Effects of DEM Source on the Accuracy of Derived Hydrological Networks in Marin County

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ABSTRACT

The multitude of publicly available Digital Elevation Models (DEMs) requires end users to assess which DEM best represents surface topography for a given region. The differences in coverage and spatial resolution between DEMs is clear, but site specific accuracy can vary significantly between sources and is difficult to measure. Data noise (randomly distributed error), biases in the pre-processing stage, and equipment malfunctions can all impact the DEM's representation of the Earth's surface. This error can compromise the utility of one of the most common products derived from DEMs, the digital stream network (DSN). This analysis seeks to examine the differences in accuracy of DSNs obtained from three sources: The National Elevation Data, the Spectral Radar Topography Mission and the Advanced Spaceborne Thermal Emission Radar. Accuracy of hydrology networks is measured using the figure of merit (FM ratio), which measures the overall agreement of DSNs with a reasonably accurate baseline, the National Hydrography Dataset. Accuracy is evaluated and compared on two scales, the bounded study region in Marin County and at a local resolution across the same study region. My results show that errors are not randomly distributed. Overall accuracy results are given for the Tuolomne River Valley and Marin County study regions. The local accuracy statistics for Marin County are presented along with visualizations of error and significant error clustering. I present the semivariograms of error and my spatial variables of interest for a stream network cell resolution size of 30 meters. My results show the degree to which slope and elevation vary with network error. Furthermore, my results reveal how these spatial relationships depend on the source of the DEM.

KEYWORDS

elevation, flow accumulation, figure of merit, ASTER, spatial analysis

INTRODUCTION

Multiple methods of remote sensing have been developed to model terrestrial surfaces. Interferometric synthetic aperture radar, or InSAR, is a widely used method where artificially generated energy sourced are transmitted from a sensor to a target and reflected back to the sensor to gain information about the landscape (Nick et al. 2012). InSAR's low cost, approximate accuracy, and ability to provide wide spatial coverage makes it an ideal method for producing Digital Elevation Models (DEMs). DEMs are efficient and versatile representations of elevation data and can be used to derive topographical characteristics of landscapes. Accurately representing the topography and elevation of landscapes is critical to research in the field of geography, hydrology, and a variety of other Earth-science related disciplines. Spatial variables such as slope, viewshed, and aspect can easily be derived from DEMs. One of the most common uses of DEM's is to use the local surface gradient and orientation to calculate areas of significant flow accumulation across a landscape (Lindsay 2016). This results in the Digital Stream Network (DSN), which can then be used to delineate watershed boundaries, serve as the hydrographic basis for flood modeling, and model the output potential of hydropower generation (Lee et al. 2010, Shaw 2014). As DEMs have become more popular as a tool to model elevation the number of sources of DEMs have increased.

Publicly available DEMs each have differing degrees of spatial resolution, vertical and horizontal error, and site suitability, which provides data users with a significant choice in selecting which DEM to use (Baker et al 2006). The sources with the widest spatial coverage and most ubiquitous use in hydrological modeling research include the National Elevation Dataset (NED), the Shuttle Radar Topography Mission (SRTM), and DEMs derived from LiDAR data (Sanders 2007). Version 2 of the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global DEM (ASTER) is the first publicly available elevation dataset to span the entire globe (NASA Jet Propulsion Laboratory 2012). Like the SRTM, it is an important publicly available source for governmental and research organizations which do not have access to the technology or funds necessary to develop or purchase higher quality elevation models (Rexer and Hirt 2014). ASTER was developed to be an InSAR alternative to the SRTM dataset, improved with a higher degree of accuracy in sensing topographically steep areas and a wider spatial coverage (Kaku et al 2011).

DEMs sensed using InSAR come with limitations. The NED only covers the United States and produces overly smooth representations of terrain, and SRTM data suffers from poor vertical accuracy in general and has trouble sensing areas with high relief (Shumann et al. 2008). One alternative to these two sources is LiDAR, a laser based scanning system which takes highly accurate point based measurements of elevation at sub-meter resolution and above (Liu et al 2012). However, LiDAR can be expensive, it takes up a large amount of memory, and free and publicly available coverage is limited (Liu et al 2012). The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is an alternative, research grade DEM that performs well in certain mountainous areas where SRTM produces surface models with noise in the data and a relatively high degree of vertical elevation error (**Farr et al. 2007**). ASTER elevation data has been designated as research grade since version 1 released in 2009, as it suffers from an average elevation bias of negative 5 meters and has been found to have relatively high amounts of vertical elevation error in multiple regional analysis (Dong et al. 2015, Thomas et al. 2014). These site specific characteristics of different DEM sources can have implications for which DEM source is most accurate for building hydrological networks.

Hydrological river networks are one of the common products of DEMs and can be used to approximate river flow, model floods, and delineate watershed boundaries. The source of the DEM used has possible implications for the validity of flood simulations or flow analysis conducted using the network (Li and Wong et al 2010). Although SRTM data has been shown to perform poorly in mountainous regions compared with ASTER in regional analyses, the accuracy of ASTER in mountainous regions is not well understood. (Rexer and Hirt 2014, Rexer and Hirt 2010). The effects of DEM source on accurate analysis of hydrology in mountainous regions require further examination. Local accuracy assessment is an emerging field in GIS science. There are numerous studies which document the overall root mean squared error of the DEM of a particular region, along with other global scale statistics related to accuracy (Lindsay 2008). Yet there are currently limited methods developed to assess the local accuracy of DEMs using only remotely sensed data.

This analysis will examine how digital stream networks (DSNs) derived from the ASTER GDEM compares with NED and SRTM DEMs using two tests of accuracy: (a) an assessment of the figure of merit ratio (FM ratio), which is the overall relative agreement with the National Hydrography Dataset and (b) a comparison of semivariogram of the local FM ratio and spatial variables for each dataset. I will calculate these statistics using raster overlay to answer how DEM source and vertical accuracy affects hydrological networks derived from DEMs and by comparing local error values derived from hydrology network cell counts. Finally, I will describe how these two measures of DEM accuracy demonstrate the site suitability of the ASTER GDEM, in comparison with NED and SRTM, to model hydrology networks in topographic environments that have moderate to high slope and elevation.

METHODS

Study site

To compare the intrinsic accuracy and the accuracy of derived stream networks of NED, SRTM, and ASTER DEM data, I examine data for all data sources at a resolution of 1 arc second in Marin County, California, U.S.A. The length of the minimum bounding rectangle of the study site spans from the San Pablo Bay near the city of Novato, California (Lat - 38° 2'4.56"N, Long - 122°31'49.19"W) to Tomales Bay (Lat - 38° 7'34.87"N, Long - 122°51'37.52"W), also in Marin County, to total approximately 30 kilometers x 14.5 kilometers (Figure 1). Within this area is an overall elevation range of 0 meters near the shore of San Pablo Bay River to 537 meters at the peak of the Marin hills. The area includes an abundant number of peaks, valleys, and an overall diverse topography. Furthermore, the area has a considerable amount of hydrological activity that has been recorded by the National Hydrography Dataset, a standard used to compare the accuracy of derived hydrological networks (Li and Wong 2010).

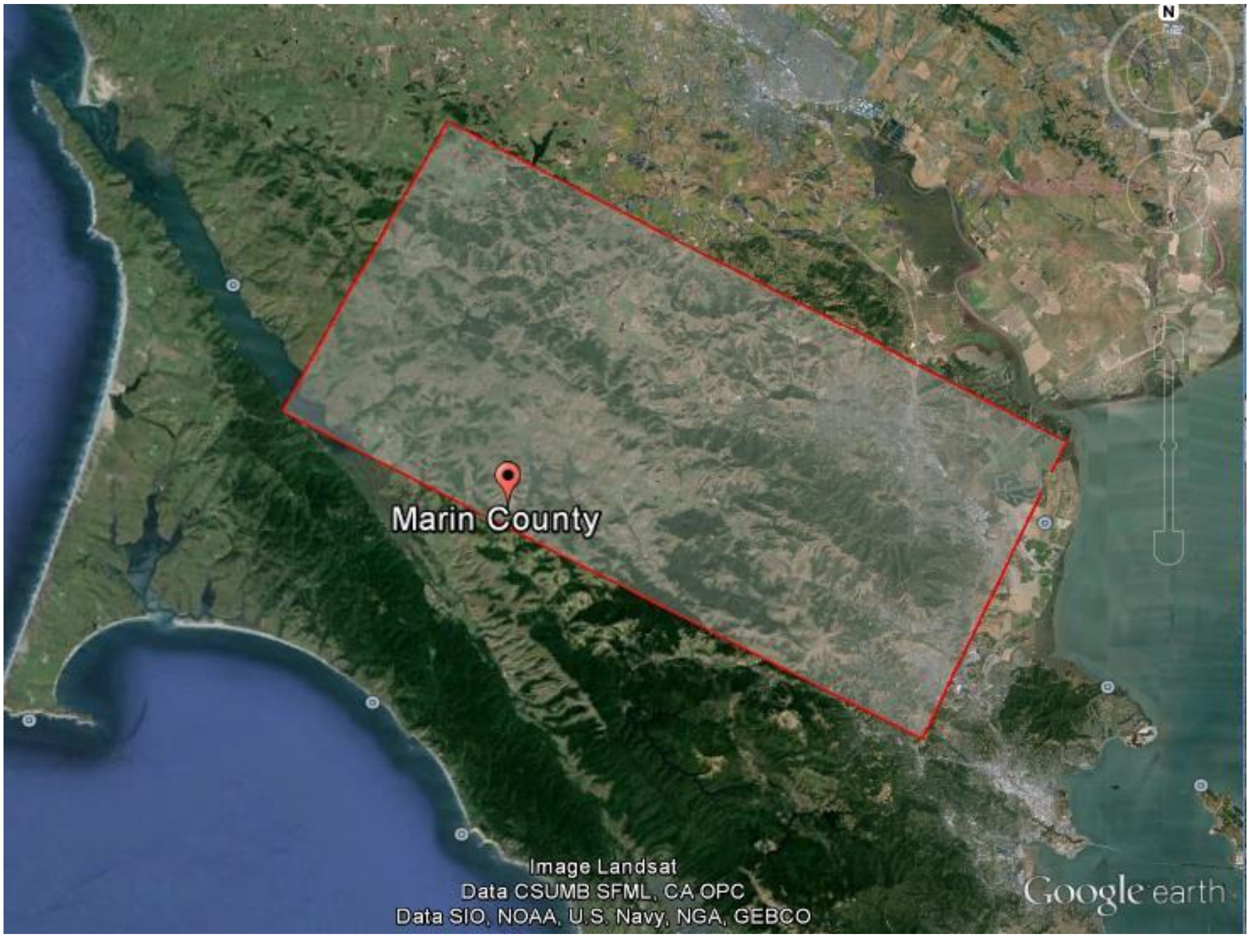

Figure 1: A Landsat image of my study site in Marin County and surrounding area. Geographic Coordinate System of this imagery is in WGS_1984. All data were projected into NAD 1983 State Plane Meters Zone 2.

Data sources

Multiple elevation sources are available within my study area, including 1 arc second NED, 1 arc second SRTM, and 1 arc second ASTER. NASA gathered SRTM data in the year 2000 and ASTER in the year 2009 using InSAR. No-data values, outliers, and accuracy errors are intrinsic to this method and are likely to occur in areas with steep slope, high elevation, and areas with dense forest canopy and water cover (ASTER Global Digital Elevation Model Version 2 – Summary of Validation Results 2011, Feigl and Massonnet 1998). The first full elevational coverage NED dataset of the United States was completed in 1999 and has since been updated using local LiDAR data, InSAR, and contour data. It is the standard elevational dataset in the United States and is managed by the USGS (Gesch et al. 2002).

The National Hydrography Dataset, or NHD, is a 0.0000001-degree resolution hydrography dataset that has been applied as a baseline to assess the accuracy of derived hydrological networks in a numerous studies and is also provided for download by the USGS (e.g. Di Luzio, Srinivasan, & Arnold, 2002). I downloaded data using the USGS Map Viewer TNM 2.0 Viewer and Earth Explorer GIS portals (USGS 2015 Accessed: 3/2/2016).

Data processing

I processed each DEM via the same processing workflow in ArcGIS 10.2.1 to obtain rasterized stream networks at different cell sizes (ESRI 2016) (Figure 2). First, I identified sinks in the DEM using the standard Sink tool and filled all sinks with the Fill tool. Sinks are single pixel areas of a digital elevation model into which all surrounding raster cells of a flow direction raster flow. These single pixel sinks are not significant or realistic representations of the landscape and are filled using a nearest neighbor averaging technique to take on the mean value of all adjacent nearest neighbors. I then used the ArcGIS Flow Accumulation, Flow Direction, and Conditional tool to create a raster dataset with positive values of 1 in cells that were found to have at least 5 cells upstream flowing into them, in order to create a grid with significant stream locations. This threshold of 5 was visually determined to be the threshold that most closely matched the National Hydrography dataset baseline. With this raster dataset I then created a vector network and re rasterized that network to different cell sizes ranging from 10 meters all the way up to 100 meters.

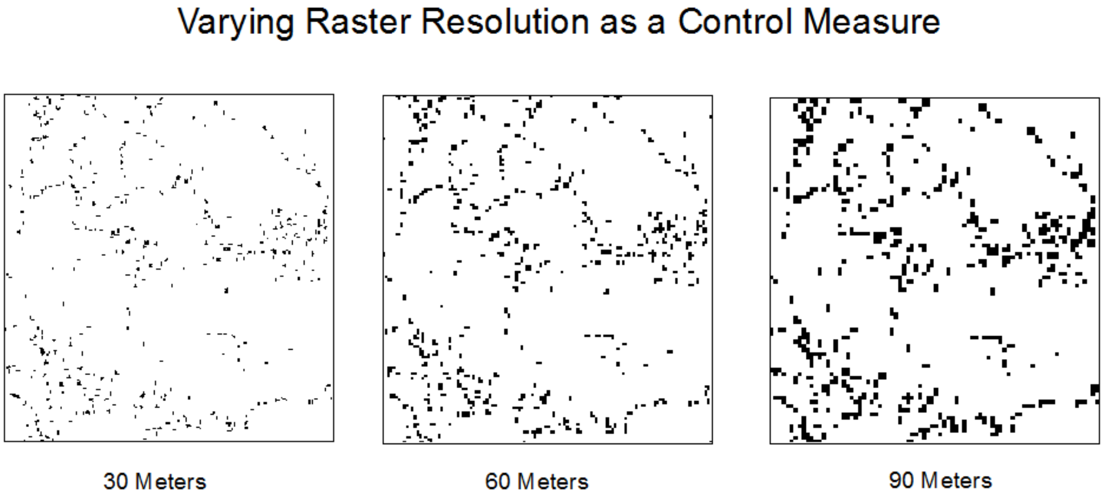

Figure 2: Rasterized DSN extracted from ASTER at a scale of 1:100, 000.

This range of stream networks of varying cell sizes were created in order to account for the fact that networks of larger cell sizes will tend to more readily overlap partially with each other (Li and Wong 2010) (Figure 3).

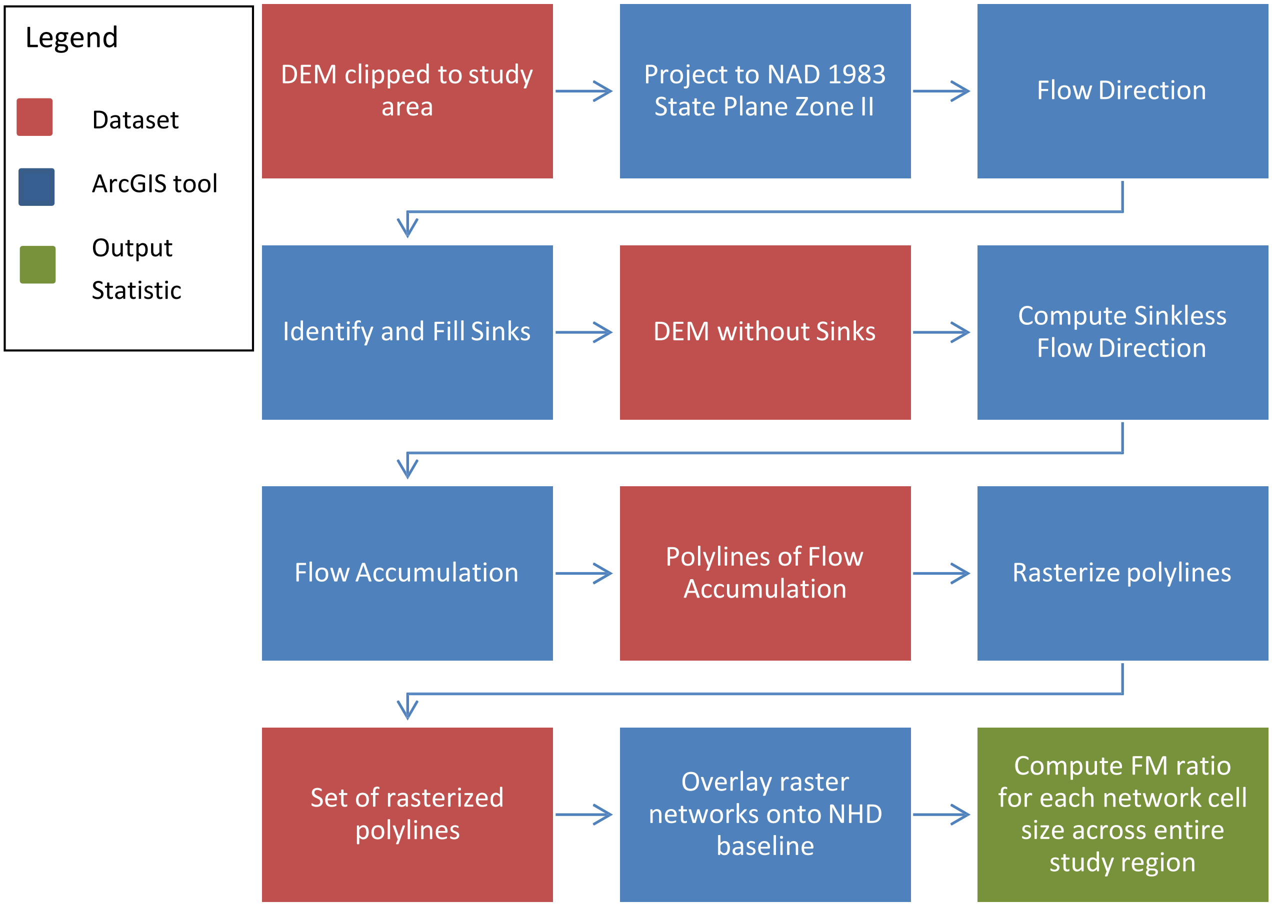

Figure 3: Simplified workflow used to obtain the FM ratio for each DEM source

I used the Zonal Statistics Tool in ArcGIS in an iterative process to calculate the FM ratio within each individual zone within each of my dataset's span over Marin County. I then compared this local error to slope and elevation across my landscape by conducting a semivariogram analysis. I chose to use stream networks with a cell resolution size of 30 meters, as the first stage of my accuracy assessment shows that raster resolution does not have a significantly disjoint impact on accuracy between different DEM sources.

Analysis

I measured accuracy based on how well each dataset's hydrological network product agrees with the National Hydrography Dataset (NHD). Horizontal accuracy assessments have not been completed for the NED and vertical accuracy of SRTM and ASTER has been shown to be variable based on regional characteristics, such as slope and elevation (ASTER Global Digital Elevation Model Version 2). To compare the accuracy of these data, I rasterized these polylines at a resolution of 30 meters and overlaid each of these extracted networks with the rasterized NHD. I computed the figure of merit, which offers a better indication of how well the extracted network can represent the baseline network. It is calculated by dividing the intersection of cells of the baseline and extracted network by the union of the cells in each network (Pontius et al. 2008). The figure of merit index for each source will be compared to determine which source has higher overall accuracy.

I conducted a local analysis of accuracy using the Fishnet, Zonal Statistics, and Geostatistical Analysis toolset. I created a fishnet grid with which to aggregate the cell values of each network so that each zonal grid within my fishnet could be assigned its own FM ratio. Local error is represented by the local FM ratio of each zone. I computed the FM ratio for each zone grid at a resolution of 1,700 by 1,500 meters (Figure 4). I ran a Global Moran's I analysis to determine if local network error was significantly clustered and a Local Moran's I analysis to determine where statistically significant clustering of error occurs across the landscape. I then conducted a semivariogram analysis to compare the variances of error and spatial variables across my study area. The semivariogram depicts the relationship of variance between two variables across the landscape at varying spatial scales and is appropriate for examining the relationship between spatial variables and error (J. Radke, personal communication).

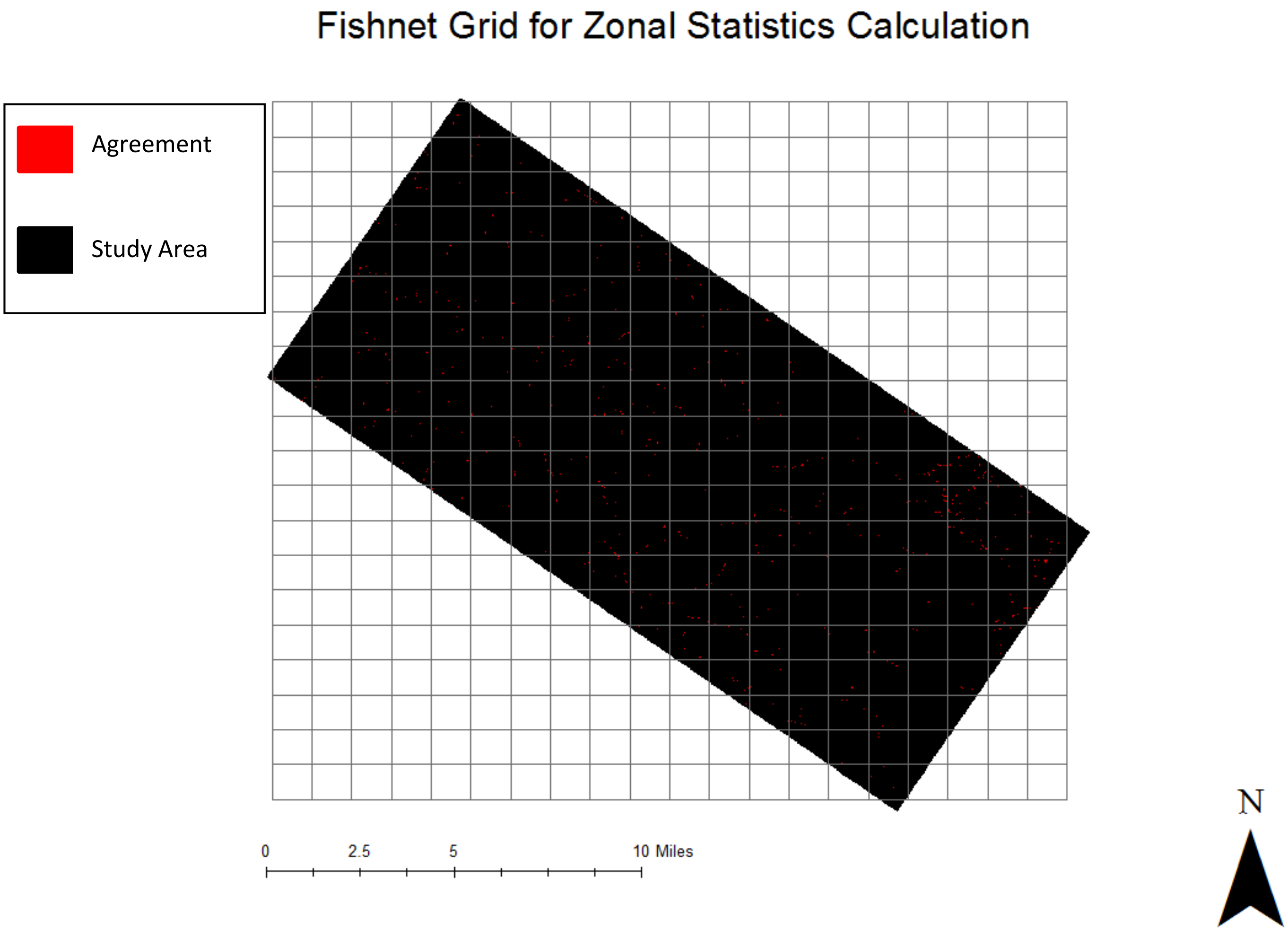

Figure 4: The fishnet grid used to delineate zones to compute local error (FM ratio). Agreement refers to cells that overlap between the NHD and extracted network. In this example, a 30-meter ASTER network has been overlaid with a 30-meter NHD raster network to get the intersection of cells that agree.

I sampled an interpolated elevation and interpolated slope value using an Inverse Distance Weighting Method from the National Elevation Dataset to ensure that the slope value used to assess error is not an outlier or no data value due to error inherent in InSAR sensing. I evaluated the fit of each model, qualitatively compared the semivariograms of each DEM source, and analyzed the performance of each DEM source's ability to produce an accurate, 30-meter resolution network at different magnitudes and variations of elevation and slope.

RESULTS

Overall Accuracy Indices

Accuracy for all DEM sources ranges from 0.05 to 0.35 (Figure 5). For the majority of cell resolutions NED is the most accurate, followed by SRTM, and then ASTER. The average difference in accuracy between NED and SRTM is 0.050, whereas the average gap in accuracy between SRTM and ASTER is .025. As expected, the FM ratio increases with coarser resolution for all DEMS. The trend line for the ASTER dataset asymptoticly levels off below a FM ratio of 0.3, whereas the trend line for varying raster resolution and FM ratio are more linear for both SRTM and ASTER, increasing beyond the ASTER dataset past a resolution of 70 meters (Figure 5).

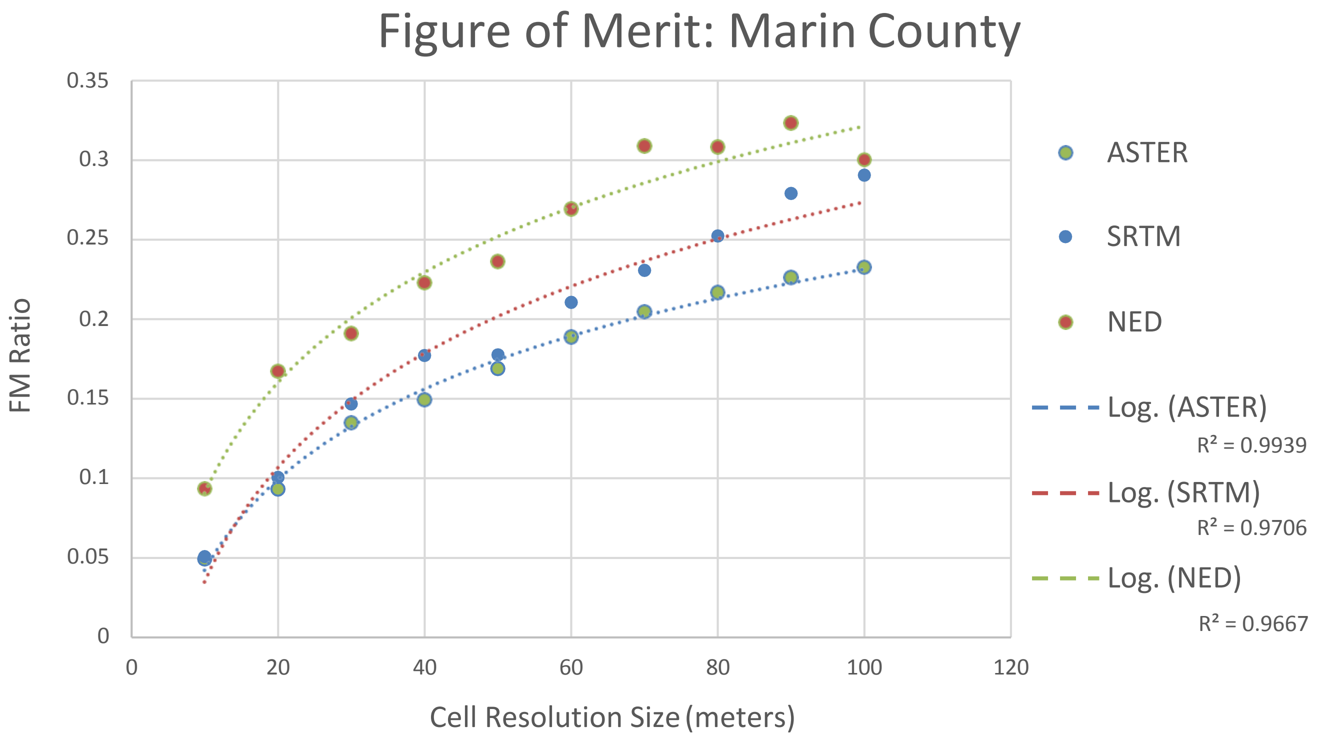

Figure 5: Comparison of FM ratios for each DEM source's digital stream networks. R squared values show the correctness of fit of the trendline to the data.

Spatial Autocorrelation of Error

The FM ratio ranged from 0 to .23 for ASTER. FM ratio maps were generated for ASTER and the National Elevation dataset, but not for SRTM, as the data was corrupted. Grids of

FM ratio are compared with the standard deviation of slope (Figure 6, Figure 7).

Geostatistical analysis of local error could not be conducted due to corruption in the data and due to errors inherent in converting FM ratio grids from raster to polygon.

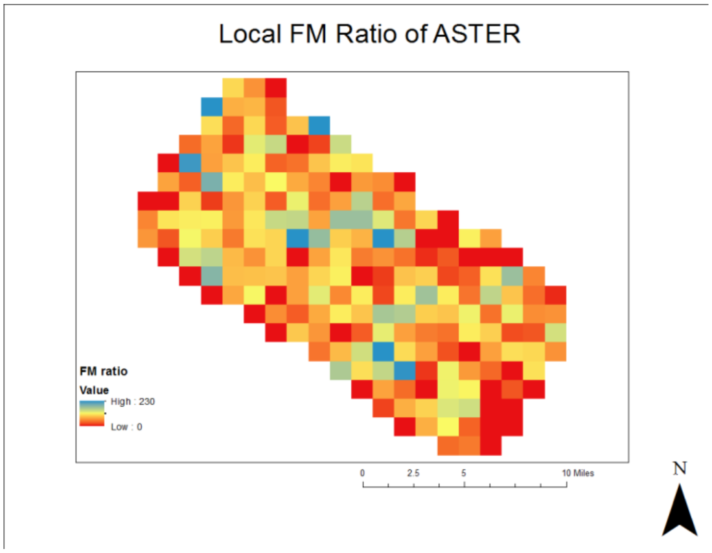

Figure 6: FM ratio across my study area at a resolution of 1700 by 1500 meters.

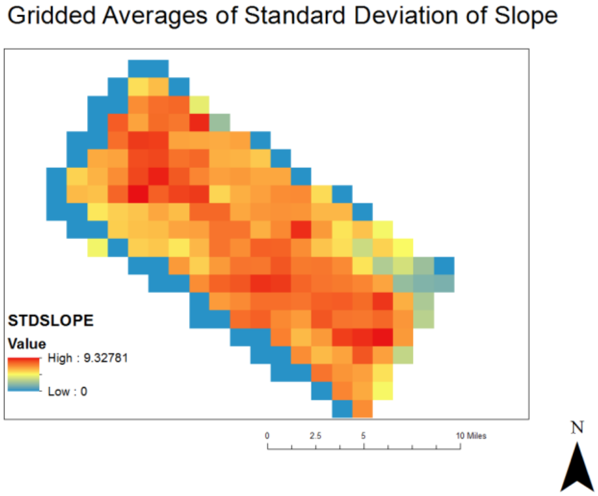

Figure 7: Standard Deviation of slope across my study area at a resolution if 1700 by 1500 meters.

DISCUSSION

Accuracy Assessment of DEM Derived Hydrological Networks

In this study, I examined the effect of DEM source on a primary hydrological spatial application, the extraction of Digital Stream Networks (DSNs.) I expected that overall accuracy indices would be higher for the National Elevation Dataset, and that both SRTM and ASTER would have significantly more error bias in regions with an average higher slope. Overall the findings are in agreement with the literature for global accuracy indices for the study region. The possibility and utility of semivariogram analysis of local error and topographic and land cover variables are discussed and qualitative comparisons are made between slope and error. I include limitations and suggestions of how to incorporate this methodology to assess the suitability of a DEM product for regional hydrological applications.

Measures of Global Accuracy

An important preliminary statistic that should be computed for any DSN is the overall positional accuracy of a network. The computed value of the figure of merit for each source reflects that, as expected, error decreases as raster cell size is increased. This decrease is because larger raster cells in the stream network have more potential to partially overlap than smaller raster cells. Because the figure of merit counts partial overlap of raster cells as agreement between my baseline and extracted network, rasterized networks at coarser resolutions will have inflated correctness indices. For almost all raster cell sizes between 10 and 100 meters resolution, the NED is moderately superior in accuracy compared to SRTM and ASTER. There is a significant difference in intercept, indicating that the NED does have a higher overall accuracy but that it's accuracy does not increase at a greater rate with increasing raster resolutions (Figure 5).

Although the National Elevation Dataset has been shown to have significantly higher amounts of elevational error near streamlines compared to SRTM, in another comparative study which assessed the accuracy of each DEM compared with highly accurate ground control points, SRTM and ASTER both perform poorly compared to the NED (Holmes et al. 2000). From the distribution of stream grid cells in the SRTM, there appears to be significant concentrations of noise in the data in low slope, low elevation areas. This noise could be because SRTM and ASTER datasets are sensed solely using InSAR, whereas the NED is a product of both InSAR and rectification with contour lines and digitization and can thus better deal with detecting flow accumulation in low lying, low slope areas (The National Elevation Dataset 2011, J. Radke personal communication). The SRTM dataset also has a disproportionate amount of data noise in flat areas, which explains why my stream network appears is so discontinuous and random towards the western flatlands near Tomales Bay (Guth 2006) (Figure 6).

Another possible explanation for the large amount of error in my networks near the flatlands of the city of Novato is that there are an abundance of abandoned channels, which the NHD is able to represent due to the resolution at which it was digitized but which my extracted networks cannot capture at a resolution of 30 meters (P. Mendez, personal communication). This could explain why there appears to be a significantly higher concentration of error within this area than other flat landed areas across my study area.

Though SRTM and Aster performed poor relative to the NED, an interesting trend comparison can be made between these results and past studies. Li and Wong found that in a topographically flat area, the maximum difference in correctness index between the NED and SRTM for all cell sizes was 0.3, whereas my results show that the maximum difference for all cells sizes is less than 0.15 (Li and Wong 2010). This discrepancy could be due to the fact that the National Elevation Dataset over smooths topographically diverse landscapes, leading to horizontal and vertical error that can compromise the accuracy of extracted network in these areas (Sanders 2007). It could also largely be the result of the smaller amount of flat lands in my study area compared with the Kansas River Delta. This finding indicates that the National Elevation Dataset has a lower overall accuracy compared to SRTM and ASTER in landscapes that have as diverse a topology as Marin. Further exploration is necessary to determine whether SRTM and ASTER perform significantly better than comparable DEMs. Although these measures are useful for gaining an idea of the overall correctness of a DSN, it is more useful to examine the local variation in error when deciding to use a particular DEM dataset.

Autocorrelation of Positional Error and Correlations

Spatial autocorrelation was qualitatively evaluated to determine if there are existing patterns of error caused by the remote sensing process, such as striping, noise in the data, and the tendency for stream errors to be linearly clustered. It appears that there is a moderate spatial bias in error within the outer edge areas of the study region for all DEMs. This could due to the fact that the extracted networks tend to sense extraneous networks in flat areas where the NHD does not exist, resulting in no-agreement (Figure 6). It appears that there is a moderate relationship between the variability of slope, as measured by the standard deviation, and the FM ratio. Towards the edges of all datasets, we see that in areas of low variability of slope, there are likewise lower FM ratios. However, no comment can be made as to the statistical significance of this relationship.

Alternative Sources of Error

Although the relationship between error and spatial correlates may not be numerically significant, spatial variables can still have regional and identifiable impacts in localized areas of a DSN. In our dataset, error is primarily concentrated in the southeastern quadrant where slope and elevation are higher on average (Figure 3). It is also apparent that this error is due to superfluous overlap between the extracted network and the baseline. This seemingly random pattern of error likely results from the generation of superfluous polylines in our baseline, the National Hydrography Dataset (Figure 9). This phenomenon is potentially the result of the heads up digitization method employed to create the National Hydrography Dataset. Heads-up digitization is the technique of creating feature data, such as streams, by tracing their outline from imagery or contour lines (Feigl and Massonet 1998). It is likely that humans that digitized this section of the NHD decided to digitize abandoned channels, pipelines, or other linear features to represent hydrography. This results in error because our extracted networks from InSAR sensing only detect flow accumulation at a resolution of 30 meters. Therefore, there is significant overlap of our extracted network in seemingly random areas simply because the concentration of polylines in the NHD is high.

Limitations

No model of the earth is completely without fault, and the LiDAR data used to assess elevation accuracy contain irregularities caused by land cover, slope, and elevation, though to a lesser degree than DEMs acquired with InSAR methods (Hofton 2006). The primary limitation of this study is the reference data that the DSNs and DEMs are compared to. Although the NHD is used throughout the literature as a reasonably accurate baseline, the abrupt change in stream network density observed in areas other than Marin county possibly signals an error inherent in how the data was developed (Figure 4).

In addition, this study only examines a single location within the boundaries of a state plane projection zone. It is important to account for the fact that the sources examined in this study do not all have the same datum as my baseline, NAD 1983. SRTM has a datum and geographic projection of WGS 1984, which causes there to be slight but perceptible datum shifts when projecting to a California State Plane Zone 2 coordinate system. I attempted to control for this phenomenon by using a statistic for local error that generalizes error to occur within a relatively large local gridded area as opposed to using a raster overlay method. A datum shift could significantly impact the amount of local error found in areas that would otherwise have partial overlap without a datum shift (Moore 1991). This method of measuring error is less accurate than an overlay method in saying at what exact 30 by 30-meter pixel error occurs at, but it is more accurate in saying with certainty that error occurs within a grid.

Future Directions

Future studies should utilize more accurate baseline data, account for the effect of geographic location, and projection on the error of different DEMs. Hydrography polylines derived from digitized sources more accurate that the National Hydrography Dataset may be developed elsewhere and could serve as a better baseline than the NHD. Biological habitat models could employ the methods used in this study to pinpoint error in existing DSNs in order to develop more accurate DSNs for use in riparian habitat modeling that takes into account local stream characteristics, especially those dependent on accurate measurements of geomorphology. Future studies with more time and more robust computational resources would be able to incorporate more regions of the world into a similar study to see if these findings hold for areas with low relief, land cover types not accounted for in this study, and regions that span greater total areas.

This study also did not use preprocessing methods to remove large scale depressions and flat areas with undefined downslope accumulation as such a step was beyond the scope of this study (Liu et al. 2009, Barnes et al. 2014). However, employing such methods would reduce error in each stream network. Further work needs to be done to ensure that this pre-processing method is standardized for all DEM sources that are evaluated in an accuracy assessment in order to avoid bias.

A major next step is to refine the preprocessing of the data to return a workable FM ratio grid that can be used in geostatistical analysis software.

Broader Implications

Confidence in the accuracy of your data and knowledge of its limitations is imperative to using it to its fullest potential. Using digital elevation models and their derived stream networks without both a sense of its global accuracy and regional accuracy invalidates their application in research and management. My findings provide both a framework for conducting regional accuracy assessment of DSNs as well as a case study of the performance of my three target data sources, NED, SRTM, and ASTER. NED performs better than SRTM in flat areas, which confirms what we already know about these elevation models with wide global coverage. Yet, the NED is not available outside of North America, and therefore it is useful and necessary to examine the relative accuracy of alternatives to SRTM. My finding that ASTER performs with near identical accuracy, on a global scale, as SRTM is significant. It confirms that in regions with similar land cover characteristics as Marin, ASTER can serve as an alternative or as a complementary dataset to building a more accurate DSN over a large area. In an ideal world, high resolution elevation models would be publicly available, vastly increasing the capabilities for anybody to conduct more accurate geospatial projects. But the reality is that in many parts of the world, particularly developing regions, ASTER and SRTM are the only publicly available datasets available.

This reproducible methodology can show where and to what degree error and slope are related to one another. This geostatistical mapping approach to estimating error is helpful for hydrological applications as it allows users to pinpoint where errors are occurring in a dataset product and if such a product is suitable enough for use.

ACKNOWLEDGEMENTS

This undergraduate thesis was conducted as part of the Environmental Science major requirement in the department of Environmental Science, Policy and Management. Many thanks to my Kurt Spreyer and Patina Mendez; their good cheer coupled with astute criticism were essential in my completing this project. Thank you also to John Radke and Maggi Kelly, for answering my numerous questions and helping me formulate my project. The Geospatial Information Facility and the D-lab were both integral in providing me with technical support, particularly Drew E. Hart, Brian Galey, and Eric Lehmer. I also greatly benefited from the peer editing support of my ES cohort, Annika Min, Adrian Lee, and Manda Au. Finally, thank you Mom and Dad for your love and support. Without you all this thesis, let alone my education, would not have been possible.

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APPENDIX

Marin County

NED Pixel Counts and Indices			
Cell Size	AND	OR	Figure of Merit
10	18119	194103	0.093347347
20	15143	90529	0.167272366
30	11248	58896	0.190980712
40	9536	42791	0.222850599
50	7951	33658	0.236229128
60	7298	27114	0.269159844
70	6933	22451	0.308805844
80	6019	19534	0.308129415
90	5504	17027	0.323251307
100	4655	15513	0.300070908

SRTM Pixel Counts and Indices			
Cell Size	AND	OR	Figure of Merit
10	9876	194816	0.050693988
20	9312	92693	0.10046066
30	8655	59030	0.146620363
40	7605	42924	0.177173609
50	6054	34107	0.17750022
60	5788	27496	0.210503346
70	5314	23041	0.230632351
80	4973	19713	0.252270076
90	4757	17050	0.279002933
100	4381	15082	0.290478716

ASTER Pixel Counts and Indices			
Cell Size	AND	OR	Figure of Merit
10	9576	194816	0.049154074
20	8631	92693	0.093113827
30	7955	59030	0.134761985
40	6405	42924	0.149217221

50	5760	34107	0.168880289
60	5188	27496	0.18868199
70	4712	23041	0.204505013
80	4273	19713	0.216760513
90	3857	17050	0.226217009
100	3507	15082	0.232528842