The impact of the DEM on archaeological GIS studies

A case study in Ecuador

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Abstract: Digital elevation models (DEMs) are an important basis for many archaeological GIS studies like predictive modelling, visibility and least-cost path analysis. Issues in DEM data have been discussed in textbooks dealing with archaeological GIS applications and in some papers published more than ten years ago. But lately hardly any archaeological GIS study relying on DEM data refer to these issues though the problems connected with DEM use have not decreased with increasing availability of DEM data. This contribution presents a case study in the East Andean slopes of Ecuador analysing the impact of DEM choice on slope and aspect calculation as well as least-cost site catchments and least-cost paths. Four freely available elevation data sets are considered: ASTER GDEM2, SRTM at 3 arc-second and 1 arc-second resolution as well as a DEM derived from digitised contour lines of the official 1:50,000 maps provided by the Military Geographical Institute of Ecuador. Issues discussed are DEM resolution, horizontal and vertical accuracy, filling voids, and creating a DEM from contour lines.

Keywords: digital elevation models, digital terrain models, slope, aspect, Ecuador

Introduction

Images based on Digital Elevation Models (DEMs) are often used in archaeological papers to present a pretty picture of the study area. These images include shaded relief maps (e.g., CHAPMAN 2006:133), contour line plots and projections of a 3D DEM with some drape file (e.g., CONOLLY & LAKE 2006:102, 110). DEMs and derived attributes like slope are also an important basis for many archaeological GIS studies like predictive modelling, viewshed and least-cost path analysis (e.g., CONOLLY & LAKE 2006:182, 217–221, 226–233). It is for this reason and due to the complexity of the topic that two important textbooks on GIS in Archaeology dedicate a chapter to DEM issues (WHEATLEY & GILLINGS 2002:107–120; CONOLLY & LAKE 2006:101–111). In 2003, Willem Beex held a workshop on the use and abuse of DEMs and digital terrain models (DTMs) in Vienna discussing some additional issues (BEEX 2004).

In a paper published in 2000, HAGEMAN and BENNETT note that most archaeological studies using DEM data “have not provided an explicit rationale behind the use of a particular algorithm in the creation of a DEM”. With increasing availability of DEM data there is often no longer a need for the archaeologist to create the DEM. Consequently, hardly any archaeological GIS study discusses DEM issues though the problems connected with DEM use have not decreased. This contribution presents a case study in the east Andean mountains of Ecuador involving elevation data. In most European countries more accurate data at a higher resolution is available. For these high resolution European data sets, some of the DEM problems discussed in this paper are still relevant, but on a different scale. In some countries, archaeologists have to pay for acquiring these DEMs or for publishing map images based on such data so that they might consider alternatively using the freely available DEM data that we analyse in this paper.

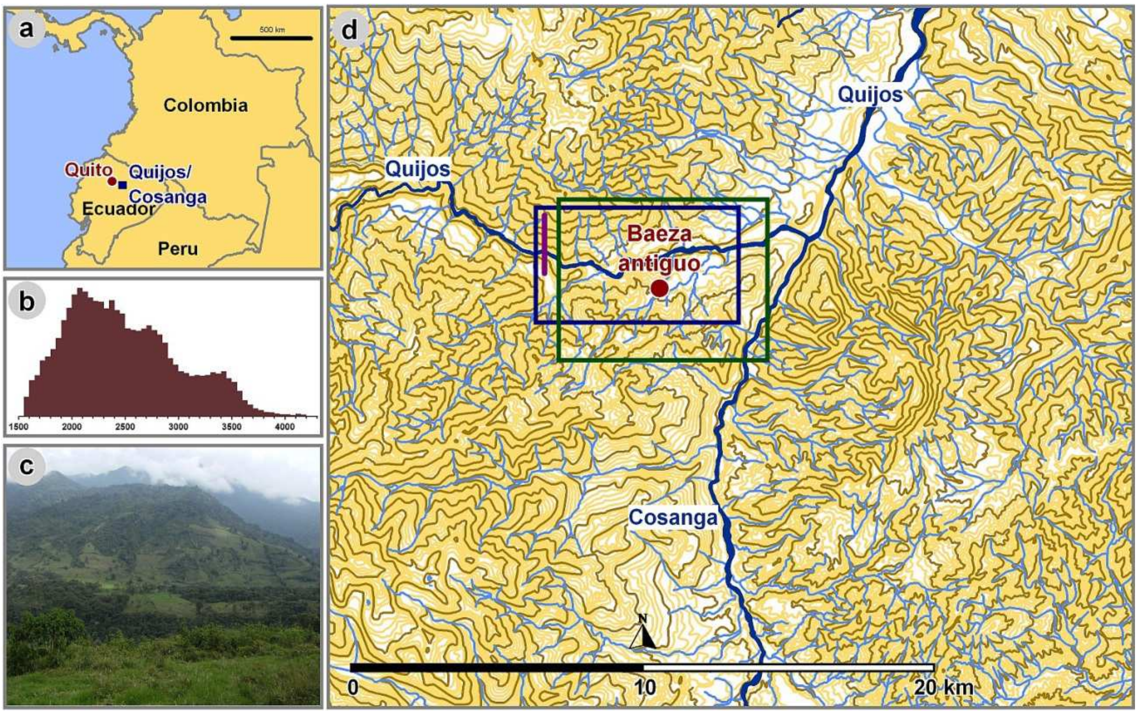

Fig. 1 – (a) The location of the study area in Ecuador (b) Histogram of altitudes in the study area. Altitudes vary between 1560 and 4280 m asl (c) Landscape in the study area (photo by Alden Yépez) (d) Topographic data provided by the Instituto Geográfico Militar, Ecuador: Contour lines and rivers, the main rivers Quijos and Cosanga are highlighted.

When we first started the GIS analysis for the study area some years ago, only ASTER GDEM and low resolution (3 arc-seconds, ca. 90 m cell size; short term: SRTM 3’’) SRTM elevation data were available. Since recently, additional elevation data for Ecuador can be downloaded for free from the web: (i) digitized contours of the 1:50,000 topographic maps (short term: Topo50 data) and (ii) higher resolution SRTM data (1 arc-second, ca. 30 m cell size; short term: SRTM 1’’).

Some colleagues are convinced that the ASTER GDEM is highly inaccurate and that all GIS analysis results based on this data set are invalid. In this contribution, ASTER, SRTM and Topo50 data are compared both with respect to the altitudes and derived variables like slope and aspect for our study area. As mentioned above, DEMs are discussed in several publications written by and for archaeologists. However, some of the issues encountered when dealing with the data in Ecuador are not mentioned in these books. These include systematic horizontal errors and bias in altitude when trying to combine two DEMs. Moreover, this paper compares the DEMs not only with respect to the altitudes but also the derived attributes slope and aspect as well as the outcomes of least-cost site catchments and least-cost paths.

Most of the results were created by the Vertical Mapper 3.1 plugin of MapInfo. The Sextante plugin of gvSIG was applied for raster data conversion, clipping and change of the initial projection.

DEM data

According to WHEATLEY and GILLINGS (2002, 110), "the most frequently used form of DEM is a regular rectangular grid of altitude measurements in which each cell is assigned its corresponding altitude value". Well-known examples of pre-generated DEM data provided in grid files are ASTER and SRTM data.

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) was developed jointly by the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). The initial version GDEM1 was released in 2009, the improved GDEM 2 is available since 2011 (TACHIKAWA et al. 2011; http://gdem.ersdac.jspacesystems.or.jp/index.jsp).

The elevation data recorded by the Shuttle Radar Topography Mission (SRTM) allowed generating a near-global DEM (RODRÍGUEZ et al. 2005; http://earthexplorer.usgs.gov/). This DEM is a result of the collaboration between NASA and the National Geospatial-Intelligence Agency. Overview maps are published on the web (http://srtm.usgs.gov/data/coveragemaps.php) showing that most of Germany was covered at least four times by the mission, whereas most areas of Ecuador were imaged only twice. Starting in 2003, the near-global SRTM 3'' data set was released first. The data was post-processed by flattening lakes and rivers and ensuring that rivers smoothly descend toward the ocean (GUTH 2006). At the time of writing, the improved version 4.1 of SRTM 3'' data set is available. The SRTM 1'' data set was released in phases starting September 24, 2014 (http://www2.jpl.nasa.gov/srtm/).

The GeoTIFF format allows storing rectangular grids as georeferenced raster imagery (http://trac.osgeo.org/geotiff/). The ASTER GDEM and SRTM data in two resolutions can be downloaded in GeoTIFF format. Unfortunately, Vertical Mapper 3.1 is not able to deal with GeoTIFF, therefore the Sextante plugin of gvSIG was applied for converting the clipped elevation data to the ESRI ASCII Raster format (http://resources.esri.com/help/9.3/arcgisdesktop/com/gp_toolref/spatial_analyst_tools/esri_ascii_raster_format.htm; https://en.wikipedia.org/wiki/Esri_grid).

Moreover, since January 2013 the contour line data Topo50 is available for the study region (http://www.geoportaligm.gob.ec/portal/index.php/cartografia-de-libre-acceso-escala-50k/) and on this basis a DEM can be generated (for details see section "Generating a DEM grid based on contour line data" below).

Assessing the accuracy and the resolution of DEM data

A first check of DEM data is provided by a shaded relief visualization of the DEM: This allows detecting local anomalies due to past or modern construction work or due to problems in the data or the interpolation (e.g., Fig. 2, left).

According to BEEX (2004), the Nyquist limit determines the minimum size of features to be detected on the DEM surface: To identify a circular pit with a diameter of 20 m in a DEM, the maximum distance within the set of altitude points forming the basis of the DEM should not exceed 10 m, and 5 m is the recommended maximum distance. The maximum distance between elevation points agrees with the resolution of the raster DEM only if the DEM is generated by sampling the surface at regular intervals along both the x- and the y-axis. By applying interpolation, DEM grids of different resolution can be created on the basis of irregularly distributed altitude points; in this case, the Nyquist limit cannot be derived from the resolution. This is one of the reasons why detailed information on the DEM should be studied before using a pre-generated DEM. TACHIKAWA et al. (2011) discuss effective resolution versus spacing of postings (nominal resolution). The spacing of postings (=pixel size) of the ASTER GDEM2 is about 31 m in Ecuador, but the effective resolution is between 71 and 82 m. The effective resolution is determined by comparing the GDEM2 to a low-pass filtered or re-sampled higher resolution DEM. The filter size corresponds to a sampling rate, and the sampling rate resulting in the closest match to the GDEM2 is the effective resolution. RODRÍGUEZ et al. (2005:114) analyzed the SRTM 1'' and found that "the SRTM effective resolution would be 90 m". GUTH (2006) compares not only the elevations of SRTM 1'' with a reference DEM (NED data, according to Guth, "NED represents the "best available" elevation data for the United States") but also includes derived variables like slope in his comparison. Although the elevations were highly correlated, some of the derived attributes had only correlations below 0.30. Based on re-sampled reference DEMs in two study areas and derived average slope grids GUTH (2006) comes to the conclusion that the effective resolution of the SRTM 1'' is about 2 arc-seconds (ca. 60 m) in his US study area, and between 2.25 and 3 arc-seconds in another study area in Canada.

When dealing with contour line data, the altitude differences between consecutive contour lines have an impact both on the accuracy and the detectability of landscape features: Chances are low that a shallow lake with a depth of 5 m can be discerned in a DEM consisting of contour lines at a 10 m altitude interval.

The Topo50 contour lines most probably describe a DTM, i.e. represent the surface of the landscape because according to the legends of the corresponding paper maps, the altitudes were derived by photogrammetric methods. Cartographers using these methods try to see through the vegetation in the original aerial photographs (GUTH 2006). ASTER and SRTM DEMs include the heights of objects like houses or trees on the surface, with SRTM data recorded in February during leaf-off conditions for northern deciduous forests (GUTH 2006; TACHIKAWA et al. 2011).

HAGEMAN and BENNETT (2000) discuss the accuracy of DEMs: Quantitative approaches like the root mean square error (RMSE) between the estimated altitudes at reference points with known heights allow a systematic comparison of different DEMs. TACHIKAWA et al. (2011) compare the ASTER GDEM2 data to reference elevation data in Japan and to GPS benchmarks in the US. Based on the US GPS benchmark elevations TACHIKAWA et al. (2011) come to the conclusion that the errors are uniformly distributed about the zero error axis (e.g., the errors appear to be unbiased; mean = -0.20). The GPS benchmarks are on the bare Earth and consequently the mean errors vary depending on the land cover class between –2.27 m (cultivated crops) and +5.00 m (woody wetlands).

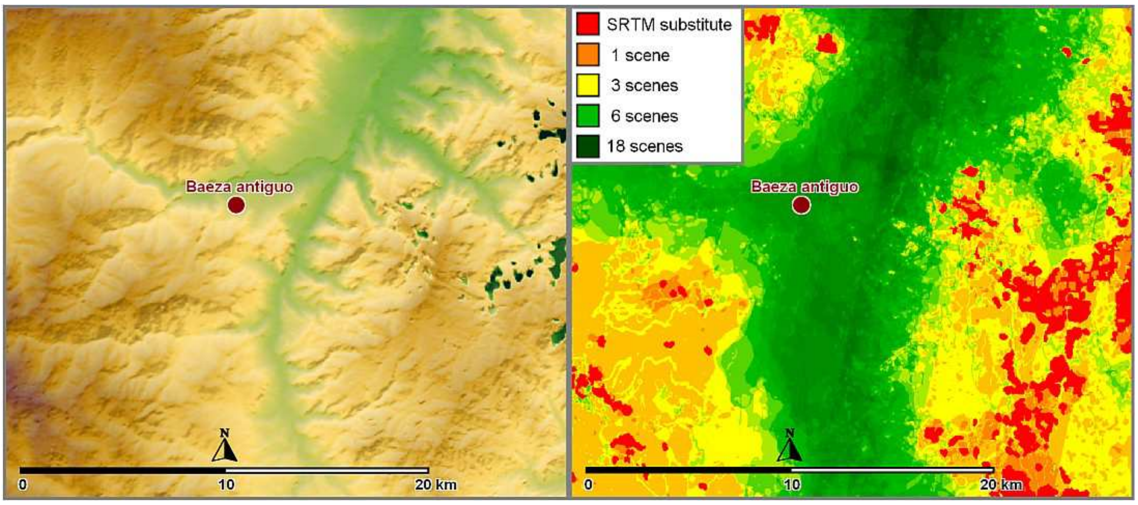

Fig. 2 – ASTER data of the Quijos/Cosanga study area: Shaded relief DEM (left), QA data (right). Gross errors are clearly visible in the eastern part of the shaded relief map. Coverage by DEM scenes is low outside the Quijos and Cosanga river valleys.

The ASTER GDEM combines different DEM scenes to the final GDEM value for each raster cell with a cell size of 1 arc-second. The QA GeoTIFF file distributed along with the GDEM data stores for each raster cell either the number of scene-based DEMs contributing to the final GDEM value (stack number) or a negative number indicating the source data set used to replace identified bad values in the ASTER GDEM. As expected the mean errors vary depending on the stack number, and TACHIKAWA et al. (2011) note that “larger errors are associated with fewer than ten scenes, and especially fewer than three scenes”.

Whereas the voids of ASTER data are filled with data from other sources, SRTM 1’’ data include voids, such areas with missing values are mainly located in mountainous regions like the Andes (http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1, see also Fig. 3 and Fig. 8). With ASTER data, anomalous data resulting in spikes and wells can mostly be found in areas with low stack numbers or with replaced elevation data (e.g., Fig. 2).

RODRÍGUEZ et al. (2005:44-54) calculate the differences between the SRTM 1’’ and ground control points in South America. The horizontal bias is 0.5 m, and the absolute difference exceeds 8.5 m only for 10% of the SRTM data. According to the tests by TACHIKAWA et al. (2011), the vertical accuracy of the ASTER GDEM2 amounts to 17 m at the 95% confidence level. The tests of this working group cover also the SRTM 1’’ DEM; they record a vertical bias of 0.73 m, and the vertical accuracy is 7.86 m at the 95% confidence level. Unfortunately, we do not know of any study assessing the accuracy of the Topo50 data.

The Quijos / Cosanga case study

Several sources indicate that the pre-Columbian inhabitants of the Quijos/Cosanga area had trade relationships to the Amazon and the northern and central highlands of Ecuador (CUÉLLAR 2009: 9–13; BRAY 1995). This is one of the reasons why CUÉLLAR (2009) initiated a survey project in this region and why we are interested in the patterns of movement and of settlement in this area. Due to steep slopes and high altitudes varying between 1560 and 4280 m asl (Fig. 1) DEM data plays an important role in analysing the landscape. Past research covered the find distributions, the patterns of movement and of settlement in this area (HERZOG & YÉPEZ 2012; HERZOG & YÉPEZ 2015). These studies relied on the ASTER GDEM2, supplemented by SRTM 3'' data, because these were the only freely available elevation data of the study area at that time. The recent releases of the Topo50 and the SRTM 1'' data allow us now assessing the reliability and stability of our past results.

Nowadays only very small settlements can be found in this region, the with 1,667 inhabitants in the biggest settlement Baeza (census in 2001). The site Baeza antiguo is recorded in the national archaeological monuments and site data base of Ecuador (held at the Instituto Nacional de Patrimonio Cultural del Ecuador) and is located about 350 m south of the modern settlement Baeza.

Transforming elevation data to an adequate projection

The ASTER GDEM and the SRTM DEMs are provided with geographic latitude/longitude coordinates, referenced to the WGS84/EGM96 geoid. Close to the equator the 1 arc-second grid cells are quadratic (about 31 m x 31 m), but in Germany, these cells are rectangular (about 19 m x 31 m).

In the past, topographic maps of our study areas were based on the projection PSAD56 / UTM zone 17S (EPSG: 24877), nowadays geographic data is provided with the WGS 84 / UTM zone 17S (EPSG: 32717) projection. Confusing the two projections will result in horizontal errors of several hundred meters. For any medium or small scale archaeological GIS analysis it is recommended to convert the DEM data to the local topographic projection in order to avoid grid cells with different spacing of postings in the two coordinate directions. This involves some re-sampling or interpolation. Warning: Inadequate re-projection may create artifacts like consecutive rows of cells with identical altitude values.

Fig. 3 shows shaded relief maps of the four DEMs available for the Quijos/Cosanga study area, transformed to the WGS 84 / UTM zone 17S projection. The gross errors of the ASTER GDEM2 are clearly visible (see also Fig. 2). The Topo50 DEM was generated by bilinear interpolation of the nodes extracted by the Poly-to-Point tool of Vertical Mapper (see section “Generating a DEM grid based on contour line data” below). As expected, the SRTM 3'' DEM looks quite blurred compared to the other DEMs. The gray circle in one of the big voids of the SRTM 1'' DEM has a radius of 660 m. For the subsequent analyses the SRTM 1'' voids were filled by bilinear interpolation.

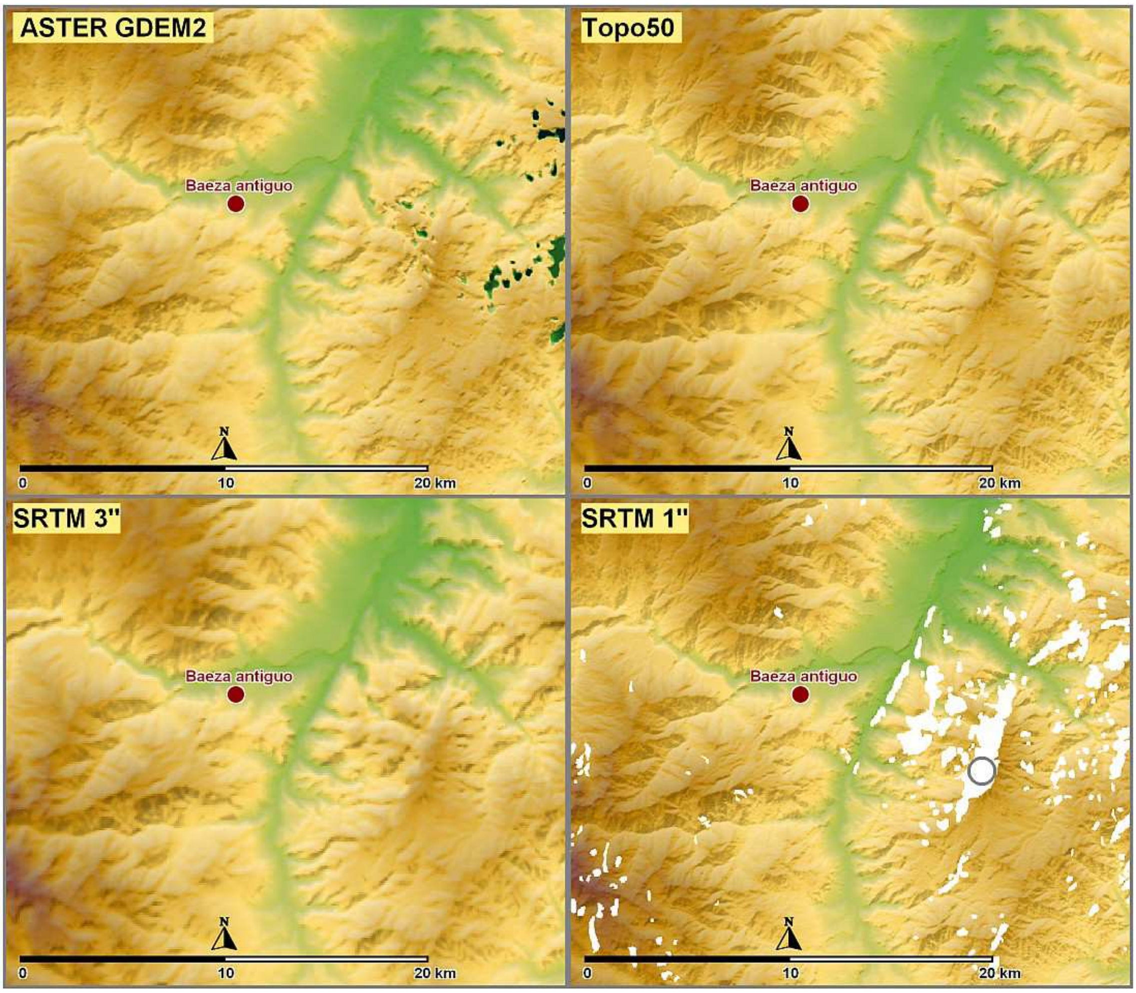

Fig. 3 – Quijos/Cosanga study area: Shaded relief maps based on four different DEMs.

Correcting the horizontal error

TACHIKAWA et al. (2011) estimated the horizontal error of the ASTER GDEM2 with respect to the reference DEM by shifting the GDEM2 by integer sample increments, in both x and y directions, and the standard deviation of the differences between the shifted ASTER DEM and the reference DEM was computed. The optimal shift parameters exhibit the lowest standard deviation. The horizontal shift magnitude for Japan was 0.601 arc-seconds, this is less than 20 m.

This method is similar to the approach presented by Ralf Hesse at the Vienna Workshop in 2015 for correcting the horizontal shift of Lidar data sets prior to comparing an older Lidar based DEM with a newer one. Ralf Hesse identified the optimal shift parameters by computing the RMSE. RODRÍGUEZ et al. (2005:110) compared the SRTM 1'' data to another DEM and found by cross correlation computations that the SRTM data "was planimetrically correct to better than 1 SRTM pixel".

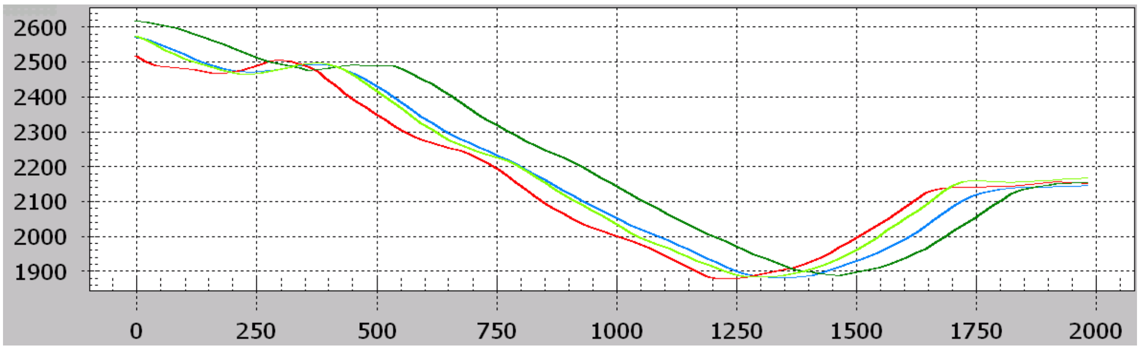

Fig. 4 – North-south cross section covering 2 km in the Quijos/Cosanga study area: ASTER GDEM2 – blue; SRTM 3" – dark green; SRTM 1" – light green; Topo50 – red. The red Topo50 curve is the reference profile. Shifting the other curves to the left (i.e. in north direction) could achieve a better fit. So there is some horizontal error in the ASTER and SRTM DEMs. The location of the cross section is indicated by a vertical violet line in Fig. 1d.

Fig. 4 provides evidence that horizontal shifts of ASTER and SRTM DEMs could improve the agreement between these DEMs and the Topo50 DEM. The Topo50 DEM is the reference DEM because it is derived from official maps of Ecuador; other topographic data like rivers were digitized from these maps as well, and we need this data for our calculations. Unfortunately, our GIS software does not provide any procedure comparable to those used by TACHIKAWA et al. (2011) or Ralf Hesse for computing the optimal shift. Manually shifting the DEM several hundred times and calculating the RMSE for each shift parameter set is too time consuming. So we first tried estimating the shift parameters based on cross sections like Fig. 4. This is difficult if shifts in both coordinate directions are required or if the shift is quite large. Later we found that estimating shift parameters by matching flow accumulation grids with digitized rivers is easier (Fig. 5).

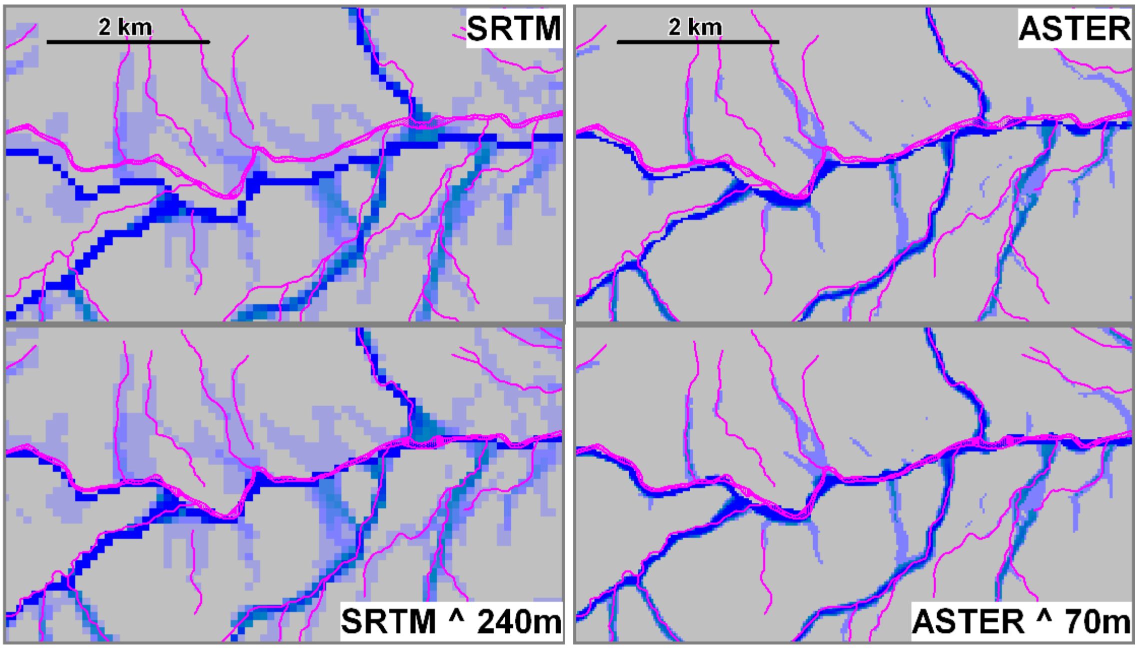

Fig. 5 – Correcting the horizontal error based on flow accumulation grids and the vectorized stream layer (pink). Initial grids are shown in the top row, correction results are placed below. Both DEMs are moved in north direction: SRTM 3'': 240 m; ASTER GDEM2: 70 m. The location of the study area section considered here is marked by a dark blue rectangle in Fig. 1d.

Flow accumulation grids were calculated by gvSIG Sextante. Descriptions of the flow accumulation algorithm can be found in DE SMITH (2007: 282) as well as in WHEATLEY and GILLINGS (2002: 121–123). Our approach relies on visual inspection, and another shift parameter close to the one we have chosen may result in a smaller RMSE. Therefore it would be most welcome if a procedure like that used by Ralf Hesse was included in standard GIS software.
So contrary to the previous studies referred to above, we come to the conclusion that there is a need for correcting the horizontal error for ASTER and SRTM data. Re-projecting the initial DEM data to the WGS 84 / UTM zone 17S system could be one of the reasons for the horizontal errors.

Identifying the vertical error

At the time when SRTM 1'' and the Topo50 data were not available, the ASTER GDEM2 was the basis for our computations. To fix the gross errors clearly visible in Fig. 2, SRTM 3'' data was used. Any systematic differences in altitude between the SRTM and the ASTER data should be fixed before replacing ASTER GDEM2 elevations by those derived from the SRTM DEM. To estimate the systematic difference, we selected all ASTER cells with stack number exceeding 4. These cover 49.3% of the study area, and their elevation mean is 2165.85 m. After deriving the elevations of these cells from the SRTM DEM, the SRTM-mean elevation was computed: This mean is 2180.49 m, resulting in a difference of 14.64 m.
Fig. 6 shows the results of our attempts to correct gross errors in the ASTER GDEM2 with the help of the SRTM 3'' data.

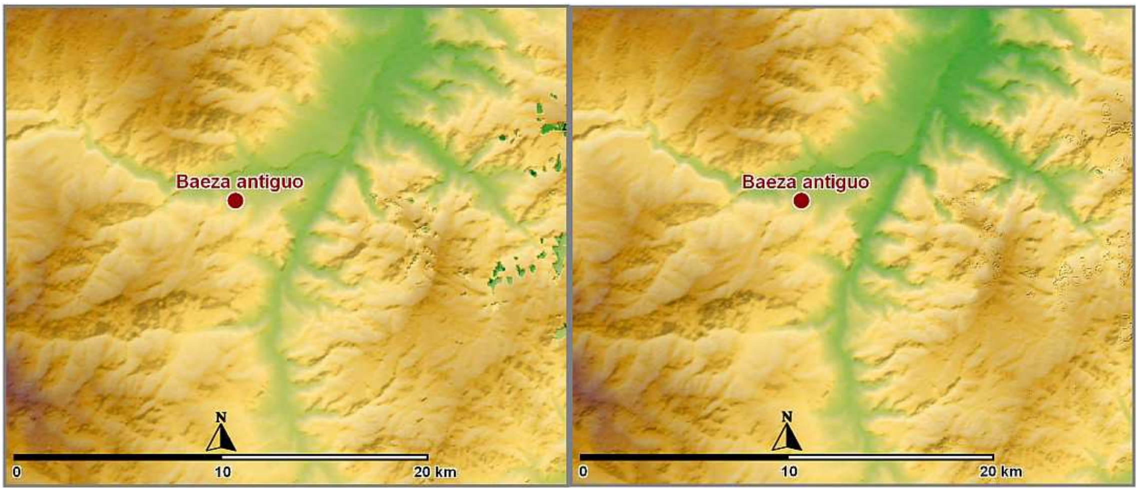

Fig. 6 – Correcting gross errors in the ASTER GDEM2 by replacing cell values on the basis of SRTM 3'' data: (a) first attempt, (b) second attempt.

In our first attempt (Fig. 6 left) we substituted ASTER altitude data if the quality value of the corresponding cell was 1 (stack number = 1) or below zero (SRTM substitute) as follows:

- SRTM substitute: srtm – 14.6
- 1: 0.5*(aster + srtm – 14.6)

In the resulting DEM (Fig. 6 left) the gross errors showing in Fig. 2 (left) are still visible, though the erroneous pits are not as deep as before. So we tried another more refined correction: After identifying all cells with altitude differences between SRTM and ASTER exceeding 50 m, we generated a correction grid based on the

IDW interpolation (search radius: 120 m) of these differences. Fig. 6 (right) is the result of adding the correction grid to the ASTER GDEM2.

The second result (Fig. 6 right) is clearly better than our first attempt but the locations of gross errors are still visible. The focus of the previous archaeological studies was on the river valleys and no gross errors are in these valleys. Therefore we decided to continue our research with the DEM produced by our second correction attempt.

Generating a DEM grid based on contour line data

For generating a shaded relief map, slope or aspect maps as well as viewshed analysis a grid based DEM is required. So a method for creating a DEM from contour lines is required. Several publications discuss an approach consisting of first rasterising the vector contours and afterwards filling the cells between the contour cells by some interpolation variant (WHEATLEY & GILLINGS 2002: 114–118; HAGEMAN & BENNETT 2000; CONOLLY & LAKE 2006: 109–110). This approach is not supported by our software, therefore we used the Poly-to-Point tool of Vertical Mapper to extract the nodes from the digitized contour lines and thereafter a standard interpolation algorithm for altitude point sets. Due to space limitations we cannot discuss the pros and cons of different interpolation methods but refer to the GIS books by DE SMITH et al. (2007: 286–324), CONOLLY and LAKE (2006: 94–102) as well as WHEATLEY and GILLINGS (2002: 114–118).

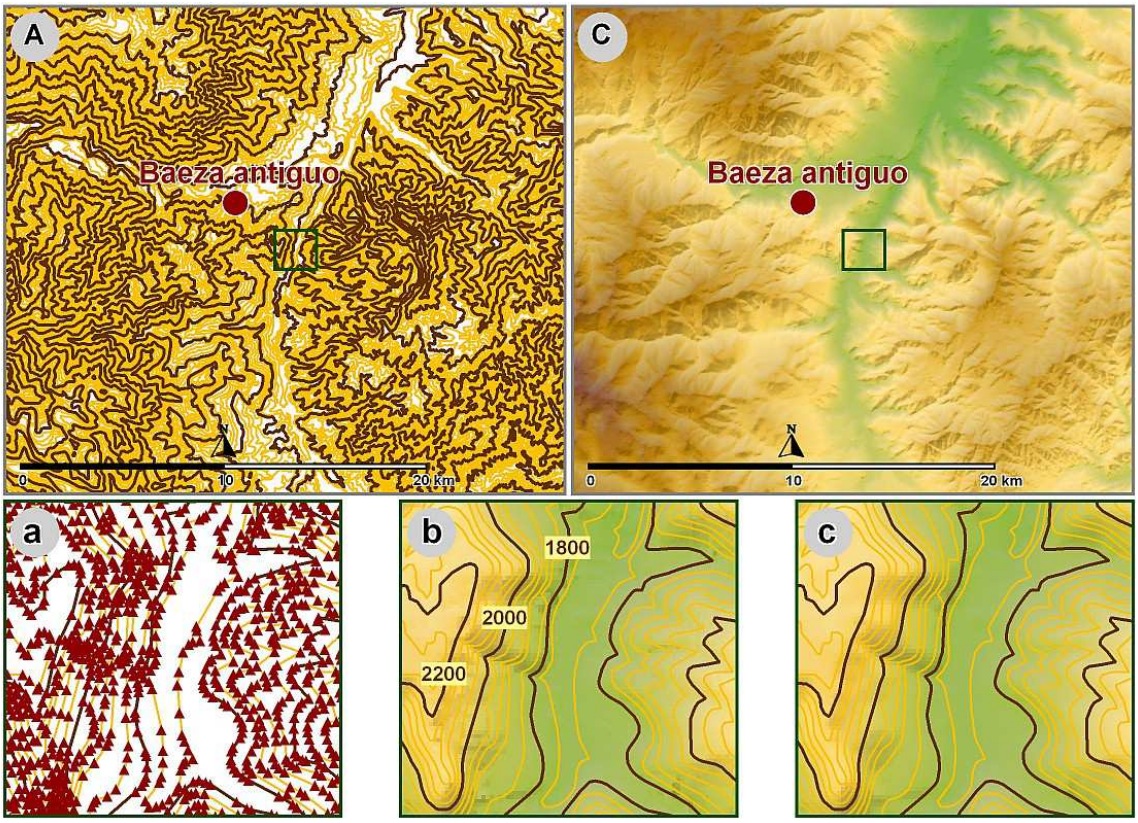

Fig. 7 – (A): Topo50 contour lines, brown lines at 100 m vertical distance, yellow lines at 20 m vertical distance. (C): Filtered Interpolation result. The green rectangle marks the location of the detailed images (a)-(c). (a): contour lines and the nodes (triangles) identified by the Poly-to-Point tool. (b): bilinear interpolation of the nodes. (c): smoothed billinear interpolation, smoothing window size 3, central cell weight 2.

CONOLLY and LAKE (2006: 103–105) describe the problems encountered when using contour data for interpolation and state that “there is no established best practice for converting contour data to a continuous surface” (p. 104). They also list several methods for checking the accuracy of the interpolation result. A non-smooth histogram of elevation values, i.e. ‘spikes’ at the contour line values, indicates a poor interpolation result.

At first, we applied linear triangular interpolation (TIN) of the points extracted by the Poly-to-Point tool to create the Topo50 DEM. This DEM showed the disadvantages discussed in the relevant text books: spikes in the histogram of altitudes, ‘tiger-striping’ of the slope map (CONOLLY & LAKE 2006: 105). The bilinear interpolation outcome suffered less from these unwanted effects, and these could be further reduced by smoothing the DEM using a filter with a 3 x 3 window size and central cell weight 2. Smoothing filters introduce blur and this effect increases with incrementing the window size, i.e. effective resolution is reduced. For this reason we used a small filter window, although the unwanted effects were not completely removed in the Topo50 DEM created this way. Fig. 7 shows the contour lines (A), the final interpolation result (C) and illustrates the process from contour line to filtered interpolation results for a map section (a to c).

Comparison of the DEM elevations

Fig. 8 shows the altitude differences between the void-filled SRTM 1’’ and the Topo50 elevations. To account for vertical bias, the means of the elevations were computed (SRTM 1'': 2504.48, Topo50: 2488.64) resulting in a mean difference of 15.84. With hindsight, using only cells outside the voids and the median instead of the mean is more appropriate.

As mentioned above, the Topo50 elevation data most probably describe a bare Earth DEM, whereas ASTER and SRTM DEMs include the heights of trees. This probably explains some differences shown in Fig. 8: Vegetation cover in the Quijos/Cosanga region is predominantly grassland and forest, with mostly grassland in the lower areas (Fig. 1c). For this reason, the negative difference values in the main river valleys were expected. Fig. 8 also shows that filling large voids by bilinear interpolation in this steep terrain results in large errors of up to 350 m.

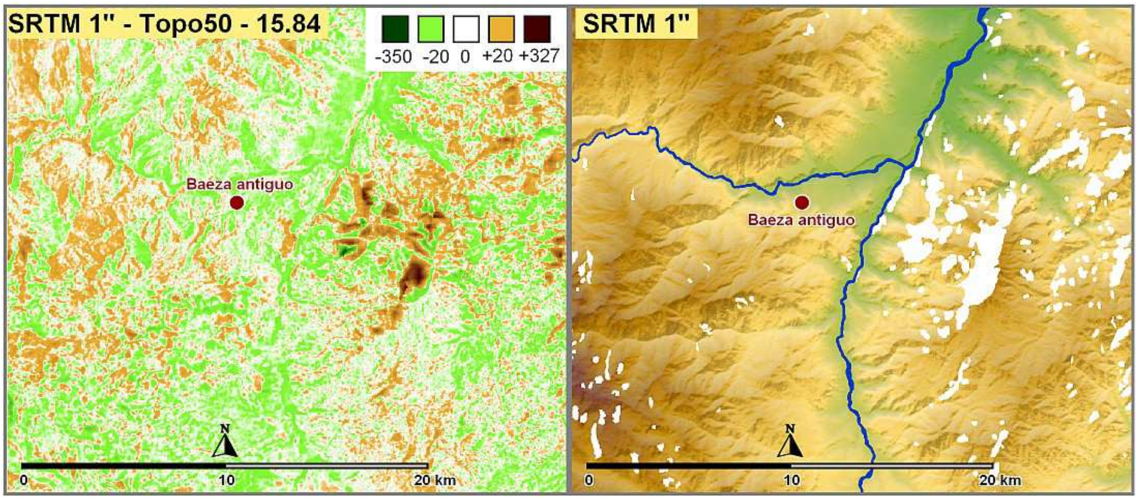

Fig. 8 – Left: Difference between SRTM 1'' and Topo50 elevations: These differences vary between -350 and + 327 m. The differences are large in areas of SRTM 1'' voids (compare to SRTM 1'' DEM data on the right).

Fig. 3 creates the impression that there are no large differences between the four DEMs considered. This impression is supported by the correlation calculation in Tab. 1.

	ASTER	SRTM 3"	SRTM 1"	Topo50
ASTER	1.00000	0.99951	0.99851	0.99796
SRTM 3"		1.00000	0.99922	0.99783
SRTM 1"			1.00000	0.99691
Topo50				1.00000

Tab. 1 – Correlation of the altitudes of the four DEMs considered

Comparison of the DEM slope values

As mentioned above, a slope map showing ‘tiger stripes’, i.e. steep slopes interspersed with plateaus, is a possible result of poor contour line interpolation (CONOLLY & LAKE 2006: 105–106). This effect was clearly visible in the slope map derived from the initial linear TIN interpolation of the Topo50 data but cannot be detected in the slope map based on filtered bilinear interpolation (Fig. 9: Topo50).

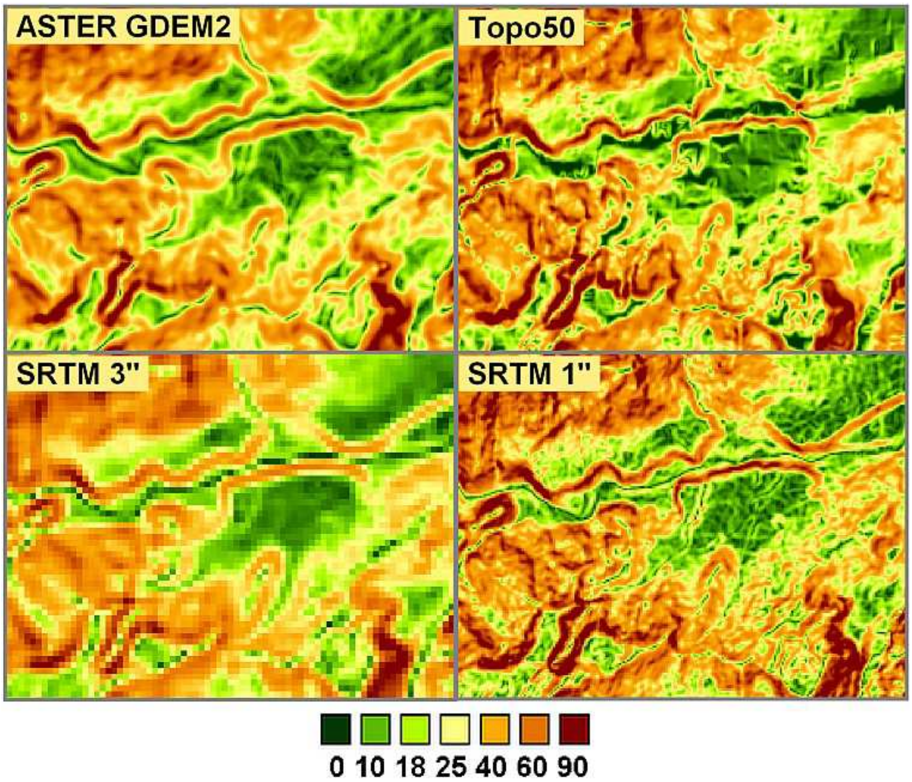

Fig. 9 – Comparison of the slope values (in percent) for the four DEMs considered. The location of the study area section shown here is marked by a green rectangle in Fig. 1d.

In general, the slope maps of the four DEMs show the same trend (Fig. 9), but differences in detail are clearly visible. The correlations of the slope maps (Tab. 2) are significantly lower than those of the elevations (Tab. 1).

	ASTER	SRTM 3''	SRTM 1''	Topo50
ASTER	1.00000	0.80280	0.64598	0.65142
SRTM 3''		1.00000	0.78772	0.74529
SRTM 1''			1.00000	0.60397
Topo50				1.00000

Tab. 2 – Correlation of the slope values for the DEMs considered

DE SMITH, GOODCHILD and LONGLEY (2007: 260) note that slope calculation results depend on effective resolution: “larger grid intervals will result in smoothing of slope values” (see also: HERZOG & POSLUSCHNY 2011; GUTH 2006: fig. 8). Tab. 3 shows this effect by comparing the distribution of slopes for the four DEMs considered: The SRTM 3’’ slopes are in general lower than the SRTM 1’’ slopes.

	5%	1st quartile (25%)	Median (50%)	3rd quartile (75%)
ASTER	1.6	24.8	39.7	58.0
SRTM 3''	1.6	23.7	37.2	53.1
SRTM 1''	1.5	27.6	44.8	64.0
Topo50	3.6	25.7	42.8	62.5

Tab. 3 – Differences in the distribution of the slope values (in percent) for the DEMs considered: A value of 39.7 for the median means that 50% of the slopes are below 39.7%.

GUTH (2006) compares average slope values derived from NED data to those computed from SRTM data. Despite a correlation coefficient of 0.976 a non-linear relationship can be observed in his fig. 5: “SRTM is too steep in flatter topography, and too smooth in steep terrain”. The main reasons are Radar speckle in SRTM data and differences in effective resolution. In Guth’s study, correlations of derived variables were significantly higher after disregarding areas with slopes below 5%. Therefore GUTH (2006) concludes that problems become most acute in low slope areas like floodplains. But the 5% column in Tab. 3 shows that the proportion of areas with slope below 5% is very low in the Quijos/Cosanga study area.

Different algorithms are available to calculate slope values and one of the DEM issues discussed in HERZOG (2014) are these algorithms (see also: CONOLLY & LAKE 2006: 191–192; DE SMITH, GOODCHILD & LONGLEY 2007: 252–253, 259–261; LOCK & POUNCETT 2010; WHEATLEY & GILLINGS 2002: 120–121). This case study relies on slopes calculated by Vertical Mapper (DE SMITH, GOODCHILD & LONGLEY 2007: 260) and did not test other slope calculation algorithms.

Comparison of the DEM aspect values

As with slope estimation, different algorithms are available to calculate aspect values (DE SMITH, GOODCHILD & LONGLEY 2007: 261–264; WHEATLEY & GILLINGS 2002: 120–121). Vertical Mapper was used for the aspect calculations in this study. Aspect is probably not relevant for low slopes and is undefined or zero on completely flat terrain (DE SMITH, GOODCHILD & LONGLEY 2007: 262–263). Therefore the approach of GUTH (2006) mentioned above seems reasonable: For comparing DEMs with respect to derived DEM attributes like aspect, GUTH (2006) uses only grid cells with slopes exceeding 5%. Due to the low percentage of slopes below 5% in our study area (Tab. 3) this additional step was not considered necessary for our study area.

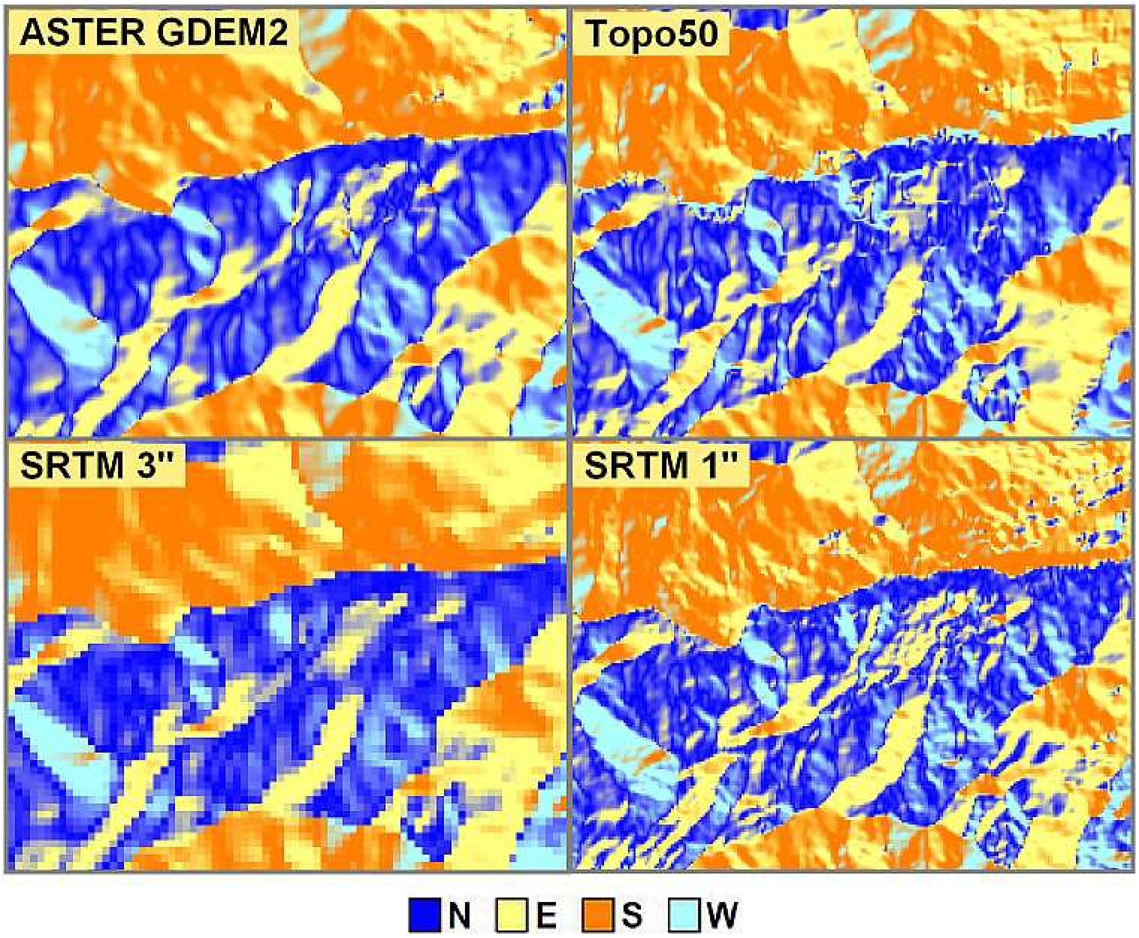

Fig. 10 – Comparison of the aspect values for the four DEMs considered. The location of the study area section shown here is marked by a green rectangle in Fig. 1d.

In general, the aspect maps of the four DEMs show the same trend (Fig. 10), but differences in detail are clearly visible.

	ASTER	SRTM 3"	SRTM 1"	Topo50
ASTER	1.00000	0.84746	0.75395	0.68171
SRTM 3"		1.00000	0.80580	0.70433
SRTM 1"			1.00000	0.62205
Topo50				1.00000

Tab. 4 – Correlation of the cos(aspect) values for the four DEMs considered

Aspect is usually calculated in degrees, with 0° = 360° representing north. WHEATLEY and GILLINGS (2002: 121) mention that aspect "is not readily amenable to statistical treatment" due to the 0° = 360° issue. This can be avoided by computing the cosine of the aspect value thus assigning 1 to north and –1 to south aspects. The correlations of the (cosine-)aspect maps (Tab. 4) are significantly lower than those of the elevations (Tab. 1). In archaeological landscape analysis, often the difference between north and south facing slopes is more important than the difference between slopes facing east or west. For statistical tests of east-west aspects, a sine transformation may be applied.

Comparison of least-cost analysis results

In the last decade, least-cost path analysis and calculating least-cost site catchments have become standard procedures in archaeological GIS computing (e.g., CONOLLY & LAKE 2006: 214–226, 252–256; WHEATLEY & GILLINGS 2002: 151–163; CHAPMAN 2006: 107–111; HERZOG & YÉPEZ 2014; HERZOG & YÉPEZ 2015; LOCK & POUNCETT 2010). Nearly all archaeological least-cost studies include a slope cost component. The Tobler hiking function (TOBLER 1993) is the most popular cost estimator depending on slope. Therefore this cost function was used for the calculations presented in Fig. 11, with averaging the costs in both directions, i.e. the same path is taken for walking back to the initial location. The cost unit applied for these calculations is the time required for walking 1 km on flat terrain. Fig. 11 (left) shows catchments with a cost limit of 4, 8, and 12 cost units.

Radial least-cost paths expend a given cost limit and cover longer distances from the origin than paths to targets in the neighbourhood (HERZOG 2013). The cost limit for the radial paths in Fig. 11 (right) is 12 cost units, and the minimum distance between any two radial path targets was set to 5 km.

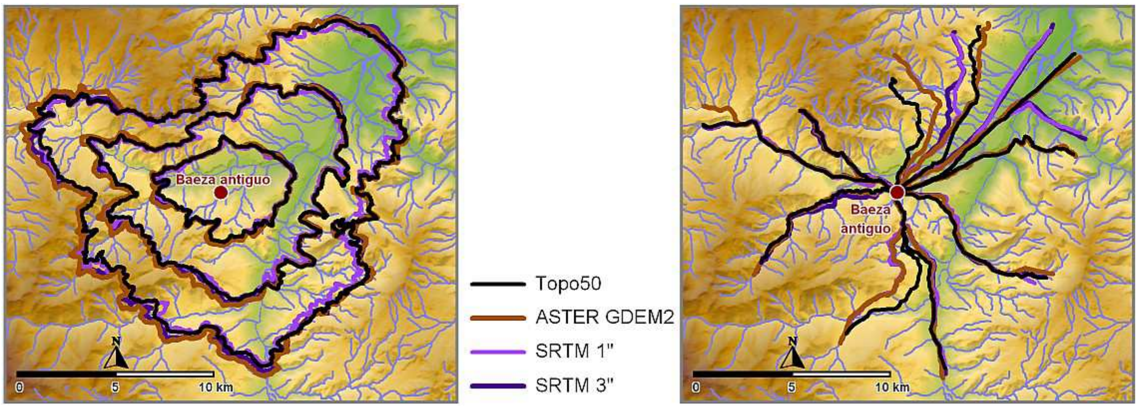

Fig. 11 – Comparison of least-cost analysis results for the four DEMs considered. Left: site catchments. Right: radial least-cost paths

Although the correlations of the slope values of the different DEMs considered are not very high, the slope-dependent catchments by and large coincide. Similarly, most of the LCPs forming the radial networks agree quite well, but there are some exceptions, mainly in north-east directions. So this small test case creates the impression that the results in this steep study area do not depend heavily on the DEM used.

Discussion and Conclusions

In any analysis relying on DEM data, the first step should be the visualization, preferably applying shaded relief because this often reveals DEM errors that have to be fixed before proceeding with the analysis. Voids in satellite data are an issue. Even if a DEM looks quite similar to another DEM of the area and the correlation between the DEMs is very high, substantial local errors may be present (cf. Fig. 8) and the correlation between derived attributes like slope or aspect may be a lot lower. But in our small case study we found that the impact of the DEM selection on the LCP and site catchment calculations is quite low. This is probably due to the fact that the topography in this steep terrain generates unambiguous corridors of movement.

Additional issues in archaeological applications of DEM data are geomorphological processes since the time period considered such as erosion, landslides or flooding. Moreover, the DEMs often show past construction work. This is a most welcome feature for many archaeological Lidar applications. On the negative side is the fact that modern activities like bulk material extraction, and construction work like dams and motor ways often supersede the ancient landscape. Landscape reconstructions are often on a fairly global scale ignoring landscape elements on a lower scale. The impact on the slope and aspect attributes is similar to decreasing the resolution of the DEM. Moreover, the mean error of the reconstructed DEM will probably be larger than with a modern DEM.

For all archaeological studies relying on DEM data we recommend additional tests with slightly modified DEMs (add random noise) to assess the stability of the GIS analysis results (for examples see HERZOG & POSLUSCHNY 2011; HERZOG & YÉPEZ 2015).

With the differences in DEM data, and differences in slope, aspect and LCP calculation algorithms it is extremely difficult to re-produce the results of another research project. A necessary prerequisite is a meticulous recording of the data and algorithms used in any archaeological study involving DEM data.

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List of Tables:

	ASTER	SRTM 3''	SRTM 1''	Topo50
ASTER	1.00000	0.99951	0.99851	0.99796
SRTM 3''		1.00000	0.99922	0.99783
SRTM 1''			1.00000	0.99691
Topo50				1.00000

Tab. 1 – Correlation of the altitudes of the four DEMs considered

	ASTER	SRTM 3''	SRTM 1''	Topo50
ASTER	1.00000	0.80280	0.64598	0.65142
SRTM 3''		1.00000	0.78772	0.74529
SRTM 1''			1.00000	0.60397
Topo50				1.00000

Tab. 2 – Correlation of the slope values for the DEMs considered

	5%	1st quartile (25%)	Median (50%)	3rd quartile (75%)
ASTER	1.6	24.8	39.7	58.0
SRTM 3''	1.6	23.7	37.2	53.1
SRTM 1''	1.5	27.6	44.8	64.0
Topo50	3.6	25.7	42.8	62.5

Tab. 3 – Differences in the distribution of the slope values (in percent) for the DEMs considered: A value of 39.7 for the median means that 50% of the slopes are below 39.7%.

	ASTER	SRTM 3''	SRTM 1''	Topo50
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