geomorphological and hydrological characteristics (Niipele & Chen, 2019). In this sense, to contrast the results found, drainage extraction was conducted with the three DEM that presented the most auspicious results of RMSE, being ALOS, SIGTIERRAS and SRTM, in order to compare the drainage network generated with each of these elevation models as seen in FIGURE 5.

The results found in the extraction of drains with the three digital elevation models, reflects the benefits and limitations that these present for the real representation of the territory. As observed in FIGURE 5A and 5B, the network of drains derived from the DEM ALOS, SRTM and SIGTIERRAS have a very good agreement between their products, with slight differences mainly in the minor drains, but which in general terms are similar. However, the drainage network obtained for the case study of the Amazon region (FIGURE 5C), denotes a clear divergence between the results of the SIGTIERRAS

FIGURE 4. Correlation graph between the control heights and the DEMs analyzed

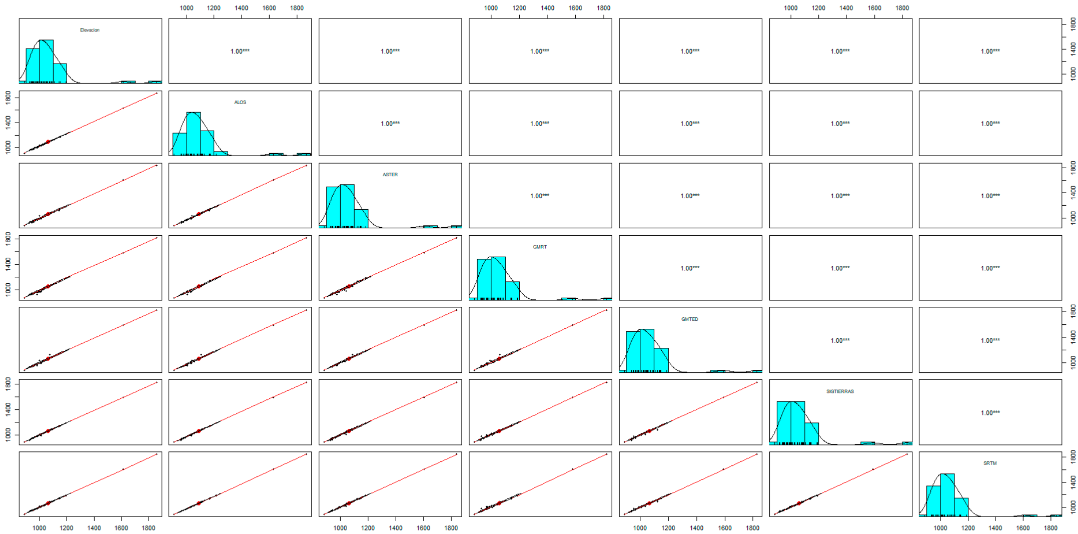
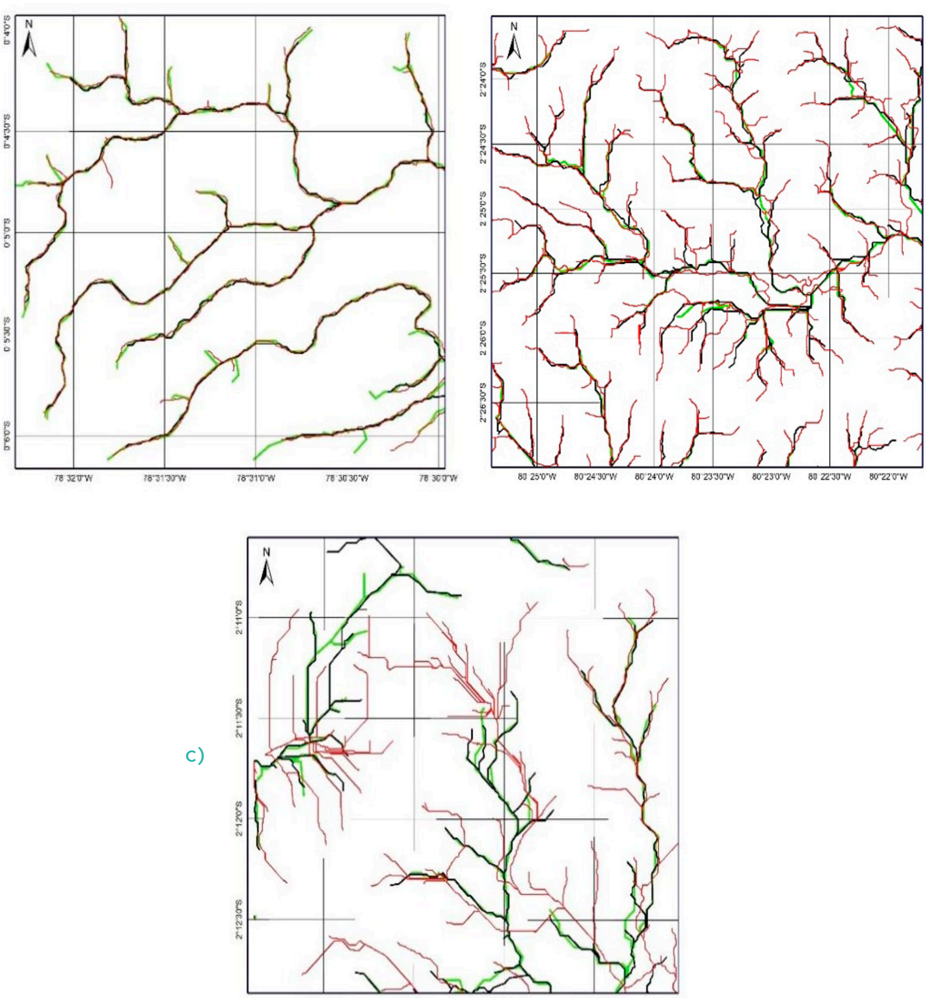


FIGURE 5. Drainage network extracted from the DEM of ALOS, SRTM and SIGTIERRAS, in the three study cases: **a)** Quito, **b)** Guayaquil, **c)** Macas. The color palette represents a digital model, as follows: red - SIGTIERRAS, green - SRTM, black - ALOS

a) b) c)



model with those of ALOS and SRTM, while the global ALOS and SRTM models have good agreement between their drains, the local model erroneously indicates natural channels elsewhere.

With the performed example of the extraction of hydrological characteristics, such as natural drainages, it can be indicated that in the Coastal lowlands and Highlands regions of Ecuador, the three DEMs used present a good coherence between them, while in the Amazon region, the divergent behavior of the derived product with the local model (SIGTIERRAS) reflects problems for the extraction of drains, unlike the global ALOS and SRTM models. The latter may be related to the way in which the national DEM was generated, since for the Coastal and Highlands region photogrammetric data were combined with LIDAR (SIGTIERRAS, 2016), and in the Amazon little or nothing was applied the same criteria for obtaining, producing errors like the ones shown.

A quantitative way to evaluate the precision of the characteristics extracted from the DEMs is by calculating the line correspondence coefficient (CLC), which allows identifying coincident (or not) linear geometries between two separate drainage networks (Stanislawski *et al.*, 2018). CLC is calculated using the following expression:

$$CLC = \sum \left(\frac{L_m}{L_a}\right)$$

Where L_m is the sum of the length of the lines (drains) that coincide between both data sets (DEM), and L_a represents the sum of the length of the total of lines in both data sets. CLC ranges from 0 to 1, where the unit represents a complete match between the two data. In this case, the CLC values were obtained between the three digital models ALOS PALSAR, SRTM and SIGTIERRAS, compared to each other, the results of which are shown in TABLE 2.

With the results of the line correspondence coefficient, the achievable precision of the products generated with the digital elevation models that presented a better RMSE is reflected, where the CLC values found in the littoral zone (Guayaquil) denote a good coincidence between the drains extracted (mainly between ALOS and SIGTIERRAS). In the northern zone (Quito) the highest CLC values were obtained, and therefore greater coincidence between the drainage networks extracted, while in the eastern region (Macas) the CLC value reflects again that the local SIGTIERRAS model presents errors in its product, unlike the ALOS and SRTM models that reached high coincidence values.

Finally, as they were verified with the values of the statistics, as with the example applied to hydrology, the pixel size is not an absolute determining factor for this type of spatial data, since they present noise that influences their height values, and therefore in the derived products obtained with these, and that in the case of the local model for Ecuador, can be attributed to the way it was generated, mainly in the Amazon region where there are also gaps of information. Another point to highlight is that the potentiality and concordance of the data

TABLE 2. CLC results in the three study areas

Quito			
	ALOS PALSAR	**SRTM**	**SIGTIERRAS**
ALOS PALSAR	-	0.758	0.841
SRTM	0.758	-	0.712
SIGTIERRAS	0.841	0.712	-
Guayaquil			
	ALOS PALSAR	**SRTM**	**SIGTIERRAS**
ALOS PALSAR	-	0.624	0.751
SRTM	0.624	-	0.592
SIGTIERRAS	0.751	0.592	-
Macas			
	ALOS PALSAR	**SRTM**	**SIGTIERRAS**
ALOS PALSAR	-	0.753	0.153
SRTM	0.753	-	0.105
SIGTIERRAS	0.153	0.105	-

from the global models, specifically from the DEM SRTM and ALOS PALSAR, was verified in the three regions analyzed in this study, which is why they continue to be widely used in various applications, including as covariates with multispectral satellite images (Salah, 2021; Wang *et al.*, 2020), or geodetic applications (Palacios *et al.*, 2021).

4. Conclusions

Of the six digital elevation models analyzed, the DEMs from SIGTIERRAS, ALOS PALSAR and SRTM are the ones with the highest altitude precision. For the SIGTIERRAS model, an RMSE of 2.498, 1.556 and 7.428 meters was obtained, with ALOS PALSAR an RMSE of 3.725, 4.117 and 5.792 was reached, while with the SRTM model, an RMSE of 3.604, 4.314 and 6.249 meters was reached in Quito, Guayaquil and Macas, respectively.

According to the values of the statistical indicators calculated, the SIGTIERRAS model performs more favorably in the topography of the Coast and Highlands, while the ALOS PALSAR model better adjusts to the topographic conditions of the Amazon region of Ecuador.

The analysis of the quality of the DEM is of vital importance to know the limitations in its use, the errors that can be assumed up to certain scales of work and the applications in different branches of engineering, since the precision of the products generated with the digital models considered.

By comparing it with more exact height values, such as those derived from GPS / leveling control points (geometric or GPS), it was possible to evaluate the real precision of the DEM studied, with which it was possible to infer which ones were more auspicious to use according to the conditions of the relief in the regions of Ecuador.

5. References quoted

ASF 2021. *ALOS PALSAR – Radiometric Terrain Correction*. Available in: https://asf.alaska.edu/data-sets/derived-data-sets/alos-palsar-rtc/alos-palsar-radiometric-terrain-correction/#ASF8217s_Radiometric_Terrain_Correction_Project.

ABDULHASSAN, A. A.; NAJI, A. A. & H. H. ABBOOD. 2021. "Vertical accuracy of Digital Elevation Models based on Differential Global Positioning System". *Iraqi Journal of Science*, 91-99.

ABRAMS, M.; CRIPPEN, R. & H. FUJISADA. 2020. "ASTER global digital elevation model (GDEM) and ASTER global water body dataset (ASTWBD)". *Remote Sensing*, 12(7): 1.156.

ALGANCI, U.; BESOL, B. & E. SERTEL. 2018. "Accuracy assessment of different digital surface models". *ISPRS International Journal of Geo-Information*, 7(3): 114.

AZIZIAN, A. & L. BROCCA. 2020. "Determining the best remotely sensed DEM for flood inundation mapping in data sparse regions". *International Journal of Remote Sensing*, 41(5): 1.884-1.906.

BANERJEE, P.; FOULGER, G.; SATYAPRAKASH, Y. & C. DABRAL. 1999. "Geoid undulation modelling and interpretation at Ladak, NW Himalaya using GPS and levelling data". *Journal of Geodesy*, 73: 79-86.

BOUVET, A.; MERMOZ, S.; LE TOAN, T.; VILLARD, L.; MATHIEU, R.; NAIDOO, L. & G. P. ASNER. 2018. "An above-ground biomass map of African savannahs and woodlands at 25 m resolution derived from ALOS PALSAR". *Remote sensing of environment*, 206: 156-173.

CARRERA, D.; PALACIOS, I.; ALBÁN, T.; BARAHONA, J.; CALDERÓN, D.; CASTEO, A. & M. VEGA. 2021. Variation in drinking water consumption due to the health emergency of SARS-CoV-2 through dynamic modeling in Macas City, Amazon from Ecuador. In: C. E.-G.

SALGADO & GUERRERO J. P. (Ed.), *Conference on Information and Communication Technologies of Ecuador. TICEC 2021*. 1456, Springer, (pp. 267-280).

CORRAL, L. R. & C. E. M. OLEA. 2020. "What drives take-up in land regularization: Ecuador's rural land regularization and administration program, Sigtierras". *Journal of Economics, Race, and Policy*, 3(1): 60-75.

CUMMING, G. 2014. "The new statistics: Why and how". *Psychological Science*, 25(1): 7-29.

DeMERS, M. 2001. *GIS Modeling in Raster. GIS & Remote Sensing*. John Wiley and Son. (1ra. Ed). New York, USA.

DU, X.; GUO, H.; FAN, X.; ZHU, J.; YAN, Z. & . ZHAN. 2016. "Vertical accuracy assessment of freely available digital elevation models over low-lying coastal plains". *International Journal of Digital Earth*, 9(3): 252-271.

FELICÍSIMO, A. 1994. *Modelos digitales del terreno. Introducción y aplicaciones en las ciencias ambientales*. Pentalfa. España.

FISHER, P. & N. TATE. 2006. "Causes and consequences of error in Digital Elevation Models". *Progress in Physical Geography*, 30(4): 467-489.

FOTOPOULOS, G.; KOTSAKIS, C. & M. SIDERIS. 2003. "How accurately can we determine orthometric height". *Journal of Surveying Engineering*, 129(1): 1-11.

GMRT 2020. *About GMRT*. Available in: https://www.gmrt.org/about/

GOODCHILD, M. F. 1992. "Geographical data modeling". *Computers & Geosciences*, 18(4): 401-408.

GUPTA, Y.; AJITHKUMAR, B.; KALE, H. S. ... & S. ROY. 2017. "The upgraded GMRT: opening new windows on the radio Universe". *Current Science*, 707-714.

HENGL, T. 2007. *A practical guide to geostatistical mapping of environmental variables*. EUR 22904. En: Luxembourg (Luxembourg): Office for Official Publications of the European Communities; 2007. JRC38153.

JABOYEDOFF, M.; CHOFFET, M.; DERRON, M. ... & A. PEDRAZZINI. 2012. "Preliminary slope mass movement susceptibility mapping using DEM and LiDAR DEM". In: B. PRADHAN & M. BUCHROITHNER (Eds.), *Terrigenous Mass Movements*. pp. 109-170. Springer-Verlag.

JASIEWICZ, J.; STEPINSKI, T. & J. NIESTEROWICZ. 2018. "Multi-scale segmentation algorithm for pattern-based partitioning of large categorical rasters". *Computers & Geosciences*, 118: 122-130.

LI, Z.; LI, P.; DING, D. & H. WANG. 2018. "Research progress of global high resolution Digital Elevation Models". *Geomatics and Information Science of Wuhan University*, 43(12): 1.927-1.942.

MANCERO, H.; TOCTAGUANO, D.; TACURI, C.; KIRBY, E. & A. TIERRA. 2015. Evaluación de Modelos Digitales de Elevaciones obtenidos por diferentes sensores remotos. *X Congreso de Ciencia y Tecnología ESPE*, 107-111.

MASSONNET, D. & C. ELACHI. 2006. "High-resolution land topography". *Comptes Rendus Geoscience*, 338(14–15): 1.029-1.041. https://doi.org/10.1016/j.crte.2006.06.001

MICHALAK, J. 2004. "DEM data obtained from the Shuttle Radar Topography Mission–SRTM-3". *Annals of Geomatics*, 2(1): 34-44.

MUHLENKORT, R. 2011. "Supporting Ecuador's National GIS Initiative". *GeoInformatics*, 14(7): 46.

MUKUL, M.; SRIVASTAVA, V.; JADE, S. & M. MUKUL 2017. "Uncertainties in the shuttle radar topography mission (SRTM) Heights: Insights from the Indian Himalaya and Peninsula". *Scientific reports*, 7(1): 1-10.

MUNOTH, P. & GOYAL, R. 2019. "Effects of DEM source, spatial resolution and drainage area threshold values on hydrological modeling". *Water Resources Management*, 33: 3.303-3.319.

NASA 2019. *New Version of the ASTER GDEM*. Available in: https://earthdata.nasa.gov/learn/articles/new-aster-gdem.

NIIPELE, J. & J. CHEN. 2019. "The usefulness of alos-palsar dem data for drainage extraction in semi-arid environments in The Iishana sub-basin". *Journal of Hydrology: Regional Studies,* 21: 57-67.

OYOSHI, K.; MIZUKAMI, Y.; KAKUDA, R.; KOBAYASHI, Y.; KAI, H. & T. TADONO. 2019. "Japan Aerospace Exploration Agency's public-health monitoring and analysis platform: A satellite-derived environmental information system supporting epidemiological study". *Geospatial health,* 14(1).

PAKOKSUNG, K. & M. TAKAGI. 2021. "Assessment and comparison of Digital Elevation Model (DEM) products in varying topographic, land cover regions and its attribute: a case study in Shikoku Island Japan". *Modeling Earth Systems and Environment,* 7(1): 465-484.

PALACIOS, I. & C. LEIVA. 2019. "Establecimiento del estado de conservación en yacimientos arqueológicos mediante UAVS: estudio de caso: Cerro Catequilla". *La Zaranda de Ideas,* 17(2): 6-20.

PALACIOS, I. & C. LEIVA. 2018. "Evidencia de la relación entre Arqueoastronomía y Geodesia satelital en el Cerro Catequilla, Ecuador". *Revista de Arqueología Americana,* 36: 177-193.

PALACIOS, I. & T. TOULKERIDIS. 2020. Evaluation of the susceptibility to landslides through diffuse logic and analytical hierarchy process (AHP) between Macas and Riobamba in Central Ecuado. *7th International Conference on EDemocracy and EGovernment, ICEDEG 2020,* (pp. 201-207).

PALACIOS, I. 2020. *Generación de un modelo de crecimiento tendencial urbano de la ciudad de Macas (Ecuador) al año 2030, mediante técnicas de modelación espacial multivariable*. Universitat de Barcelona, España.

PALACIOS, I. 2019. *Generación de un modelo de predicción de la variable ondulación geoidal, para la zona rural del cantón Guayaquil, mediante el uso del método cokriging*. Universidad de las Fuerzas Armadas ESPE. Ecuador.

PALACIOS, I.; LEIVA, C.; BUENAÑO, X.; CHICAIZA, E. & T. TOULKERIDIS. 2021. "Geoid undulation modeling through the Cokriging method–A case study of Guayaquil, Ecuador". *Geodesy and Geodynamics,* 12(5): 356-367.

PARDO, J. A.; AGUILAR, W. G. & T. TOULKERIDIS. 2017. Wireless communication system for the transmission of thermal images from a UAV. In *2017 CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON),* (pp. 1-5). IEEE.

PÉREZ, A. & J. FRANÇOIS. 2009. "Evaluación de los errores de modelos digitales de elevación obtenidos por cuatro métodos de interpolación". *Investigaciones Geográficas,* 69: 53-67.

POPPENGA, S. & B. WORSTELL. 2016. "Hydrologic connectivity: Quantitative assessments of hydrologic- enforced drainage structures in an Elevation Model". *Journal of Coastal Research,* 76: 90-106.

RABUS, B.; EINEDER, M.; ROTH, A. & R. BAMLER. 2003. "The shuttle radar topography mission-a new class of digital elevation models acquired by spaceborne radar". *ISPRS Journal of Photogrammetry and Remote Sensing,* 57(4): 241-262.

RODRÍGUEZ, E.; MORRIS, C.; BELZ, J.; CHAPIN, E.; MARTIN, J.; DAFFER, W. & S. HENSLEY. 2019. *An Assessment of the SRTM Topographic Products.*

RYAN, W.; CARBOTTE, S.; COPLAN, J., ..., & R. ZEMSKY. 2009. "Global Multi-Resolution Topography synthesis". *Geochemistry, Geophysics, Geosystems,* 10(3): 1-9.

SAKSENA, S. & V. MERWADE. 2015. "Incorporating the effect of DEM resolution and accuracy for improved flood inundation mapping". *Journal of Hydrology,* 530: 180-194.

SALAH, M. 2021. "SRTM DEM correction over dense urban areas using inverse probability weighted interpolation and Sentinel-2 multispectral imagery". *Arabian Journal of Geosciences,* 14: 801.

SANTISE, M.; FORNARI, M.; FORLANI, G. & R. RONCELLA. 2014. Evaluation of DEM generation accuracy from UAS imagery. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* XL–5: 529-536.

SHARMA, A.; TIWARI, K. & P. BHADORIA. 2009. "Measuring the accuracy of contour interpolated Digital Elevation Models". *Journal of the Indian Society of Remote Sensing,* 37: 139-146.

SHI, W.; WANG, B. & Y. TIAN. 2014. "Accuracy analysis of Digital Elevation Model relating to spatial resolution and terrain slope by bilinear interpolation". *Mathematical Geosciences,* 46: 445-481.

SIGTIERRAS 2016. *Modelo Digital del Terreno (MDT) de Ecuador*. Available in: http://metadatos.sigtierras.gob.ec:8080/geonetwork/srv/spa/catalog.search#/metadata/MDT_SIGTIERRAS_16092016.

STANISLAWSKI, L.; SURVILA, K.; WENDEL, J.; LIU, Y. & B. BUTTENFIELD. 2018. "An open source high-performance solution to extract surface water drainage networks from diverse terrain conditions". *Cartography and Geographic Information Science,* 45(4): 319.328.

SU, J. & E. BORK. 2006. "Influence of vegetation, Slope, and Lidar Sampling Angle on DEM Accuracy". *Photogrammetric Engineering & Remote Sensing,* 11: 1.265-1.274.

USGS. 2018. *GMTED2010*. Available in: https://www.usgs.gov/core-science-systems/eros/coastal-changes-and-impacts/gmted2010?qt-science_support_page_related_con=0#qt-science_support_page_related_con.

VIERA-TORRES, M.; SINDE-GONZÁLEZ, I.; GIL-DOCAMPO, M.; BRAVO-YANDÚN, V. & T. TOULKERIDIS. 2020. "Generating the baseline in the early detection of bud rot and red ring disease in oil palms by geospatial technologies". *Remote Sensing,* 12(19): 3.229.

WACHA, K. M.; PAPANICOLAOU, A. N.; GIANNOPOULOS, C. P., ... & T. HOU. 2018. "The role of hydraulic connectivity and management on soil aggregate size and stability in the Clear Creek Watershed, Iowa". *Geosciences,* 8(12): 470.

WANG, X.; HOLLAND, D. & G. GUDMUNDSSON. 2018. "Accurate coastal DEM generation by merging ASTER GDEM and ICESat/GLAS data over Mertz Glacier, Antarctica". *Remote Sensing of Environment,* 206(1), 218-230.

WANG, X.; ZHANG, Y.; ATKINSON, P. & H. YAO. 2020. "Predicting soil organic carbon content in Spain by combining Landsat TM and ALOS PALSAR images". *International Journal of Applied Earth Observation and Geoinformation,* 92: 102182.

WU, S.; LI, J. & G. HUANG. 2008. "A study on DEM-derived primary topographic attributes for hydrologic applications: Sensitivity to elevation data resolution". *Applied Geography,* 28: 210-223.

YANG, L.; MENG, X. & X. ZHANG. 2011. "SRTM DEM and its application advances". *International Journal of Remote Sensing,* 32(14): 3.875-3.896.

YAO, J.; CHAO, Y. & F. PING. 2020. Evaluation of the Accuracy of SRTM3 and ASTER GDEM in the Tibetan Plateau Mountain Ranges. *2020 2nd International Conference on Geoscience and Environmental Chemistry (ICGEC 2020),* 01027. Available in: https://doi.org/10.1051/e3sconf/202020601027

ZHAO, S.; CHENG, W.; ZHOU, C.; CHEN, X., ...& H. CHAI. 2011. "Accuracy assessment of the ASTER GDEM and SRTM3 DEM: an example in the Loess Plateau and North China Plain of China". *International Journal of Remote Sensing,* 32(23): 8.081-8.093.

Lugar y fecha de finalización del artículo:
Sangolquí, Ecuador; septiembre, 2021