

USING HIGH RESOLUTION SYNTHETIC APERTURE RADAR FOR TERRAIN
MAPPING: INFLUENCES ON HYDROLOGIC AND GEOMORPHIC INVESTIGATIONScott N. Miller¹, D. Phillip Guertin²,
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ABSTRACT: A high resolution digital elevation model (DEM) was constructed for the USDA-ARS Walnut Gulch Experimental Watershed located in southeast Arizona using interferometric synthetic aperture radar (IFSAR) processing techniques. Three lower resolution DEMs had previously been constructed for the watershed; a 40m photogrammetrically derived surface, a combination USGS Level I and II 30m surface, and a derivative 10m surface. The IFSAR DEM, with a resolution of 2.5m and high vertical accuracy, is potentially a significant improvement in terrain representation. This study investigates the differences in topographic representation among the photo, USGS, and IFSAR DEMs and illustrates the influence they have on hydrologic and geomorphic studies. Watershed characteristics such as area, geometry, drainage network, slope, and drainage density, derived from the DEMs, are compared. Results from these studies demonstrate the impact of using IFSAR technology on watershed hydrologic and geomorphic research at a range of watershed scales.

KEY TERMS: Interferometry; SAR; DEM; watershed modeling

INTRODUCTION

Topography is one of the most important landscape features for hydrologic simulation modeling. Relatively recent innovations in geographic information systems (GIS) and landform modeling have produced realistic representations of the earth's surface in digital form. These digital elevation models (DEMs) serve as the foundation for a great deal of research into hydrologic and geomorphic processes and application of hydrologic and natural resource models. For many analyses where small-scale processes dominate, such as hillslope studies, detailed erosion studies, or for distributed models incorporating complex routing, very high quality DEMs may be required (Bloschl and Sivapalan, 1996). Even results from large-scale hydrologic modeling and land classification may be affected by the choice of terrain data. For instance, the original and

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Revised Universal Soil Loss Equation are highly dependent on an accurate representation of slope, and topography-based watershed models have been demonstrated to be sensitive to DEM data quality (Wolock and Price, 1994; Syed, 1999).

An emerging technology for high-quality DEM generation is synthetic aperture radar (SAR). Where multiple sensors are used to survey the same ground location, a pair of coherent images of the surface may be combined to form a detailed representation of the earth's surface (Henderson and Lewis, 1998). Such interferometric SAR (IFSAR) DEMs may be used to detect changes in the earth's surface at approximately the scale of the application wavelength, typically between 3 (X-band) and 70 (P-band) centimeters. The use of SAR in semi-arid regions is particularly applicable to land surface and geomorphic mapping due to the relative lack of impingement on the signal from vegetation and soil moisture.

Since multiple IFSAR DEMs can be created with a relatively high frequency for a given area, time-integrated land surface change resulting from erosion or depositional processes may be determined (Lane, 1998). With a fine enough resolution, relatively small landscape features, such as stream channel geometry or rill and gully development can be discriminated within a scene. Obtaining an accurate spatial characterization of sediment movement within a basin through interferometry would represent a significant advance in the study of erosion and geomorphic processes. However, such analyses are strictly dependent on the statistical height accuracy and resolution of the IFSAR terrain models.

Results from analyses of four DEMs of differing sources and resolutions (2.5, 10, 30, and 40m cell size) covering the USDA-Agricultural Research Service Walnut Gulch Experimental Watershed in southeastern Arizona are presented. Numerous hydrologic and geomorphic characteristics were extracted from each of the DEMs for a range of watershed sizes. The relative influence of the spatial resolution and quality of the DEMs as a function of scale was evaluated.

DESCRIPTION OF THE STUDY AREA

The Walnut Gulch Experimental Watershed is located in southeastern Arizona surrounding the town of Tombstone (Figure 1). The watershed has a nested design with many subwatersheds that drain to a series of supercritical flumes, v-notch weirs, and gaged stock tanks. A dense network of 85 rain gages distributed across the 148 km² watershed provides long-term climatological information necessary for hydrologic studies. The watershed is predominantly underlain by deep alluvial deposits, with some exposed and shallow bedrock near the southern and eastern boundaries of the watershed. The climate is classified as semiarid or steppe (Renard et al., 1993). Mean annual precipitation is approximately 324 mm, and the average annual temperature in Tombstone is 17.6° C. Annual precipitation is highly variable in both timing and intensity, with the majority of the rainfall occurring as convective summer storms and the remainder resulting from low-intensity winter frontal storms.

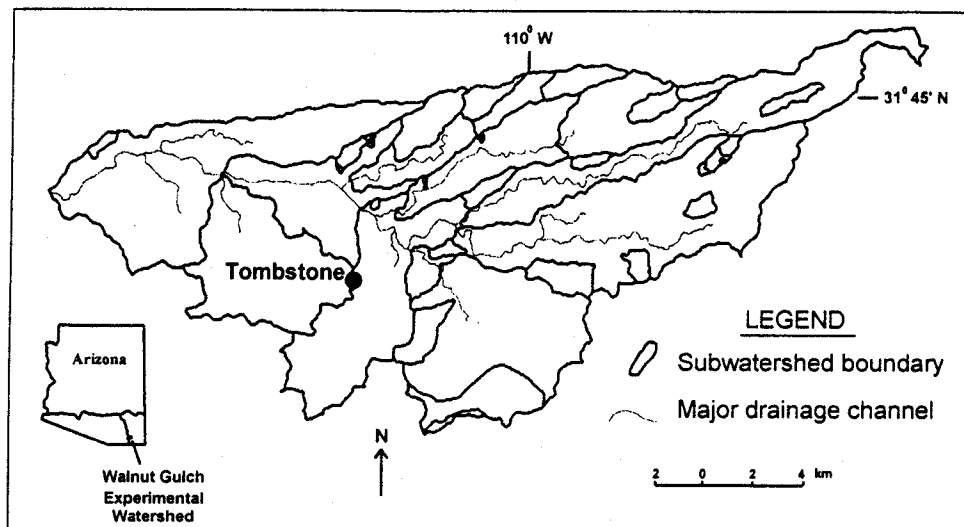


Figure 1. Location of the USDA-ARS Walnut Gulch Experimental Watershed showing nested subwatersheds and major stream channels.

METHODS

Three principle techniques were used to create the DEMs for this study. The lowest resolution DEM was created from low-level aerial photography (1:24000 with 0.5m pixels) with elevation post-points estimated at 40m intervals. A mixture of standard USGS Level I and II DEMs was used to form a 30m resolution (out of six 7.5' quadrangles covering the study area, three Level II DEMs are currently available). A detailed GIS theme layer of the stream channel network, digitized from 1:5000 orthophotographs, was used to form breaklines to improve the surface articulation of the 40m DEM to form a 10m grid. Lastly, Intermap, a private company specializing in SAR topographic characterization, developed an IFSAR DEM with 2.5m resolution (we gratefully acknowledge the scientific expertise and data provided by Intermap). All the DEMs were imported into the Walnut Gulch GIS database, and basin analysis was conducted using Unix Arc/Info (Names are necessary for factual reporting; however, the USDA neither guarantees nor warrants the standards of this product, and the use of the name by the USDA implies no approval of the product to the exclusion of others that may be suitable).

The primary objective of this study was to investigate the impacts of DEM accuracy and resolution on hydrologic characterization. Each of the four DEMs was subjected to limited post-processing to ensure hydrologic continuity throughout the watershed. The minimal smoothing was applied as necessary to ensure adequate routing and still retain the independent characteristics of the various surfaces. In addition, a low-pass filter was run over the USGS data to remove anomalies and reduce edge effects that impeded routing across boundaries of the quadrangles. The elevation in each map coincident with the position of 145 total station survey points showed that the 2.5m, 10m, 30m, and 40m DEMs had mean errors of 0.052%, 0.049%, 0.254%, and 0.186%, respectively (Syed, 1999). Their respective absolute errors were 0.753m, 0.709m, 3.72m, and 2.71m. Figure 2 shows the relative differences in estimated elevation for the DEMs.

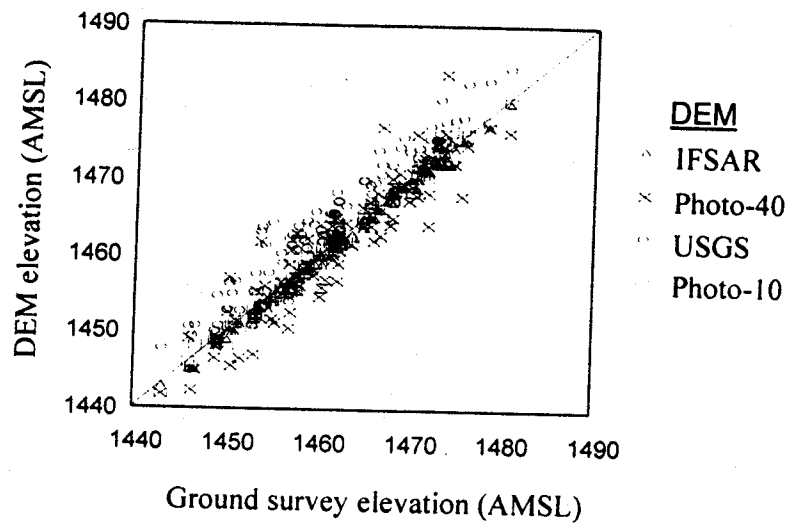


Figure 2. Comparison between DEM elevation data and total station survey points for 145 sites where IFSAR = 2.5m IFSAR, Photo-10 = 10m photo-based DEM, USGS = 30m USGS, Photo-40 = 40m photo-based DEM.

Standard GIS techniques were used to derive flow direction and accumulation maps from the DEMs (ESRI, 1998). These maps illustrate watershed routing and concentrated flow areas (stream channels). Stream channel networks were extracted from the flow accumulation maps using a critical source area of 0.35 ha; each cell with a drainage area greater than this value was classified as a stream. The value of 0.35 ha was derived from a random sampling of 100 contributing source areas as observed on 1:5000 aerial orthophotographs. A detailed stream network was traced and digitized from these photographs, and the area contributing runoff to each of the 100 selected first order channels was determined using GIS. This average channel threshold was applied to all levels of DEM to ensure consistency in comparative analyses.

Table 1. Descriptive statistics of watershed characteristics.

	<i>IFSAR</i>	<i>Photo-10</i>	<i>USGS</i>	<i>Photo-40</i>
mean watershed slope (%)	11.750	9.246	7.118	7.105
min. watershed slope (%)	5.929	4.357	2.551	3.587
max. watershed slope (%)	18.709	15.755	15.847	13.111
mean watershed slope std. dev.	10.397	5.197	3.978	3.910
min. watershed slope std. dev.	8.443	1.567	0.783	0.727
max. watershed slope std. dev.	14.084	11.896	8.619	9.557
mean drainage density (m)	0.0104	0.0085	0.0101	0.0085
min. drainage density (m)	0.0070	0.0053	0.0053	0.0067
max. drainage density (m)	0.0148	0.0111	0.0170	0.0109
mean channel slope (%)	8.997	5.308	4.393	5.069
min. channel slope (%)	6.107	2.925	0.667	2.852
max. channel slope (%)	15.693	9.783	8.085	8.518
min. watershed area (km ²)	0.00322	0.00280	0.00180	0.00160
max. watershed area (km ²)	146.82	147.70	146.42	148.10

Subwatersheds ranging in size from 148 km² (the entire watershed) to 0.0016 km² were automatically defined using the flow direction map for 40 outlet points corresponding to gaging stations on Walnut Gulch. Topographic and hydrologic characteristics, such as area, slope, drainage density, and surface variability were defined for each of these small basins for each DEM using GIS procedures. Table 1 presents descriptive statistics of the measures used in this study.

RESULTS AND DISCUSSION

Variability in predicted subwatershed area was largely a function of scale. Although the various DEMs' absolute differences in estimated areas increased with basin size, the highest percent differences were found on the smaller subwatersheds. Small errors in modeled elevation can significantly alter flow routing on small watersheds and thereby impact a proportionally larger percent of the drainage area. However, these small differences in the surface, which are apparent in the placement of watershed boundaries, become insignificant on larger drainage areas. This underscores the importance of accurate high resolution DEMs, such as IFSAR, for small watershed or hillslope studies where minor differences in GIS data can greatly impact research applications. A potential problem associated with such DEMs was outlined recently by Syed (1999) who demonstrated their high sensitivity to elevation errors. With very high resolution DEMs, even small errors can result in significant inaccuracies in watershed delineation and characterization.

The extent to which such averaging alters hydrologic analyses or influences physically based models is partially a function of scale and is dependent on the processes under investigation. Watershed slope is an indicator of topographic smoothing; as cell sizes increased, small variations in topography were averaged into larger cells (Figure 3).

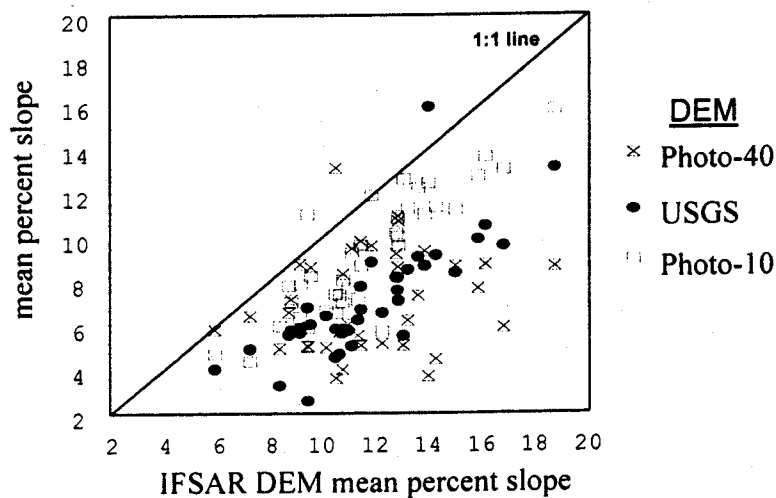


Figure 3. Mean watershed percent slope for the various DEMs relative to the 2.5m IFSAR surface. Note the overall reduction in slope with increasing cell size.

Substantial smoothing on DEM surfaces is apparent with decreasing grid cell resolution. Degrading cell size inherently entails averaging and extremes in cell values may be lost. This appears to be occurring with respect to the range in topography contained in the DEMs evaluated for this analysis. Both the mean and standard deviation of watershed slopes are highest for the IFSAR DEM. The decrease in average slope is representative of a reduction in the number of abrupt elevation differences between neighboring cells, a result of averaging. Slope standard deviation is representative of the topographic roughness; higher standard deviations imply a greater variability in the surface, such as the inclusion of topographic highs or lows that are otherwise averaged out. A reduction in slope standard deviation implies that much of the natural surface has been simplified to a more continuous smooth surface.

The most complex drainage network was defined using the 2.5m IFSAR DEM (Figure 4). Recall that the critical source area for drainage determination was the same for all four DEMs. As a result of this approach, channel initiations occur at approximately the same location throughout the watershed, independent of DEM choice, implying that the distance to the overall watershed outlet would remain equal. However, the more articulated high resolution DEMs, especially the 2.5m IFSAR DEM, allow for the generation of more tortuous flow paths, more complex routing, and hence, longer drainage networks. Certain limitations on network analysis are apparent in Figure 4.

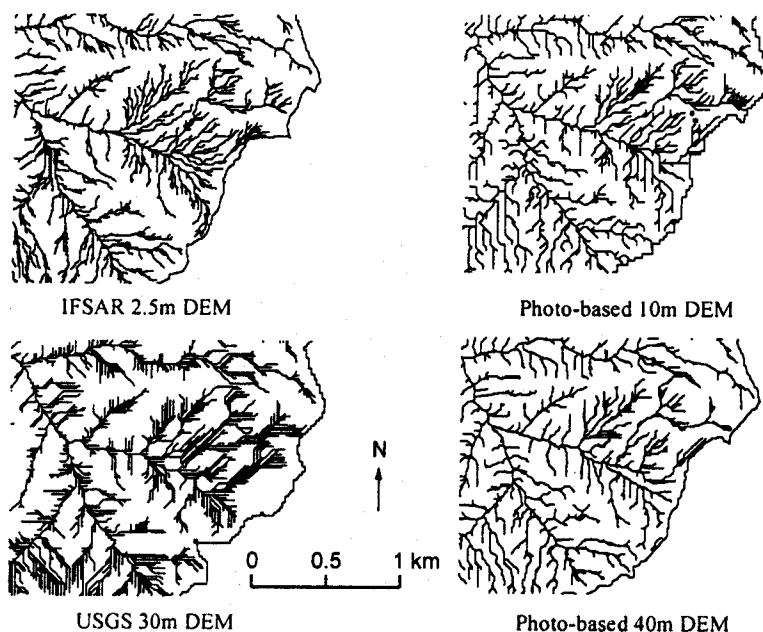


Figure 4. Drainage networks of a small section of Walnut Gulch derived from the various surface models.

The straight parallel channels evidence problems in network articulation due to the inaccurate estimation of flow direction in the USGS data, while the IFSAR data produces a much more complex network in some locations. Recall that the channel locations are dependent on flow accumulation following a critical source area of 0.35 ha. This technique produces spurious channels and represents an idealized channel network based strictly on

topographic convergence. An improved technique for producing channels incorporating field observations and other GIS data such as soil properties is needed to more accurately simulate drainage networks on complex watersheds.

Total drainage lengths were found to be considerably different among the four DEMs on smaller watersheds. Drainage density, defined as total channel length divided by watershed area, was found to be higher for watersheds and channels created with the 2.5m IFSAR DEM than for other surfaces (Figure 5). These differences could have profound impacts on flow routing, especially in semi-arid regions where transmission losses are of critical importance to watershed hydrologic and erosion modeling (Syed, 1999).

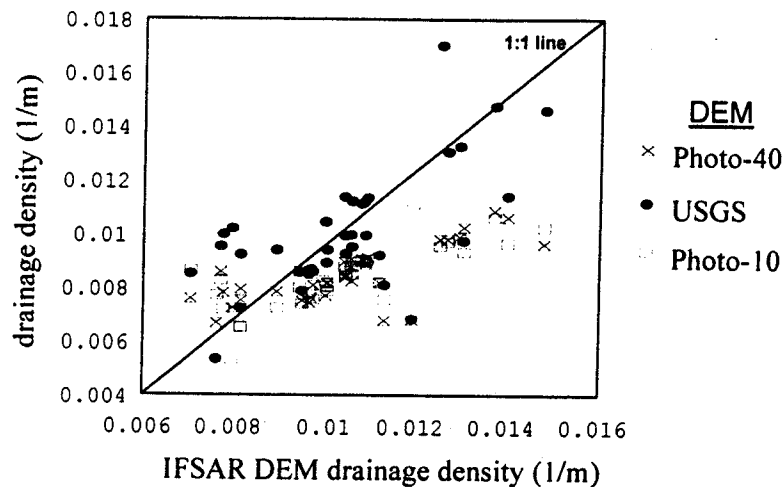


Figure 5. Drainage densities of watersheds created from three lower resolution DEMs relative to those of the 2.5m IFSAR DEM.

CONCLUSIONS

Several DEMs ranging in accuracy and resolution were used to generate standard watershed characteristics for application to hydrologic and geomorphic research at a range of basin scales. It was found that the high resolution IFSAR DEM (2.5m) provided significantly different results at small scales when compared to the other surfaces, while the differences among DEMs at larger scales were reduced. The suitability of various digital elevation data is primarily a function of the research objectives and scale of application. It is anticipated that the potential improvement in runoff process modeling provided by this emerging technology will be most significant at the small watershed and hillslope scale where processes that are affected by variability in topographic and drainage characteristics are dominant. At larger scales, the smoothing effects of larger cell sizes are reduced, obviating the need for highly articulated surfaces. Future research will focus on determining an optimal DEM as a function of scale for rainfall-runoff and erosion modeling. The IFSAR DEM data collected for this study was of significantly higher spatial resolution than conventional DEMs with very good elevation accuracy, and should prove a useful tool for detailed hydrologic and geomorphic research.

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