Estimation of Main Channel Length From Basin Length for Selected Small Watersheds in Texas Using 10- and 30-Meter Digital Elevation Models

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The statistical relation between main channel length (MCL) and basin length (BLENG) was investigated for 96 small watersheds in central Texas. MCL and BLENG were calculated using 10- and 30-meter digital elevation models (DEM). Because of a possible curvilinear relation between MCL and BLENG for watersheds with BLENG greater than about 16 kilometers, linear equations were developed for watersheds with BLENG less than 16 kilometers. The equation for the 10-meter DEM-derived characteristics based on 54 stations is MCL equals 1.21 times BLENG; and the equation for the 30-meter DEM-derived characteristics based on 74 stations is MCL equals 1.16 times BLENG. Therefore, the equation to rapidly estimate MCL from BLENG for small watersheds is MCL equals 1.2 times BLENG. The limited difference between the equations suggests that accuracy of some small watershed characteristics is not greatly increased through the use of 10-meter DEMs. *Key Words: digital elevation models; geospatial analysis; morphometry; watershed characteristics.*

Introduction

Watershed or basin characteristics are important parameters in many regional statistical studies of hydrology (Yen and Lee 1997; Jena and

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Tiwari 2006). Some examples of watershed characteristics are (contributing) drainage area, channel slope, and basin shape factor. Watershed characteristics commonly are used to parameterize hydrostatologic models for surface-water applications, including equations to estimate peak discharge, streamflow magnitude and frequency, low-flow characteristics, and percentage of zero flow days. Background, discussion, and application of hydrostatologic models are found in many hydrologic textbooks such as Chow et al. (1988), Maidment (1992), Haan et al. (1994), Dingman (2002), and McCuen (2005). These models are important in the design of infrastructure adjacent to stream channels, aquatic habitat applications, and floodplain delineation, among other applications. Example hydrostatologic studies for Texas watersheds include Slade et al. (1995), Asquith et al. (1996), Raines and Asquith (1997), Asquith and Slade (1999), Lanning-Rush (2000), and Asquith (2001).

A variety of hydrostatologic models, such as regional regression equations by Asquith and Slade (1997), often explicitly or implicitly use main channel length (MCL), a measure of length scale of a watershed that represents the longest flow path of water from the watershed boundary to the outlet. MCL can be time consuming or technically complex to determine for some model users, including those with limited access to geographic information systems (GIS). As an expedient alternative, some users apply rule-of-thumb practice to estimate MCL such as multiplying basin length (BLENG) by 1.6, a value that accounts for channel sinuosity by assuming a semi-circular planform morphology. BLENG is an alternative measure of watershed length scale and is the sum length of a small number (compared to MCL) of sequential line segments following the geometric centerline of the watershed from the drainage divide to the outlet. BLENG can be rapidly measured using manual methods, such as an opsometer or ruler.

The U.S. Geological Survey (USGS), in cooperation with the Texas Department of Transportation (TxDOT), conducted a study of the statistical relation between main channel length (MCL) and basin length (BLENG) for 96 selected small (less than about 50 square kilometers) watersheds in north- and south-central Texas (Figure 1). The study was conducted to investigate the potential for developing a reliable method by which MCL of a watershed could be estimated rapidly from a BLENG. A secondary objective was afforded, by nature of the methodology, to interpret advantages in accuracy by using either 10- or 30-meter digital elevation models (DEMs), resolutions common for contemporary DEMs.

The watersheds of the study are concentrated in the Austin, Dallas, Fort Worth, and San Antonio metropolitan areas. All of the watersheds have USGS streamflow-gaging stations at their outlets. Most of the study watersheds occur in areas of gently rolling terrain, but some are located north and west of the Balcones Escarpment, a line of low hills that separates the Edwards Plateau from the Gulf Coastal Plain physiographic regions in the Austin-San Antonio area (Figure 1). Drainage areas of the watersheds range from 0.821 to 433 square kilometers with an approximate median value of 18 square kilometers. Drainage patterns of the watersheds are dendritic or parallel. Altitudes range from 70 to 597 meters above NGVD88, and intra-watershed relief varies from about 15 to 305 meters. The largest values of relief are associated with relatively large watersheds, with a few exceptions. Dimensionless main channel slopes range from 0.0016 to 0.0158.

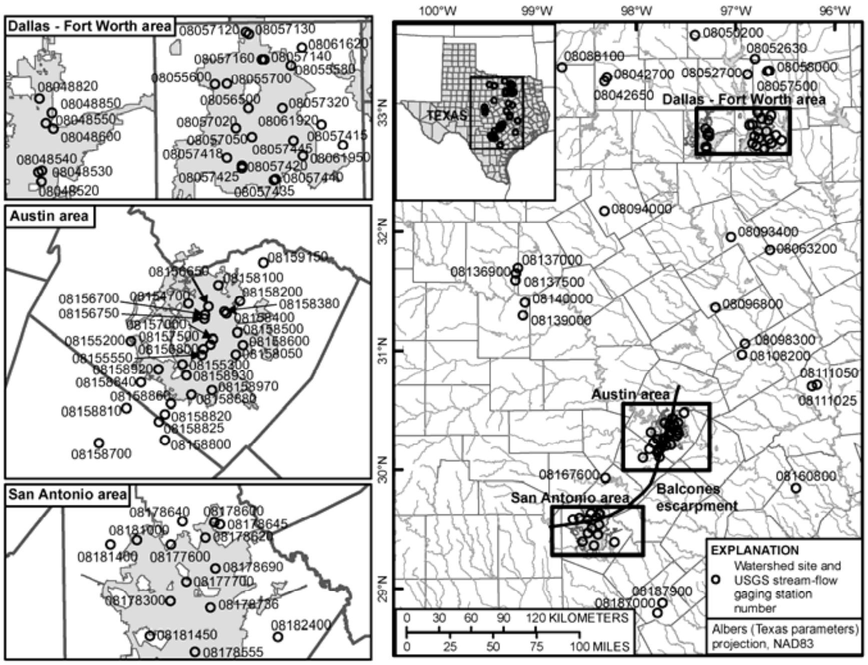

Figure 1. Locations of U.S. Geologic Survey stream-flow gauging stations used in study.

Previous Research

The quantitative relation between MCL and BLENG is considered a morphometric problem. Morphometry is the measurement and mathematical analysis of landforms and is used to establish quantitative relations between geomorphic processes and landforms (Bloom 1998). For watersheds and stream channels, morphometry relies on a suite of measurable parameters. These include, but are not limited to, drainage area, basin shape, basin length, basin slope, stream order, channel length, and channel slope. Some of these parameters are relatively easy to measure or determine, and others require laborious and subjective techniques. For example, MCL and valley axis length must be separately measured to determine sinuosity, the dimensionless ratio of MCL to valley axis length (Brice 1964).

Sinuosity, by definition, is inherently different than the ratio of MCL to BLENG, as valley axis length typically follows a different path than BLENG because watersheds usually are not symmetrical. The similar approach for computation of the two ratios, however, permits analogy and the term "sinuosity," as used in discussion below, can be considered analogous to the ratio of MCL to BLENG.

Sinuosity has been used to classify channel types (Leopold and Wolman 1957; Rosgen 1994), characterize channel symmetry (Brice 1964), establish morphometric relations (Miller 1988), and analyze river meanders (Langbein and Leopold 1966; Brice 1974; Ferguson 1977). Values of sinuosity for natural channels commonly range from 1.1 to 2.0 (Leopold and Wolman 1960). Brice (1964) comments on scale dependency in computations of sinuosity, such that restriction to particular reaches might result in values not representative of the larger system. Langbein and Leopold (1966) consider sinuosity with respect to minimum variance of values characterizing river meander geometry. Sinuosity (k) for symmetrical meandering channels is related to the maximum meander angle relative to the general channel orientation (ω) by:

$$\omega \text{ (radians)} = 2.2\sqrt{((k-1)/k)}.$$

A conceptualization of the linkage between sinuosity and MCL and BLENG is informative. The relation between MCL and BLENG can be represented by a simple geometric argument. A generalized watershed with a main channel defined by a sequence of semicircles is depicted in Figure 2. Each semicircle has a unit diameter. The MCL for this watershed is 3 times $\pi/2$ units. The BLENG is 3 units. The ratio of MCL to BLENG, or sinuosity, is $\pi/2$ or about 1.6. Other geometric arrangements of watersheds could be hypothesized. Relative to many of the watersheds considered in this study, the sinuosity depicted in Figure 2 is excessive. Therefore, the ratio 1.6 is larger than many of the sinuosities computed from measured MCLs and BLENGs of the study watersheds.

For purposes of this study, the quantitative relation between MCL and BLENG is dependent on the horizontal accuracy of the DEM. Previous research, however, is not conclusive in showing that accuracy of watershed models is considerably improved by increasing DEM resolution. For example, Chaplot (2005) shows that increasing the resolution of a DEM from 50 meters to 20 meters does not improve model estimates of runoff, sediment loads, or nutrient loads in a small agricultural watershed. Likewise, Cochrane and Flanagan (2005) show that erosion prediction models are not improved by increasing the resolution of DEMs, unless the coarseness of the DEM affects original watershed delineation. Wu et al. (2005), however, show that estima

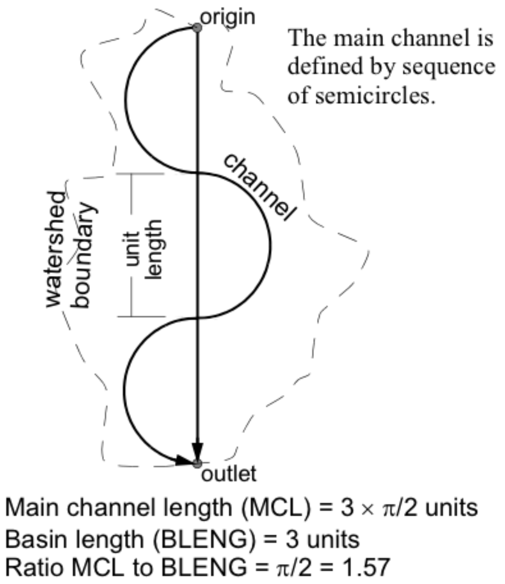

Figure 2. Schematic showing a simple geometric illustration of the relation between main channel length and basin length.

tions of soil loss are considerably affected by resampling an original 10-meter DEM to greater grid sizes. The studies mentioned above address different hydrologic models, but their conclusions warrant a brief examination of the influence of DEM horizontal accuracy on the relation of MCL and BLENG.

GIS Methods

Computer technology and GIS facilitate the generation of watershed boundaries and other watershed characteristics (Figure 3). An algorithm was developed (B.D. Reece, U.S. Geological Survey, February 2005, written communication) within GIS to compute characteristics for each of the selected watersheds using DEMs of 10- and 30-meter horizontal resolutions. The watershed characteristics for this investigation are drainage area, MCL, and BLENG. Drainage area (DA) was computed using the vector polygon of the watershed boundary. The polygon was derived from extensive processing of the foundational 10-meter and 30-meter DEM data sets (U.S. Geological Survey 2005). Conceptually, the line segments defining BLENG are more influenced by watershed shape and the line segments defining MCL are more influenced by the actual water flow path; the two segment sets are quasi coincident.

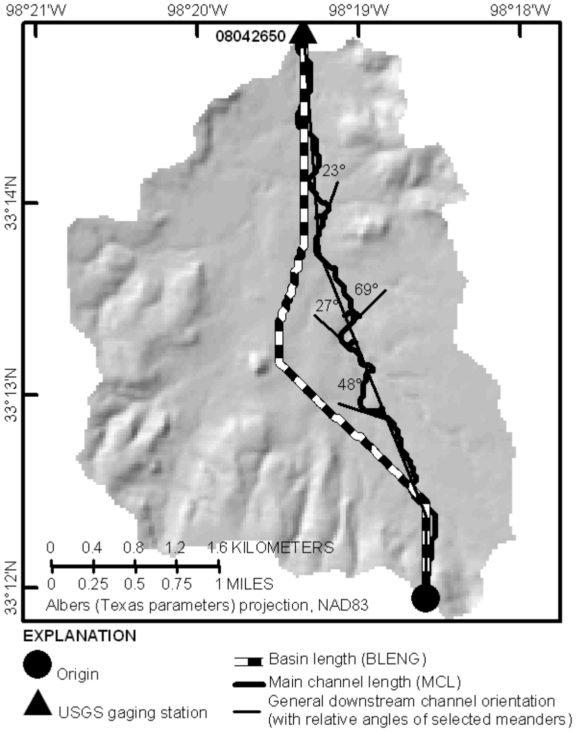

Figure 3. North Creek Subwatershed 28A near Jermyn, Texas (08042650), a representative watershed in this study.

The values for DA, BLENG, and MCL used in this study were derived entirely from digital processing. However, manual computation (results not reported here) substantiated the digitally derived watershed characteristics.

Results

Before the relation between MCL and BLENG for the selected watersheds was formally derived, an evaluation of the relation between DA and BLENG was made to determine whether watershed scale as measured by DA is important. Graphs depicting the relation between DA and BLENG for the selected watersheds are shown in Figures 4 and 5 for the 10-meter DEM data and the 30-meter DEM data, respectively. Most of the watersheds have DA less than about 50 square kilometers. Watersheds less than about 50 square kilometers are considered small. By inspection of Figures 4 and 5, a 50-square-kilometer watershed has an equivalent BLENG of about 16 kilometers.

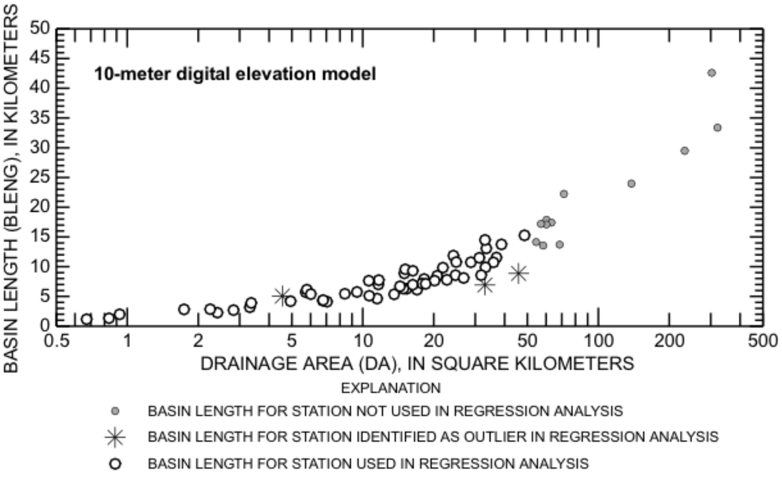

Figure 4. Relation between 10-meter DEM derived drainage area and basin length for 70 (10-meter DEM) stations.

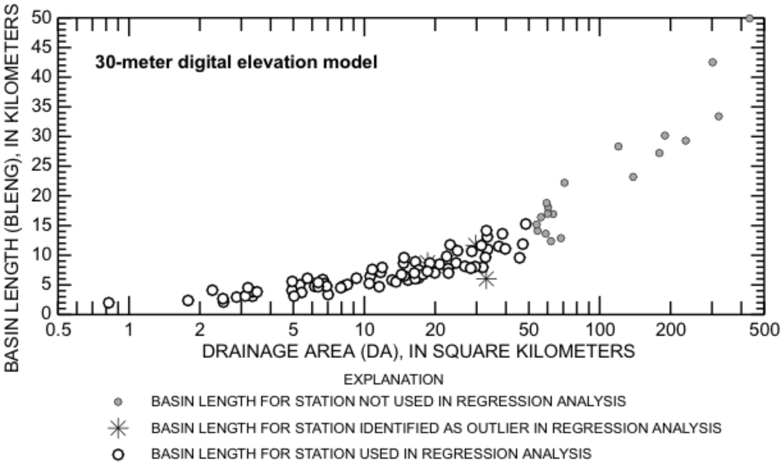

Figure 5. Relation between 30-meter DEM derived drainage area and basin length for 96 (30-meter DEM) stations.

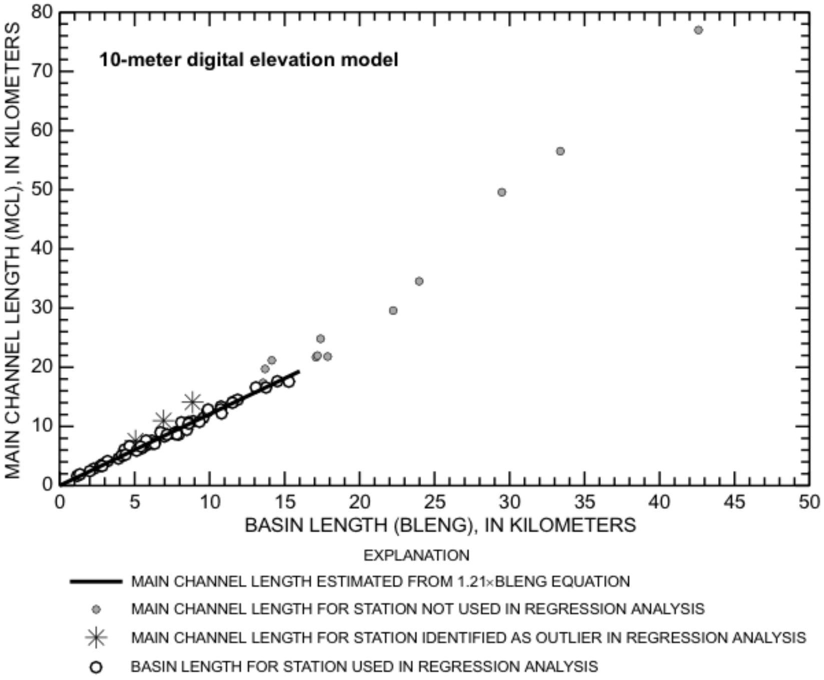

Figure 6. Relation between 10-meter DEM-derived main channel length and basin length for 70 (10-meter DEM) stations and the regression line for the subset of 57 stations with drainage area less or equal to 50 square kilometers.

Graphs of the relations between MCL and BLENG for the selected watersheds are shown in Figures 6 and 7 for the 10-meter and 30-meter DEM, respectively. Although the sample size is small, a curvilinear relation is possible for the entire range of drainage area considered (300 to 400 square kilometers [Figures 4, 5]). However, the relation between MCL and BLENG is remarkably linear in the range of BLENG from zero to about 16 kilometers — a level coincident with a DA of about 50 square kilometers. Therefore for purposes of this study, an upper limit on DA of 50 square kilometers was selected. There are 57 stations with DA less than or equal to 50 square kilometers for the 10-meter DEM. Similarly, there are 77 stations with DA less than or equal to 50 square kilometers for the 30-meter DEM. The greater number of stations is made possible by the greater spatial coverage of the 30-meter DEM for the dates of the analysis.

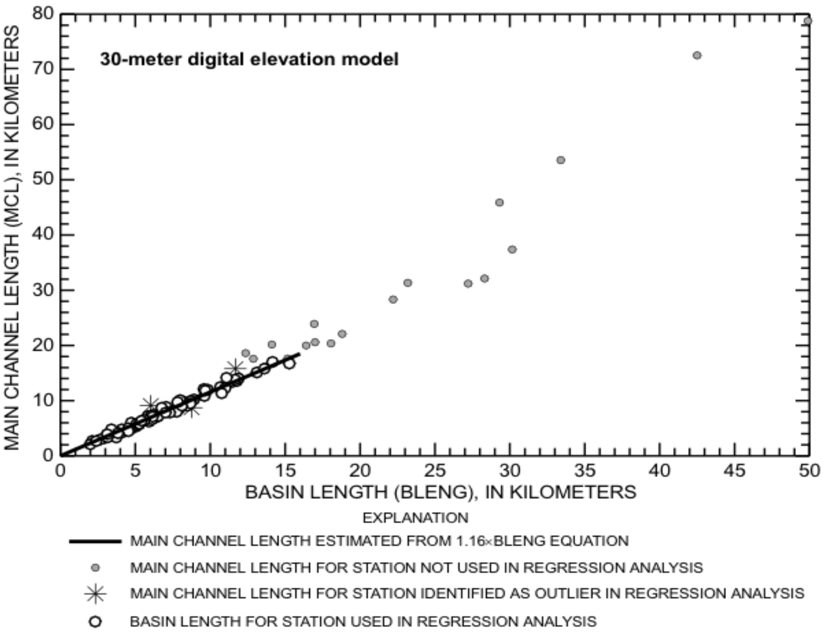

Figure 7. Relation between 30-meter DEM-derived main channel length and basin length for 96 (30-meter DEM) stations and the regression line for the subset of 77 stations with drainage area less or equal to 50 square kilometers.

The R environment for statistical computation (R Development Core Team 2004) was used to perform a simple linear regression of MCL as the regressor variable and BLENG as the predictor variable for DAs less than or equal to 50 square kilometers. The regression was configured to pass through the origin because a BLENG of zero should predict an MCL as zero. Post-regression residual analysis was performed; the results are not reported here. The analysis identified three stations as outliers for both the 10- and 30-meter DEM. The station numbers for the 10-meter outliers are 08048520, 08158100, and 08178555. The station numbers for the 30-meter outliers are 08057320, 08158100, and 08093400. The authors concluded it is appropriate that these stations be removed and regressions repeated.

The equation based on 54 stations for the 10-meter DEM-derived characteristics is MCL equals 1.21 times BLENG with a residual standard error of 0.477 kilometers and adjusted coefficient of determination (adjusted R-squared) of 0.998. The equation based on 74 stations for the 30-meter DEM derived characteristics is MCL equals 1.16 times BLENG with a residual standard error of 0.511 kilometers and adjusted coefficient of determination of 0.997. The coefficient of determination values for the regressions are acceptably large.

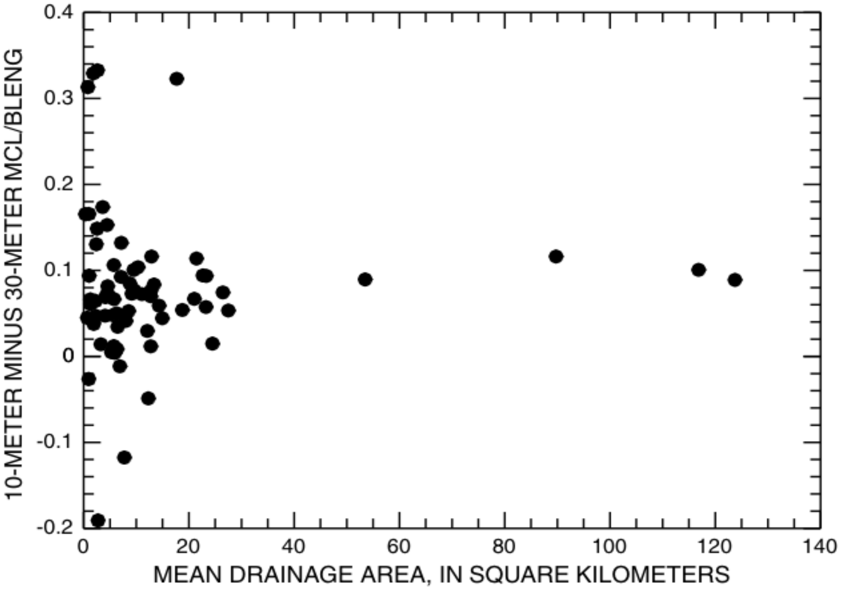

Figure 8. Relation of the mean drainage area (10- and 30-meter derived watersheds) and the difference between 10-meter and 30-meter MCL/BLENG for individual watersheds. A generally positive tendency for MCL/BLENG (10-meter) minus MCL/BLENG (30-meter) indicates that 10-meter DEMs compute longer MCL than 30-meter DEMs.

Relation Between Main Channel Length And Basin Length For Texas Watersheds

The two equations for the 10-meter and 30-meter DEMs have estimated slopes near 1.2. This value, when substituted for sinuosity in the equation for maximum meander angle relative to general channel orientation (ω) suggested by Langbein and Leopold (1966) for symmetrical meandering channels (see above), provides a value for ω of 0.898 radians, or 51 degrees. This value is representative of the study watersheds (Figure 3). For the sake of consistency and because of inherent uncertainties in hydrostatologic models, a regression-estimated equation to rapidly estimate MCL from BLENG for small watersheds is MCL equals 1.2 times BLENG. The equation is expected to be reliable for DAs of about 50 square kilometers or less and BLENG of about 16 kilometers or less that display dendritic or parallel drainage. Additionally, the range of dimensionless channel slopes for the study watersheds is about 0.002 to 0.02. Applicability of the equation for slopes outside this range is diminished.

The limited difference between the two regression equations for 10- and 30-meter DEMs suggests that accuracy of estimates of small watershed characteristics is not greatly increased through the use of 10-meter DEMs. However, 10-meter DEMs tend to compute slightly longer MCL than 30-meter DEMs (Figure 8) as a result of increased meander resolution. In part, this is because 10-meter DEMs commonly are created by combining high-resolution hydrography data with background hypsography data, thereby accounting for observed meanders at increasingly finer scales. Accuracy of small watershed characteristics should improve when using 10-meter DEMs for watersheds with DA at the lower end of this dataset, however there are not enough watersheds greater than 30 square kilometers in this study to make a conclusive statement.

Conclusions

The statistical relation between main channel length (MCL) and basin length (BLENG) for 96 selected small (less than about 50 square kilometers) watersheds in north- and south-central Texas was determined to provide a rapid method to estimate MCL. For purposes of this study, an upper limit on drainage area (DA) of 50 square kilometers was selected. Simple linear regression between MCL and BLENG was performed. The equation for the 10-meter DEM-derived characteristics based on 54 stations is MCL equals 1.21 times BLENG; and the equation for the 30-meter DEM-derived characteristics based on 74 stations is MCL equals 1.16 times BLENG. Therefore, the equation to estimate MCL from BLENG for small watersheds is MCL equals 1.2 times BLENG. The equation is expected to be reliable for DAs of about 50 square kilometers or less and BLENGs of about 16 kilometers or less that display dendritic or parallel drainage. Additionally, the range of dimensionless channel slopes for the study watersheds is about 0.002 to 0.02. Applicability of the equation for slopes outside this range is diminished. Finally, the limited difference between the two regression equations for 10- and 30-meter DEMs suggests that accuracy of estimates of small watershed characteristics is not greatly increased through the use of 10-meter DEMs. Increased computer processing times associated with 10-meter or higher resolution DEMs warrant a consideration of desired accuracy, especially when analyzing characteristics of numerous watersheds.

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