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Influence of different relief information sources on the geomorphological characterization of small watersheds

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Abstract: Mathematical models have been widely used to quantify hydrological processes for various practical purposes. These models depend on geomorphological attributes which are derived from relief information represented by Digital Elevation Models (DEM). The objective of this study was to evaluate the influence of relief information sources (ASTER, SRTM-30, SRTM-90, and TOPO) over geomorphological characterization of five Brazilian watersheds. Geoprocessing tools were applied for extraction of the following geomorphological attributes for each DEM: drainage area, perimeter, and watershed slope; length and slope of the main stream; total length of streams; bifurcation, stream length and stream area ratios; and length of the highest order stream. The differences in the values of attributes were calculated in relation to the reference DEM (TOPO). It was found that: i) slope of main stream and bifurcation ratio were the most sensitive parameters regarding the relief information source; ii) flat watersheds were more susceptible to altimetric errors; iii) ASTER did not adequately represent drainage networks for flat watersheds; and iv) the differences in the geomorphological attributes increased as drainage area decreased. The results indicate that DEM may exert influence on the use of hydrological models that depend on geomorphological attributes.

Key words: Advanced Spaceborne Emission and Reflection Radiometer, Digital Elevation Model, geomorphological attributes, Shuttle Radar Topographic Mission, TOPO DEM.

INTRODUCTION

Water is a natural resource indispensable to life and essential for the economic development. However, considerable changes have occurred in watersheds due to anthropogenic actions and rapid population growth, thereby quantitatively and qualitatively influencing hydrological and sedimentological processes (Andrade et al. 2013). Among these factors, climate change resulting from alterations in the atmospheric composition due to anthropogenic actions stands out for its increasing influence on frequency and magnitude of extreme rainfall events (Fang et al. 2018, Mikhailova et al. 2012).

Such phenomenon has led to consequences in terms of flood related hazards, sediment transportation and deposition in watersheds, and collapse of hydraulic structures (Ghumman et al. 2014).

In the context of a changing environment, the ability to simulate hypothetical scenarios with the aid of hydrological modeling techniques plays a fundamental role in the planning, development, and management of water resources. However, the limitation of hydrological data in developing countries (e.g. Brazil) makes the use of more robust hydrological models a challenging task, especially in small

to mid-sized watersheds (Beskow et al. 2013). Therefore, models that require geomorphological attributes for flood modeling have been widely applied, such as the dimensionless unit hydrograph and the triangular unit hydrograph (SCS 1971), the Clark's and Nash's instantaneous unit hydrographs (Clark 1945, Nash 1957), and the geomorphological instantaneous unit hydrograph (GIUH) (Rodriguez-Iturbe & Valdes 1979).

Watershed delineation has been automatically executed in geoprocessing softwares, which significantly reduce the processing time and improve the accuracy of such task (Charrier & Li 2012). For this process, some specific algorithms require Digital Elevation Models (DEMs) to identify drainage divides (Sharma & Tiwari 2014, Elkhrachy 2017). DEMs can be derived from interpolation of points and/or contour lines with known altitudes, extracted from topographic maps and/or survey (TOPO DEM) (Murphy et al. 2008, Neumann et al. 2012, Yue et al. 2015), radar interferometry images, such as those generated by the Shuttle Radar Topographic Mission (SRTM) (Farr et al. 2007), and stereo optical images, such as those obtained by the Advanced Spaceborne Emission and Reflection Radiometer (ASTER) (ASTER GDEM Validation Team 2011). Each source has a different way of acquiring altimetric information and uses specific algorithms for data processing, resulting in differences among the generated DEMs, mainly regarding the spatial resolution.

Depending on the technique used to obtain and process altimetric data, the available DEMs may present errors and impact the geomorphological characterization of watersheds (Li & Wong 2010, Charrier & Li 2012, Kinsey-Henderson & Wilkinson 2013, Becker et al. 2017). Several authors have investigated sources of errors in DEMs (Miliaresis & Paraschou 2005, Bhang et al. 2007, Hvidegaard et al. 2012, Satgé

et al. 2015, Shafique & Van Der Meijde 2015). According to Elkhrachy (2017), three main groups of errors might result in uncertainties in DEMs: i) imaging system's parameters defined during data acquisition (Fisher & Tate 2006, Rodríguez et al. 2006); ii) raw data processing (Li et al. 2013, Chu et al. 2014); and iii) influence of vegetation on the obtained data (Ludwig & Schneider 2006, Bhang et al. 2007).

In the last few years, some authors have investigated the impact of DEMs on the extraction of relief related attributes needed for hydrological modeling, such as watershed area, perimeter (Mispan et al. 2015, Brubacher et al. 2012), and drainage network (Mantelli et al. 2011, Charrier & Li 2012, Las Heras et al. 2012). However, little is known about the influence of other geomorphological attributes commonly used in hydrosedimentological models, such as slope and length of main streams, and the ratios of Horton (1945) and Schumm (1956), which are highly dependent on spatial resolution of DEMs (Mukherjee et al. 2013). Furthermore, studies of such attributes for smaller watersheds are even more rare.

To address the current lack of understanding about the impact of different relief information sources over physiographic characterization and consequent modeling of small watersheds, this study aimed to evaluate the influence of different DEMs (TOPO, SRTM-30, SRTM-90 and ASTER) over the extraction of geomorphological attributes for small watersheds. The methodological procedures were appraised in five experimental watersheds with hydrological monitoring, and the main attributes analyzed were: area and mean slope of watershed, length and slope of the main stream, bifurcation ratio, stream length ratio, stream area ratio, and time of concentration.

MATERIALS AND METHODS

Physiographic characterization of the watersheds

The following Brazilian watersheds were evaluated: Cadeia river watershed (CRW), Caneleira river watershed (CNRW), Jaguara creek watershed (JCW), Lavrinha creek watershed (LCW), and Ellert creek watershed (ECW), whose drainage areas are 121.3, 60.7, 31.8, 6.7, and 0.7 km², and mean slopes are 18.1, 9.8, 7.7, 35.0, and 13.1%, respectively. CRW, CNRW, and ECW are located in Rio Grande do Sul State (RS), whereas JCW and LCW are situated in Minas Gerais State (MG) (Figure 1).

JCW and LCW are, respectively, located in the Upper Grande river region and Mantiqueira Range. LCW is entirely in the Atlantic Forest biome (upper rainforest), whereas JCW is predominantly in the Atlantic Forest biome (semideciduals forest) with transition to the Cerrado biome. According to the Koppen's classification, the climates of JCW and LCW are, respectively, Cwa and Cwb, both characterized as mesothermal with mild and rainy summers and dry winters (Alvares et al. 2014). The remaining watersheds (CRW, CNRW, and ECW) are located in the Pampa biome under Cfa (Alvares et al. 2014), indicating the occurrence of mesothermal climate with hot summers and regular rainfall throughout the year.

In Brazil, the streamflow monitoring is concentrated in large basins, while the monitoring of small watersheds is usually scarce and their data are not publicly available (Beskow et al. 2013), hampering the description of hydrological processes at the small watershed scale in the country. CRW, CNRW, ECW, JCW, and LCW were selected as they have been monitored with temporal discretization compatible with detailed hydrological studies for watersheds with low time of concentration. The availability of hydrological data in subdaily intervals allows the application and validation of methodologies for
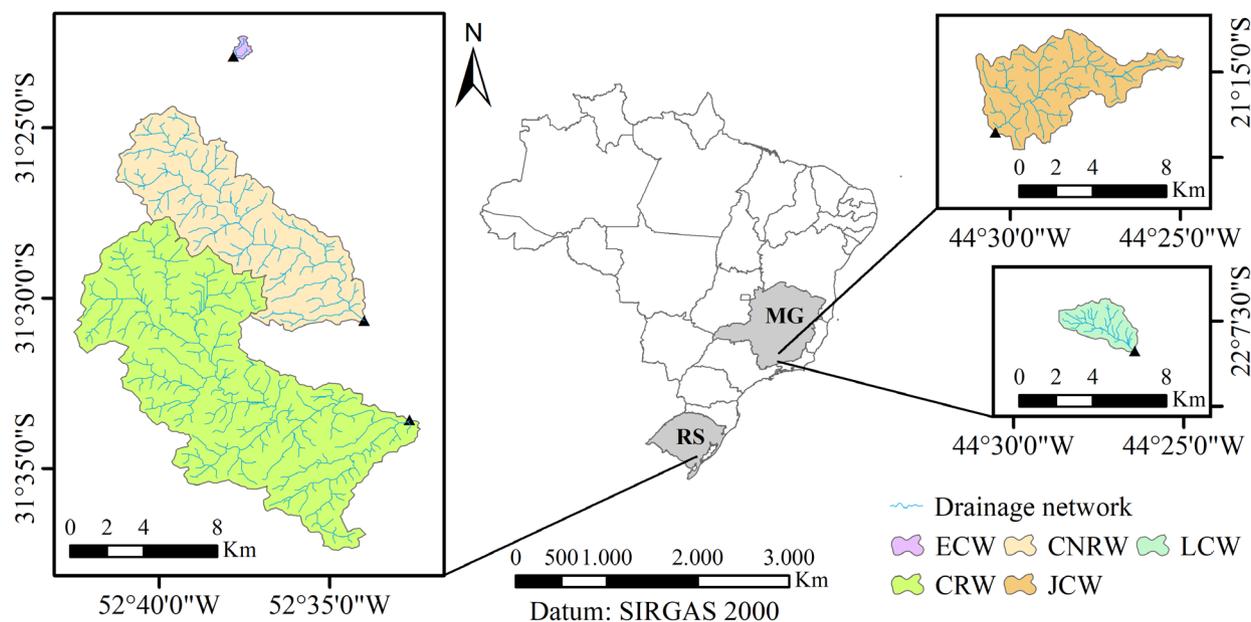

Figure 1. Location of the studied watersheds in Brazil – Cadeia river watershed (CRW), Caneleira river watershed (CNRW) and Ellert creek watershed (ECW) located in Rio Grande do Sul State (RS); Jaguara creek watershed (JCW) and Lavrinha creek watershed (LCW) in Minas Gerais State (MG) – as well as the respective drainage networks and outlets.

estimating streamflow in these watersheds. The Research Group on Hydrology and Hydrological Modeling in Watersheds, at the Federal University of Pelotas, Brazil, is responsible for monitoring the aforementioned watersheds located in RS, and the Research Group on Water and Soil Engineering, at the Federal University of Lavras, Brazil, for the aforementioned watersheds located in MG.

DEMs and watershed delineation

The following relief sources were used to derive the DEMs: SRTM image with spatial resolutions of 30m (SRTM-30 DEM) and 90m (SRTM-90 DEM), 30-meter ASTER image (ASTER DEM), and vectorized topographic maps (TOPO) at the 1:50,000 scale (Hasenack & Weber 2010, IBGE). The 90-meter SRTM images had altitudes corrected and provided by EMBRAPA (Miranda 2005) for the Brazilian territory, while the 30-meter SRTM and ASTER images were obtained from the United States Geological Survey (https:// earthexplorer.usgs.gov/). Specifically for ECW, we also elaborated a DEM (TOPO2) considering 1001 known elevation points surveyed by Veber (2016) using a total station.

The algorithm developed by Hutchinson (1988, 1989) was used to generate the DEM from TOPO (topographic maps) and TOPO2 (topographic points). This algorithm was intended specifically to build hydrologically consistent DEMs using the finite difference iterative technique. These resulting DEMs were then interpolated according to a 25-meter resolution (TOPO DEM) and 1-meter resolution (TOPO2 DEM), following the cartographic accuracy standards proposed by Decree No. 89.817 (BRASIL 1984). The TOPO DEMs were taken as reference for all the watersheds as recommended by Chagas et al. (2010), except for ECW in which the TOPO2 DEM was considered due to its higher resolution. All data were georeferenced using

the UTM cartographic projection system and SIRGAS 2000 datum (Brasil 2005).

DEMs may still have inconsistent data (spurious pixels) even after the aforementioned geoprocessing operations. The filling of these pixels was performed using the algorithm developed by Planchon & Darboux (2001), thereby providing hydrologically consistent DEMs. Their corresponding flow direction maps were then created by means of the D8 algorithm (Jenson & Domingue 1988), which in turn were used to compute the accumulated flow maps (Moore et al. 1991). Finally, the cross sections corresponding to the hydrological monitoring networks were taken as outlets and allocated in the accumulated flow maps in order to delineate the respective watersheds.

Relief characterization and statistical performance measures

The geomorphological attributes extracted from the DEMs for each watershed were: drainage area (A, in km²), perimeter (P, in km), maximum (Y_{MAX}, in m) and minimum (Y_{MIN}, in m) altitudes, and mean slope (S, in %). The drainage area was obtained considering the area of all pixels encompassed within the watershed, whereas, the perimeter was measured along watershed divide. The maximum and minimum altitudes were extracted from the DEMs of each watershed.

To compare the altitudes among the DEMs, TOPO DEM and TOPO2 DEM were generated for 30-meter spatial resolution as well, while SRTM-90 DEM was not used in this analysis. These comparisons were performed as suggested by Thompson et al. (2001) such that each DEM was compared on a pixel basis with the respective reference DEM (TOPO or TOPO2). The mean absolute error (MAE – Equation 1) (Sharma & Tiwari 2014) and the root mean square error (RMSE – Equation 2) (Miliaresis & Paraschou 2005, Shafique & Van Der Meijde 2015) were

considered as statistical measures to assess the DEM performance. For both indices, the closer to zero, the closer to the reference DEM.

Where: n is the number of pixels, y_i and o_i refer to the altitude of the pixel *i* on the analyzed DEM and the reference DEM, respectively.

The slope maps were obtained using the algorithm described in Burrough & McDonell (1998), and the mean values were classified according to the categories proposed by EMBRAPA (1979): flat (0-3%), smooth-undulated (3-8%), undulated (8-20%), strong-undulated (20-45%), mountainous (45-75%), or steep (> 75%).

Hydrography characterization

The hydrography was generated from numerical drainage taking into account thresholds required for stream formation (Ozdemir & Bird 2009), which were established by comparisons to the reference DEM (TOPO or TOPO2). For each watershed, the threshold was computed in terms of area on the reference DEM and was then converted into number of pixels for the other DEMs. The drainage area thresholds used were 0.1 km² for CRW and CNRW, 0.08 km² for JCW and LCW, and 0.03 km² for ECW.

After extracting the drainage network, the total length of streams (ΣL) was obtained. Each resulting drainage network was then hierarchically organized according to the method proposed by Strahler (1952). Afterwards, the length of the highest order stream (L_Ω) and the mean values for the following ratios were computed: bifurcation ratio (R_B) (Equation 3) and stream length ratio (R_L) (Equation 4) proposed by Horton (1945), and stream area ratio (R_A) (Equation 5) proposed by Schumm (1956).

Where: i is the stream order, N refers to the number of streams with order i, L is the mean length of the stream with order i, and

A corresponds to the mean drainage area for order i.

The main stream (L) was identified from information contained in the TOPO and TOPO2, which allowed the extraction of the features representing the drainage networks generated from the other DEMs. Their total lengths (in km) and mean slopes (in %) were then calculated. The method used to calculate the mean slope is known as equivalent slope (S_t), proposed by Taylor & Schwarz (1952). Finally, the time of concentration (t_c) was calculated from the equations suggested by Kirpich (Kirpich 1940) and Ven Te Chow (Chow 1962) for ECW and the remaining watersheds, respectively. The choice of these t_c equations was due to the compatibility between limitations for their applications and the watershed characteristics.

RESULTS AND DISCUSSION

Physiographic characterization of watersheds

The drainage areas obtained from the different DEMs were overestimated in relation to those derived from the reference sources (TOPO or TOPO2). However, they did not differ significantly from each other (Table I). This behavior was also observed by Silva et al. (2015) when assessing SRTM-90 and ASTER DEMs for a watershed in Mato Grosso State, Brazil.

For CRW and CNRW, the drainage areas were overestimated by approximately 12%, while overestimation was substantially lower (~ 2%) for the JCW and LCW. These values obtained from the different DEMs presented a coefficient of variation (CV) equal to 5.5% for the CRW and CNRW, and 1.0% for JCW and LCW. When compared to the reference (TOPO), the ASTER DEM provided relatively better estimates of drainage area for CRW and CNRW, however, it is important to note that the values of this geomorphological attribute derived from DEMs differed from the

Table I. Drainage area (A, in km²) and perimeter (P, in km) obtained from the different DEMs for the studied watersheds.

Watershed		TOPO	SRTM-30	SRTM-90	ASTER	TOPO2
CRW	A	121.3	135.8	135.9	135.7	-
	P	71.9	71.2	65.6	72.8	-
CNRW	A	60.7	67.9	68.0	67.7	-
	P	47.5	46.9	43.4	48.4	-
JCW	A	31.8	32.3	32.1	32.3	-
	P	35.1	34.7	32.5	35.1	-
LCW	A	6.7	6.8	6.9	6.9	-
	P	11.7	11.7	11.1	12.0	-
ECW	A	0.81	0.86	0.88	0.93	0.66
	P	4.00	4.07	4.03	4.03	4.15

reference values. On the other hand, the ASTER DEM resulted in the largest relative differences in the drainage area for JCW (1.8%) and LCW (2.4%). For JCW, the SRTM-90 DEM culminated in the smaller relative difference in the drainage area estimate (1.1%), while the SRTM-30 DEM accounted for the smallest difference (1.7%) for LCW.

The differences found in the drainage areas for CRW and CNRW in relation to the reference values (TOPO) may be attributed to their very flat relief, which makes difficult the automatic watershed delineation (Brubacher et al. 2012). Using SRTM-90 DEM, Chagas et al. (2010) also obtained a considerable difference in drainage area (~ 12%) for the Paraíba do Sul river watershed (Brazil). By analyzing 42 sub-watersheds (from 160.99 to 1,277,415.20 km²) in two large Indian basins, Chavan and Srinivas (2015) also reported that SRTM-90 DEM provided drainage areas greater than ASTER DEM, indicating relative differences from 0.07 to 15.3%.

It should be mentioned that some difficulties were found during ECW delineation, and this can be explained by its smaller drainage area in comparison to the DEMs' spatial resolutions. The values obtained from the DEMs were overestimated in relation to the reference (TOPO2), with differences ranging between 22.8% (TOPO DEM) and 41.9% (ASTER DEM), and CV of 12.7%. The perimeter values (Table I) were underestimated for ECW when considering TOPO2 as reference. Nonetheless, their percentage differences were less than those observed for the drainage areas, corresponding to variations between 2.0% (SRTM-30 DEM) and 3.8% (TOPO DEM), and CV equal to 1.5%.

In general, the DEMs gave underestimated perimeters for the other watersheds such that the CV was 5% for CRW and CNRW, 4% for JCW, and 3% for LCW (Table I). For these watersheds, the ASTER DEM resulted in an overestimation of perimeter values, with percentage differences between 0.2% (JCW) and 2.6% (LCW). Except for JCW, the SRTM-30 DEM presented the smallest

percentage differences in the perimeter estimation for all the watersheds, while the largest percentage differences were obtained from the SRTM-90 DEM. Furthermore, larger percentages were observed in flatter watersheds.

The poor results obtained from the SRTM-90 DEM were expected, since the pixel size did not adequately allow the extraction of some line-type features. This was mainly observed for some small watersheds, where few pixels are sufficient to encompass the entire watershed. Thomas & Prasannakumar (2015) analyzed an Indian watershed with 637.45 km² taking a topographic map (1:50,000 scale) as the reference source. They obtained overestimated perimeter values from the SRTM-90 (18.4%) and ASTER (36%) DEMs. Regarding the drainage areas, these

researchers observed a 0.7% overestimation and a 6% underestimation when deriving such geomorphological attribute from the ASTER DEM and SRTM-90 DEM, respectively. The different behaviors observed by these authors may be assigned to the fact that the watershed analyzed is larger than those of our study, and their study area is located in a mountainous region.

Relief characterization and performance of the different relief sources based on statistical measures

The maximum and minimum altitudes varied considerably among the DEMs (Table II). However, no standard behavior of the DEMs with respect to extreme altitudes was observed. Also, results indicated that neither drainage area nor average

Table II. Minimum altitude (Y_{MIN}, in m), maximum altitude (Y_{MAX}, in m), and mean slope (S, in %) obtained from the different DEMs for the studied watersheds.

Watershed		TOPO	SRTM-30	SRTM-90	ASTER	TOPO2
CRW	Y_{MIN}	40.0	61.0	64.0	64.0	-
	Y_{MAX}	363.0	364.0	355.0	364.0	-
	S	18.1	11.9	11.6	12.6	-
CNRW	Y_{MIN}	100.0	99.0	99.0	102.0	-
	Y_{MAX}	425.0	436.0	434.0	441.0	-
	S	9.8	11.0	10.6	11.6	-
JCW	Y_{MIN}	948.0	954.0	956.0	949.0	-
	Y_{MAX}	1080.0	1086.0	1079.0	1082.0	-
	S	7.7	11.3	11.6	13.5	-
LCW	Y_{MIN}	1160.0	1148.0	1151.0	1144.0	-
	Y_{MAX}	1739.0	1724.0	1723.0	1718.0	-
	S	35.0	37.2	37.0	36.9	-
ECW	Y_{MIN}	280.0	309.0	311.0	308.0	311.0
	Y_{MAX}	381.0	401.0	397.0	401.0	419.0
	S	13.1	10.2	10.6	9.1	11.2

slope explains variation in extreme altitudes. The smallest differences in minimum and maximum altitudes were identified, respectively, for CNRW and CRW (Table II). On the other hand, CRW and ECW had the greatest differences in minimum altitudes and maximum altitudes, respectively. For LCW, minimum and maximum altitudes were underestimated, with mean values of 11 m and 17 m, respectively.

For ECW, with the exception of the TOPO DEM, the DEMs produced good estimates of minimum altitudes, with a maximum difference of 3m. On the contrary, the maximum altitudes were underestimated for this watershed with differences varying from 18m (SRTM-30 and ASTER) to 22m (SRTM-90). The TOPO DEM culminated in differences of 31 m and 38 m for minimum and maximum altitudes, respectively. These findings are in agreement with the MAE and RMSE values, which demonstrated discrepancies in altitudes in relation to the other sources (Figure 2). This behavior can be justified by the underestimation by approximately 20 m in altitude of almost all the pixels when using TOPO DEM, as also verified by Brubacher et al. (2012) in the Sinos river watershed, in Rio Grande do Sul State (Brazil). Similar results

were also observed by Araújo et al. (2014) in a rural property of 0.64 km², in Paranaíta city, Mato Grosso State (Brazil), who obtained a RMSE equal to 9.69 m for the ASTER DEM taking into account the same reference source.

The greatest values of MAE and RMSE were found for flatter watersheds (CRW, CNRW, and JCW) (Figure 2). This behavior of RMSE and MAE values corroborates the finding of Brubacher et al. (2012), who state that, although the greatest differences in altitudes occur in steep areas of the watershed, their frequency is much lower than that observed in flat areas. For all the studied watersheds, the SRTM-30 DEM provided the best performance in estimating altitudes. The largest errors were obtained from the ASTER DEM, except for ECW in which the TOPO DEM had the worst performance. Although the ASTER DEM has the same spatial resolution as the SRTM-30 DEM, Jarihani et al. (2015) highlighted that the former results in greater elevation errors especially in regions covered by vegetation, thereby sometimes limiting its application in hydrological studies.

Considering a 95% confidence interval, the vertical accuracy of the SRTM DEM is 16 m (Farr et al. 2007) and 17.01 for the ASTER DEM (ASTER
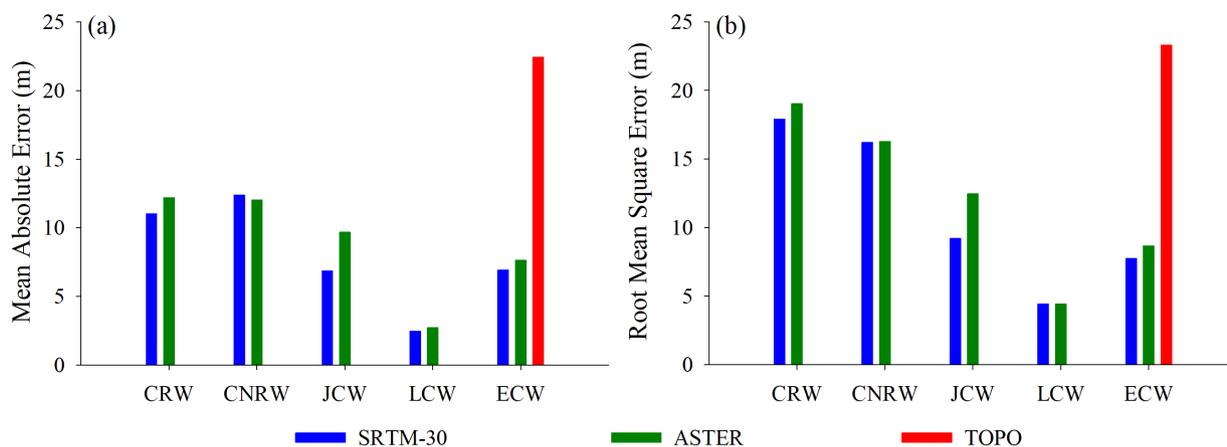

Figure 2. Values of (a) mean absolute error (MAE) and (b) mean square root error (RMSE) which were obtained from the comparison, pixel by pixel, between the altitude of each DEM and the reference altitude (TOPO or TOPO2) for the studied watersheds.

GDEM VALIDATION TEAM 2011). In general, the RMSE values obtained in this study were close or even below the above reference values for the DEMs (Figure 2). The highest values of MAE and RMSE were found for the ASTER DEM, mainly in flat watersheds. This was also identified by Sharma et al. (2014) who reported that ASTER DEM tends to smooth the altitudes in flat areas. Similar results were found by Luana et al. (2015) when comparing ASTER DEM, SRTM 30 DEM and elevation points at 1:50,000 scale in a watershed located in Shandong Province, China. The RMSE values obtained for the SRTM DEMs (Figure 2) are in agreement with those found in literature. In addition, Toutin (2002) stated that a vertical error between 12 m and 20 m is consensus on the accuracy of DEMs generated from Synthetic Aperture Radar (e.g. SRTM). In German, Ludwig & Schneider (2006) validated a SRTM-30 DEM using aerial photographs (1:25,000 scale) as reference for two watersheds with drainage areas of 145km^2 and 199km^2 and obtained a RMSE of 22.96m and 9.85m for steep and flat watersheds, respectively.

Regardless the analyzed DEM, almost all the watersheds were classified as undulating (8 – 20%). Only LCW was categorized as strong-undulating (20-45%) (Table II). It is worthwhile to mention that ECW had a different slope classification when applying SRTM-90 DEM. All the DEMs resulted in underestimated mean slopes for ECW such that ASTER DEM and SRTM-90 DEM gave relative differences of 39.1% and 64.2%, respectively. For the other watersheds, the SRTM-90 DEM provided underestimated mean slopes, while this geomorphological attribute was overestimated when it was derived from the ASTER and SRTM-30 DEMs. In general, the ASTER DEM had overestimations greater than the SRTM-30 DEM. The lowest CV was identified for the LCW (8.6%), whereas, the highest CV was calculated for the ECW (45.9%). For the other watersheds,

the CV values were 13.5%, 14.5%, and 14.9% for CRW, JCW, and CNRW, respectively.

Hydrography characterization

The total length of streams was underestimated in LCW and overestimated in CNRW and ECW (Table III). These estimations were changeable for the other watersheds in function of the used DEM. These results agree with those described by Brubacher et al. (2012) in that the largest differences associated with stream length occurred in flatter watersheds due to the determination of nonexistent streams. The ΣL was better represented when the streams were extracted from the TOPO DEM for ECW, SRTM-90 DEM for CRW and CNRW, and SRTM-30 DEM for JCW and LCW. Mantelli et al. (2011) found similar results by comparing drainage networks generated from the ASTER, SRTM-90 and TOPO DEMs for a region in São Paulo State (Brazil).

Overall, the SRTM-90 DEM culminated in the shortest total lengths, suggesting that its spatial resolution makes it difficult to adequately represent shorter streams. Thomas et al. (2014) also verified this pattern in two South Indian watersheds after comparing TOPO with 20-m contours, ASTER and SRTM-90 DEMs, and 250-m GMTED (Global Multi-resolution Terrain Elevation Data). The SRTM-30 DEM presented ΣL values closer to the references, while the ASTER DEM resulted in both longer streams and more dense drainage networks. Except for LCW, the ΣL overestimations observed from the ASTER DEM corroborate the findings of Mantelli et al. (2011) and Sharma et al. (2014). They reported that ASTER DEM was likely susceptible to smooth topographic variations, tending to generate many nonexistent streams. According to Li et al. (2013), no attempt was made to identify, delineate, and edit water bodies during the ASTER data processing, therefore, this is a possible reason for the unsatisfactory representation of drainage network.

Table III. Total length of streams (ΣL, in km), length (L, in km) and slope (S_t, in %) of the main stream, and time of concentration (t_c, in hours) obtained from the different DEMs for the studied watersheds

Watershed		TOPO	SRTM-30	SRTM-90	ASTER	TOPO2
CRW	ΣL	228.8	248.2	216.2	252.5	-
	L	23.2	23.9	23.8	23.8	-
	S_t	0.66	0.61	0.55	0.54	-
	$t_c{}^1$	7.5	7.8	8.1	8.1	
CNRW	ΣL	115.8	145.7	124.9	150.1	-
	L	20.0	21.2	21.0	20.8	-
	S_t	0.90	0.97	0.91	0.98	-
	$t_c{}^1$	6.2	6.3	6.4	6.2	
JCW	ΣL	66.4	65.8	56.6	77.2	-
	L	12.3	11.9	12.4	11.7	-
	S_t	0.28	0.31	0.38	0.45	-
	$t_c{}^1$	6.6	6.2	6.0	5.5	
LCW	ΣL	19.0	17.3	15.8	16.9	-
	L	4.5	4.3	4.5	4.8	-
	S_t	4.16	3.12	3.05	2.12	-
	$t_c{}^1$	1.4	1.5	1.6	1.9	
ECW	ΣL	2.38	2.83	2.49	3.57	2.32
	L	1.25	1.27	1.19	1.29	1.30
	S_t	4.18	4.96	4.93	3.95	3.86
	$t_c{}^2$	0.22	0.24	0.23	0.25	0.25

$t_c{}^1$ – Chow (1962); $t_c{}^2$ – Kirpich (1940).

Regarding L (Table III), the best values were obtained for CRW, with CV of 1.3% among DEMs and the most discrepant values were found for LCW (variation of 5%). The most accurate L was identified from the ASTER DEM and SRTM-90 DEM for ECW and the other watersheds, respectively. The SRTM-30 DEM, ASTER DEM, and SRTM-90 DEM, respectively, caused the largest differences in L for CRW and CNRW, JCW and LCW, and ECW.

With respect to S_t (Table III), LCW and ECW had the greatest values – average of 3.11% and 4.37%, and CV of 27% and 11%, respectively. On the contrary, JCW and CRW presented the lowest S_t values (0.36% and 0.59%) and CV equal to 21% and 9%. Although the smallest average S_t value has not been observed for CNRW (0.94%), this watershed had the lowest CV (4.2%) associated with S_t. For CRW and LCW, all DEMs resulted in underestimated S_t values, with relative differences ranging from 8 to 18% and from 25 to 49%, respectively. For the other watersheds, all DEMs overestimated S_t with maximum relative differences of 9%, 61%, and 29% for CNRW, JCW, and ECW, respectively. With the exception of ECW, the largest relative differences occurred when S_t was calculated from the ASTER DEM. On the other

hand, the smallest differences were detected in the cases of S_t extracted from the SRTM-90 DEM for CNRW and SRTM-30 DEM for CRW, JCW, and LCW. For ECW, the ASTER DEM gave the best S_t estimate, while the SRTM-30 DEM provided the worst estimation.

Regarding t_c (Table III), the highest values were obtained for CRW ($t_{c,mean}$ = 7.9 h) and the lowest t_c for ECW ($t_{c,mean}$ = 12 min), whereas, both CNRW and JCW presented $t_{c,mean}$ of 6.1 h, and LCW had a $t_{c,mean}$ of 1.6 h. Based on the t_c values computed from the reference DEMs, the smallest variations in t_c occurred for ECW (0.02 h) and CNRW (0.2 h). For JCW, CRW, and LCW, the differences in t_c were equal to 1.1, 0.6, and 0.4 h, respectively. The largest differences in their values were verified from the TOPO DEM for the ECW, SRTM-90 DEM for the CNRW, and ASTER DEM for the remaining watersheds. The lowest relative differences were determined for CNRW and CRW, with mean values equal to 1.6 and 6.8%, respectively. These values were higher for JCW (10.6%) and LCW (16.2%), whereas, ECW presented mean values of relative differences equal to 1.3% for SRTM-30 and ASTER DEMs, and 8.9% for TOPO and SRTM-90 DEMs.

Rawat & Mishra (2016) analyzed t_c of the Moolbari Experimental Watershed in India based on both a lumped approach (13.77 km²) and a spatial discretization by subwatersheds (21 subwatersheds with areas between 0.09 and 2.11 km²). The authors considered the TOPO (1:25,000 scale) as reference and appraised the DEMs derived from ASTER, SRTM-90, and SRTM-30, resulting in t_c relative differences of 0.99%, 1.74%, and 3.97%, respectively. When t_c was computed at the subwatershed scale, the relative differences were close to 25%. The values obtained in our study for ECW corroborate those found by Rawat & Mishra (2016) for the subwatershed approach. It should be mentioned that the Kirpich's equation (Kirpich 1940) was used for ECW as well as Moolbari Experimental Watershed. The relative

differences computed for the t_c values of CRW and CNRW are in agreement with those obtained by Thomas & Prassannakumar (2015). These authors noticed that SRTM-90 and ASTER DEMs resulted in differences of 3% and 5.1%, respectively, when compared to the reference t_c equal to 6.66 h. Ghumman et al. (2017) also verified differences in the t_c values calculated from interpolated topographic maps represented by 30m and 90m cells. The authors obtained relative difference of 7.7% between t_c values for a subwatershed (202 km²) located in the Kala Chitta Range (Pakistan).

According to the classification of Strahler (1952) and considering the reference source for relief, LCW and ECW were classified as 3rd order, JCW as 4th order, and CRW as 5th order (Figure 3). Only for CNRW, the DEMs generated diverging orders, i.e. SRTM-90 DEM generated streams of 4th order and the other DEMs produced 5th order streams.

The number of segments and stream orders approximately had a linear relationship, except for ECW (Figure 3). The R_B and R_L values (Table IV) were similar to those observed by Thomas et al. (2014) in two Indian watersheds, with drainage areas of 271.75 and 288.53 km². According to Horton (1945), R_B has a relationship better defined with stream order than R_L. The author affirms that uniform successive orders of river bifurcation are naturally developed regardless of geological and pedological controls, while lengths can be limited by these control factors, such as watershed boundaries.

For each watershed, the values obtained for the ratios proposed by Horton (1945) and Schumm (1956) varied widely among the DEMs (Table IV). Rodriguez-Iturbe &Valdés (1979) noted that R_B, R_L, and R_A generally fall within the ranges of 3-5, 1.5-3.5, and 3-6, respectively. The R_B, R_L, and R_A values found for the watersheds in the present study were mostly within these limits. However, it is important to highlight that there is still a
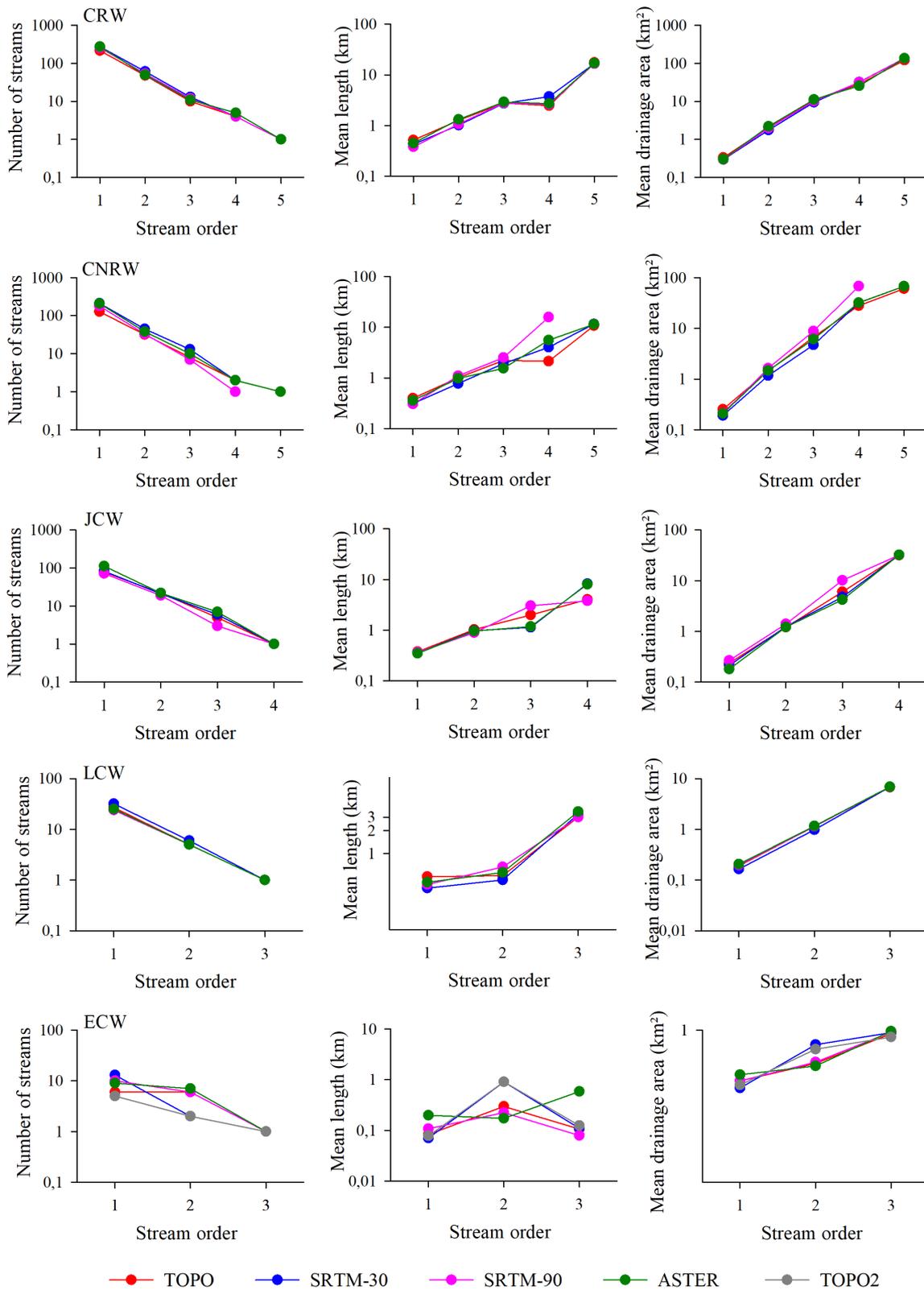
Figure 3. Number, mean length, and mean drainage area for each stream order classified according to Strahler (1952), considering different DEMs.

lack of studies in watersheds with mean slope ranging from 0 to 20% (flat to undulated), thereby reinforcing the importance of the present study.

Thomas et al. (2014) assessed two Indian watersheds using four different DEMs (20-m TOPO, ASTER, SRTM-90, and 250-m GMTED) with images resampled to 90 m for characterization of the Horton's ratios and other relief attributes.

Both watersheds presented order 4. R_B and R_L values derived from the SRTM-90 and ASTER DEMs were similar to those found for CRW, CNRW, and JCW with the same relief sources.

R_A values obtained for LCW (Table IV) are in agreement with the results published by Rawat et al. (2016) in India and by Zakizadeh & Malekinezhad (2015) in Iran. In both studies, the

Table IV. Bifurcation ratio (R_B), stream length ratio (R_L), stream area ratio (R_A), and length of the highest order stream (L_Ω, in km), obtained from different DEMs for the studied watersheds

Watershed		TOPO	SRTM-30	SRTM-90	ASTER	TOPO2
CRW	R_B	3.96	4.12	4.08	4.31	-
	R_L	3.16	2.71	3.18	3.09	-
	R_A	4.59	4.74	4.79	4.98	-
	L_Ω	17.58	16.76	16.67	17.03	-
CNRW	R_B	3.50	4.17	5.72	4.08	-
	R_L	2.68	2.48	4.05	2.49	-
	R_A	4.17	4.76	6.94	4.63	-
	L_Ω	10.75	11.55	15.80	11.43	-
JCW	R_B	4.33	4.48	4.37	5.08	-
	R_L	2.24	3.72	2.36	3.60	-
	R_A	5.13	5.48	5.23	5.96	-
	L_Ω	4.05	8.27	3.80	8.07	-
LCW	R_B	5.20	5.67	4.90	5.00	-
	R_L	3.45	4.31	3.11	3.83	-
	R_A	5.96	6.48	5.90	5.80	-
	L	3.01	3.30	3.00	3.55	-
ECW	R_B	3.50	4.25	3.83	4.14	2.25
	R_L	1.96	6.47	1.22	2.12	5.88
	R_A	4.50	7.99	4.65	4.97	5.37
	L_Ω	0.11	0.11	0.08	0.58	0.12

watersheds analyzed were classified as strong-undulated (20-45%) and had orders 4 and 5 when using SRTM-90 DEM and TOPO (1:50,000 scale), respectively.

For the CRW and CNRW, lower R_A values and higher R_B values were possibly related to the denser formation of 1st order streams in flat areas, in agreement with Brubacher et al. (2012), and Souza & Almeida (2014). Schumm (1956) affirms that the behavior of R_A values establishes one of the main indications for drainage system formation, in other words, the minimum area necessary for the development of a drainage channel. According to Chopra et al. (2005), high values obtained for R_B indicate that streamflow and other external forces contribute to the formation of the drainage network in the studied watersheds, otherwise it would be greatly controlled by geological structures. In addition, the R_B values found in the present study suggest a high degree of branching of the drainage network, thus indicating a tendency for flood peaks.

By evaluating a 5th order watershed with smooth-undulated slope, Supraja et al. (2016) determined R_L values close to those reported in our study for the flat watersheds (Table IV). Alemngus & Mathur (2014) also obtained R_L similar values in a watershed in Eritrea, Eastern Africa, whose area and mean slope values are comparable to those of CRW (Table IV). However, R_A and R_L values found by Alemngus & Mathur (2014) differed from the corresponding values for CRW (Table IV), probably due to the difference in drainage orders (5th and 3rd for CRW and watershed of that study, respectively). Studying the Iranian Kasilian river watershed of order 4 and drainage area equal to 67.5 km², Adib et al. (2010) obtained R_B and R_L values equal to 3.79 and 2.43, respectively. The characteristics of the watershed appraised by these authors are similar to those of CNRW, and the values obtained for Horton's ratios from TOPO at 1:25,000 scale go

along with those obtained for CNRW from TOPO at the 1:50,000 scale.

L_Ω values followed the same behavior observed for L, with greater values for CRW and lower values for ECW (Table IV). With respect to L_Ω values, CRW presented the smallest CV (2.4%) and ECW had the highest CV (~ 107%). The high CV value determined for ECW may be explained by the fact that ASTER DEM resulted in a L_Ω measuring 0.58 km, i.e. a much longer stream compared to the L_Ω derived from the other DEMs. Values of 71.9%, 59.6%, 50.1%, 71.2%, and 15.9% were obtained for L_Ω/L for CRW, CNRW, JCW, LCW, and ECW, respectively. Due to the lack of data, L and L_Ω are usually considered synonymous during hydrological modeling. Thus, based on the relationships obtained between them, several misconceptions could be introduced in the hydrological simulation, leading to sub or overestimation of design streamflows.

Considering the attributes variations among watersheds, one can infer that the flatter and larger watersheds resulted in smaller CV values. In general, the attributes that presented the largest CV values were the L_Ω and the R_L, with mean values of 35.3% and 28.6%, respectively. The smallest CV values were observed for Y_{MAX}, L, and P, with mean values of 1.4%, 3.1%, and 3.5%, respectively. ECW presented the largest CV for attributes, especially for L_Ω (106.8%), R_L (69.4%), and R_A (26.1%) ratios.

CONCLUSIONS

Different relief information sources (DEMs) and spatial resolutions result in different values for the characterization of some geomorphological attributes that are important for hydrological applications in small watersheds with contrasting physiographic characteristics.

Regardless physiographic characteristics of the study watersheds, S_t and Horton and Shumm's ratios were the most affected attributes by the source and pixel size of the relief information. It is expected that these differences will impact hydrological models, such as dimensionless and triangular UHs and the geomorphological approaches for Nash and Clark IUHs.

Flat watersheds were more susceptible to altimetric errors which increase as the drainage area decreases. The study watershed characterized by the steepest relief (LCW) accounted for the lowest differences between the values for each geomorphological attribute derived from the DEMs.

With respect to the drainage network delineation, ASTER DEM generated the worst results, as it tended to generate more streams than the existing ones. The SRTM and ASTER DEMs resulted in approximate values for geomorphological attributes, however, these values were different from those obtained from the TOPO DEM. The DEMs had satisfactory performance in the characterization of all watersheds but the ECW. In small watersheds, the coarse spatial resolutions of the DEMs hinder their delimitation and geomorphological characterization, as it could be observed for Ellert creek watershed (ECW).

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