INFLUENCES OF MAP SCALE ON DRAINAGE NETWORK REPRESENTATION

Scott N. Miller,[1] D. Phillip Guertin,[2] and Lainie R. Levick[1]

In hydrologic and geomorphic research, the stream channel network is the basis for modeling and interpreting surface processes. Although the automated extraction of channels from a digital elevation model is becoming more widely applied, the standard method for delineating streams has been to capture them from aerial photographs and topographic maps. Much of the original research in basin geomorphology and scaling issues in hydrology was based on network data derived from commonly available maps. A serious flaw is inherent in this approach, however; the number of streams, basin order, and the resulting network complexity is primarily a function of the scale of the base maps. Hydrologic detail is lost when small-scale maps or photographs serve as the basis for interpretation. This paper presents the results of a study using multiple maps at a variety of scales (1:12,000, two sets at 1:24,000, and 1:62,500) on the Walnut Gulch Experimental Watershed in southeastern Arizona. Significant differences in stream order, network complexity, channel length, and runoff efficiency were found as a function of scale. These differences have potentially significant implications for current research issues on the watershed, including hydrologic modeling efforts incorporating routing, watershed analyses, and multiscale watershed modeling.

The stream channel network often forms the basis for watershed, basin, and regional scale assessments of hydrologic and geologic systems. Watersheds may be characterized according to their drainage structure, which is determined by the underlying lithology and topography. Drainage patterns form in response to energy forces such that total channel length is minimized and drainage efficiency is maximized. A number of factors influence how a watershed conveys water and sediment. Rather than attempting to quantify each of these factors, it is convenient to use more readily measured geomorphic properties as proxies for other watershed characteristics. In this manner, inferences regarding hydrologic response and comparisons among catchments for classification and comparative analyses can be made (Gordon et al. 1992). This paper investigates the role that base maps have on such analyses in a semi-arid rangeland.

Intensive watershed characterization is time consuming and costly when done by traditional means. This cost has been an impediment to large-scale studies requiring morphometric measures. The advent of geographical information systems (GIS) allows for the rapid and precise determination of a host of channel and watershed characteristics. Caution is advised when undertaking these analyses. It is especially important that limitations imposed by the choice of base data be clearly defined and understood by the researcher.

Several factors are critical to the determination of stream channel location on the watershed. Most obvious is map or photo scale. At larger scales, objects are more readily detectable, and smaller features may be discriminated. In addition to the limitations on interpretation inherent in using small-scale maps, decreasing the scale also reduces the amount of information that can be included on a map for presentation. Hence, even though USGS 7.5' and 15' topographic maps may be based on the same photographic source, the small-scale 1:62,500 15' quadrangles will convey less information. Perhaps more relevant to photointerpretation is that image resolution (e.g. ground resolution distance) plays a key role in the discrimination of landscape features. Decreasing the pixel size within an image reveals smaller features, such as first-order channels or instream channel bars. Poor contrast or reduced image quality can also adversely affect photointerpretation.

[1]USDA-ARS Southwest Watershed Research, Tucson, AZ 85719
[2]Watershed Management Program, School of Renewable Natural Resources, University of Arizona, Tucson 85721

Modeling and interpretation of hydrologic processes is often reliant on a high-quality representation of the hillslope and drainage system within a watershed. Rainfall-runoff processes in the semi-arid Southwest are characterized as intermittent, high-intensity events during which water is rapidly transported through a watershed. Due to the low water tables and gravelly soils, high transmission losses predominate. Because transmission losses operate within the drainage system, adequate channel representation is important for accurate runoff modeling. Erosion and sediment transport are dominated by actions occurring within stream channels; thus, a sound depiction of the channel network is necessary for modeling and understanding the processes involved in sediment movement.

Channel morphometric measures have long been used as tools for watershed assessment and classification. The concept of channel ordering was first outlined by Horton (1932), and was later amended by Strahler (1952) to decrease the subjectivity of the analysis. The Horton-Strahler method denotes the uppermost channels, those with no incoming tributaries, as first order. Where two first-order channels converge, the downstream segment is ranked as second order. If two channels of different orders converge, the downstream segment is ranked as the higher of the two channels. In this manner, a watershed is characterized with an abundance of lower-order channels, with successively fewer higher-order channels. In his seminal research into the relationship between channel systems and their contributing areas, Horton (1945) introduced several laws governing watershed-channel relations as a function of scale, relying heavily on channel ordering. This research led to a cavalcade of geomorphologic and hydrologic research on the characteristics of drainage basins and their influences on hydrologic and erosional response (see Abrahams 1984 for a critical review).

Horton's law of stream numbers stipulates that the number of channels of a given order will decline according to a given ratio for a basin (eq. 1), whereas the law of stream lengths governs the increase in average channel length by increasing order (eq. 2), and the law of stream areas illustrates the increase in support area by order (eq. 3). As shown, these so-called laws of drainage network composition approximate to geometric progressions of inverse (law of stream numbers, eq. 1) or direct (laws of stream lengths, eq. 2, and stream areas, eq. 3) form:

$$R_B = \frac{N(w)}{N(w+1)} \tag{1}$$

$$F_L = \frac{L(w+1)}{L(w)} \tag{2}$$

$$R_A = \frac{A(w)}{A(w-1)} \tag{3}$$

where (w) denotes a given channel order, (w+1) denotes the next higher order, N is the number of channels, L the average channel length, A the watershed area, R_B the bifurcation ratio, R_L the length ratio, and R_A the area ratio. Various researchers have demonstrated that bifurcation ratios range between 2 and 5, with an average in the United States of approximately 3.5 (Leopold et al. 1964), underscoring the preponderance of lower-order channels on a landscape.

The influence of map scale on such Horton-style analyses is intuitive. With a decline in the number of lower-order channels resulting from a decrease in map scale, the overall ordering arrangement of a basin can be profoundly affected. Leopold et al. (1964) described an ordering analysis conducted in New Mexico using different map sources. With a 1:24,000 USGS topographic map, the basin was determined to be first order (a single channel), but more detailed maps showed the basin to be fifth order. Thus, ordering techniques are scale dependent and should be used with caution in comparative analyses or for watershed assessment.

Drainage density is often used in geomorphic analyses because it reflects the underlying geology, climate, soil, vegetation, and historical use of a region. Watersheds with high sediment yield, such as those found in semi-arid regions, generally have high drainage densities relative to their counterparts in more humid climates. Drainage density (R_D) is defined as the cumulative channel length (L) for n channels divided by the watershed area (A), as shown in equation 4.

$$R_D = \frac{\sum_{1}^{n} L}{A} \tag{4}$$

Recent studies into the fractal geometry characteristics of stream patterns have focused on the self-similarity of drainage networks with an eye towards inferring optimal drainage networks and self-organization (Bak et al. 1987; Rodriguez-Iturbe et al. 1992; Maritan et al. 1996). Such interpretive work relies greatly on the quality and accuracy of the maps from which the fractal structure is inferred. The fractal dimensions of the study area are not explored here, but future research regarding the role of map scale in fractal geometry in the semi-arid Southwest is surely warranted.

This paper presents the results of a GIS-based watershed and drainage analysis in a semi-arid region in the U.S. Southwest. Stream channels were digitized and captured in GIS from a variety of data sources, including those represented on USGS 7.5' and 15' quadrangles and interpreted from large-scale aerial photography. The channels were ordered according to the Horton-Strahler technique; drainage characteristics extracted for 39 subwatersheds ranged in scale from less than 0.5 km^2 to almost 150 km^2. The scale and resolution of the data used to delineate stream channels significantly affected the ordering analysis as well as other geomorphic indices commonly used for watershed characterization and comparison.

Description of the Study Area

The USDA-ARS Walnut Gulch Experimental Watershed is located in southeastern Arizona and encompasses the historical town of Tombstone (Figure 1). The 148 km^2 watershed lies within the transition zone between the Chihuahuan and Sonoran deserts, and the climate is classified as semi-arid or steppe (Renard et al. 1993). Soils within the watershed are primarily gravelly sandy loams with a moderate to high calcium carbonate content. The majority of the watershed overlies deep alluvial deposits, but in some localized areas bedrock exists near the surface and exerts a controlling influence over the stream channel system. The drainage pattern is primarily dendritic with a relatively high density, but where near-surface bedrock or faults are exposed, the pattern is less dense and is more accurately described as rectangular. Eighty-nine recording rain gauges measure rainfall across 40 nested subwatersheds, many of whose runoff is gauged with either a supercritical flume, a v-notch weir, or a stilling well. Mean annual temperature in the town of Tombstone is 17.6°C and mean annual rainfall is approximately 320 mm.

Approach

Four sets of base map data, two sets of topographic maps and two sets of low-level aerial photography, were compiled for this study (Table 1). The smallest-scale topographic maps were 1:62,500 USGS maps derived from national high-altitude photography (NHAP) with a 1–2 m pixel resolution and compiled as 15' quadrangles (USGS 1999). USGS 7.5' topographic maps (1:24,000 USGS), widely available and common in hydrologic research, were used as well. These maps were also derived from NHAP photography, but were produced on a 1:24,000 scale. Low-level aerial photographs of Walnut Gulch at a scale of 1:24,000 (1:24,000 a.p.) were taken in 1989. These photographs have a 0.5-m pixel resolution and were orthogonalized and geo-rectified to remove distortion and ensure positional accuracy. Large-scale versions of these photos, blown up to 1:5,000, were used to delineate stream channels. The largest-scale data set was a compendium of 1:12,000 aerial photographs with approximately 0.3-m pixel resolution that were neither geo-rectified nor orthogonalized. Because of the distortion inherent in these photos, direct comparison through overlays or positioning of the channels was impossible.

For direct comparison it is vital that various data sources used in an interpretation exercise be orthogonalized and geo-rectified. Orthogonalization entails removing horizontal and vertical image distortion resulting from lens curvature and instrument quality. Geo-rectification is used to properly locate landscape features relative to one another within an image. However, general trends and significant differences can be inferred from data that are not of commensurate quality. In this study, three sets of base data were geo-rectified and orthogonalized, whereas the 1:12,000 aerial photographs were not; some error is therefore accepted in the determination of channel lengths and drainage density. Any errors due to distortion or misplacement will be most significant on smaller areas; as the study area is increased, small-scale variability has less impact.

Table 1. Data sources used in the delineation of stream channels.

Data Source	Scale	Pixel Size	Orth.	Geo.
1:12,000	1:12,000	0.3m	n	n
1:24,000 a.p.	1:24,000, 1:5,000	0.5m	y	y
1:24,000 USGS	1:24,000	1–2m	y	y
1:62,500	1:62,500	1–2m	y	y

Orth. = orthogonalized; Geo. = geo-rectified.
1:12,000 = 1:12,000 aerial photographs, 1:24,000 a.p. = 1:24,000 aerial photographs, 1:24,000 USGS = 7.5' USGS topographic maps, 1:62,500 = 15' USGS topo maps.

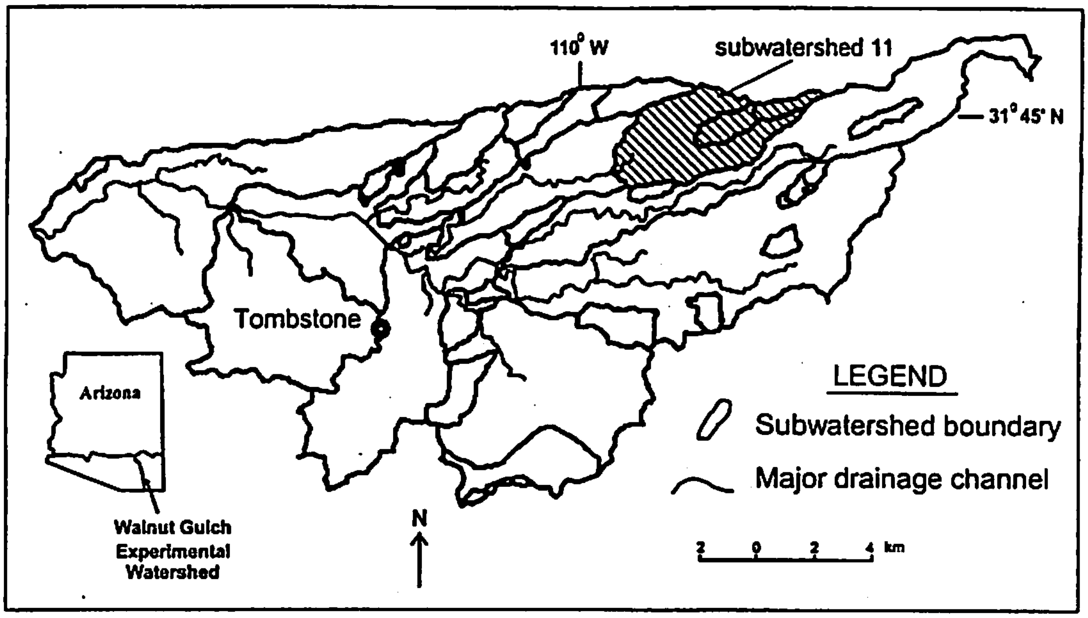

Figure 1. Location of the USDA-ARS Walnut Gulch Experimental Watershed showing nested subwatershed design with major stream channels. Subwatershed 11 is highlighted for reference in Figure 2.

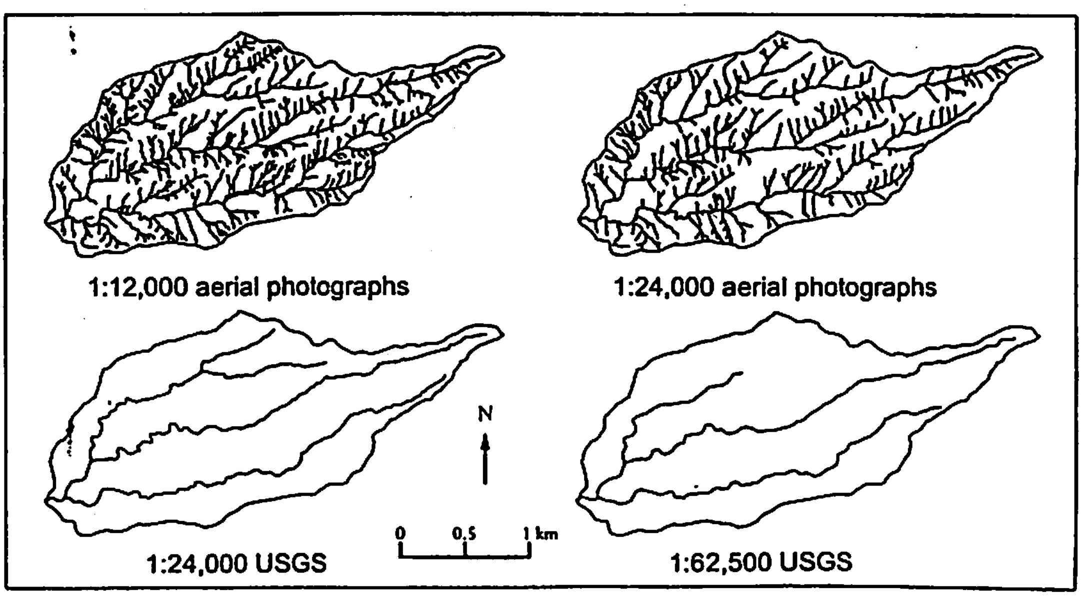

Figure 2. Digitized stream channels within subwatershed 11 on Walnut Gulch. Note how the drainage density decreases with decreasing scale while the underlying structure of the drainage pattern is retained.

Both of the USGS topographic map products are produced with defined stream channels; therefore, no interpretation as to channel position or length was made. Each of the blue lines designating a channel, including dashed lines indicating an ephemeral drainage, was digitized into Arc/Info GIS (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). Minor editing was done to ensure connectivity between quadrangles. Note that only larger channels are included in the USGS topographic maps due to the limitations imposed by national mapping standards; incipient drainages and small channels are generally not included on USGS maps. Determining channel locations from the aerial photography was a multistep process. In the case of the 1:12,000 photos, Wallace and Lane (1978) had previously traced the channel networks from a series of overlapping aerial photographs onto individual sheets. These tracings were digitized into Arc/Info, where some rubber sheeting was necessary to join and edge-match the sheets. Obvious position locators, such as channel intersections, were used to geo-position the digitized data. Because the 1:24,000 aerial photographs were geo-rectified and blown up to a scale of 1:5,000, no such data smoothing was necessary. Stream channels in each of the 24 photographs covering the watershed were traced onto mylar using a light table. Channels smaller than 1.5 m to 2 m in width were digitized as linear features, and larger channels were digitized as polygons, including alluvial features such as mid-channel bars and floodplains. Where channels were digitized as polygons, a perpendicular bisector was drawn using GIS techniques to extract a vector-based channel network. Figure 2 shows the digitized stream channels for subwatershed 11 for each of the base data sets.

A GIS algorithm for determining channel order presented by Miller et al. (1996) was used to order the channels for each of the four stream channel theme layers. This algorithm uses the arc-node vector topology defined for linear features in Arc/Info to sequentially sort through each of the channel segments and order them according to the Horton-Strahler technique.

The nested subwatershed design of the Walnut Gulch area served as the basis for investigation into issues of scale. The outlines of 39 subwatersheds ranging in size from 0.0035 km^2 to 148 km^2 were used to clip out the stream channels that were digitized from each of the data sources using GIS techniques. In this fashion, 156 stream channel GIS theme layers were created. Stream channel properties, such as maximum channel length, drainage density, and cumulative channel length, were determined using GIS analysis. Watershed area, used in the calculation of drainage density and in analyses of scale, was extracted from the GIS database for each of the 39 subwatersheds.

Results and Discussion

According to the largest-scale data used in this analysis, Walnut Gulch is a seventh-order watershed. However, as shown in Figure 3, ordering based on the other maps did not yield the same result; decreasing the map scale results in a decrease in the order of the watershed. An analysis of the four ordering systems using Horton's (1945) law of stream numbers (eq. 1) further illustrates the impact of map scale on ordering. In theory, a watershed should be represented by a single bifurcation ratio (R_B). Note that in Table 2 the bifurcation ratios are widely scattered, with a large decline in average R_B for the USGS data, indicat-

Table 2. Results of bifurcation ratio analysis.

	1:12,000		1:24,000 a.p.		1:24,000 USGS		1:62,500	
Order	No. of channels	R_B	No. of channels	R_B	No. of channels	R_B	No. of channels	R_B
1	6,286		3,572		205		74	
2	1,419	4.43	920	3.88	49	4.18	18	4.11
3	266	5.33	189	4.87	13	3.77	6	3.00
4	60	4.43	36	5.25	5	2,60	2	3.00
5	15	4.00	10	3.60	1	5.00	1	2.00
6	3	5.00	1	10.00				
7	1	3.00						
Mean R_B		4.37		5.52		3.89		3.03

ing that substantially fewer small channels were captured in the original interpretive work. The average R_B for the 1:24,000 a.p. data is somewhat deceiving because there are a large number of fifth-order channels and only one sixth-order channel. The high R_B between orders five and six is unexpected, but can be explained by the vagaries of aerial photo interpretation.

The answer to the question as to what constitutes a channel is both somewhat arbitrary and researcher dependent. A set of rules was drawn up by Miller (1995) for the determination of stream channels from the 1:24,000 aerial photographs, but these rules assuredly differ from Wallace and Lane (1978) and USGS methodologies. Random laboratory error cannot be ignored as a source of differences among maps, although quality control practices can reduce this problem. After the discrepancy in R_B values was found for the 1:24,000 a.p. and USGS data, a survey of the original photographs was undertaken to determine if an interpretive error caused the shift. It was found that a single channel, strategically placed, would cause a cascade in the ordering system and the R_B values similar to those of the 1:12,000 maps. However, according to the rules for channel interpretation, no changes could be made to the digitized data.

The average channel length of each order by map set was determined within the GIS. These data were used in the calculation of the length ratio (Horton's law of stream lengths, eq. 2). Results from this analysis were not as well behaved as those of the law of stream numbers (Figure 4). Although the 1:12,000 and 1:24,000 a.p. data progress in the expected geometric manner with increasing order, neither the 1:24,000 USGS nor the 1:62,500 maps exhibit as direct a trend. The differences in the USGS data relative to the aerial photography are due to the lack of small channels; the average first-order channels are more than a kilometer long on the 1:24,000 USGS data, compared to slightly over 200 m for the 1:24,000 a.p. data. The average length ratio decreases with scale: the 1:62,500 data have an average length ratio of 1.2, compared to a ratio of 2.2 for the 1:12,000 a.p. data. If the law of stream numbers were to be used as a proxy for watershed response, interpretation of runoff efficiency would be greatly affected by the underlying map scale.

As there is a direct relationship between channel order and watershed area, area may be substituted for channel order to represent increasing scale in channel investigations. This substitution reduces some of the influence of a researcher's tendencies in channel delineation because small discrepancies can lead to large differences in order analysis. Watershed area was used to illustrate the loss in small watershed variability with decreasing map scale and the strong relationship between channel length and watershed area.

Drainage density (R_D), a measure of the runoff and transport efficiency of a watershed, was also found to vary a great deal as a function of map scale. Decreasing the map scale resulted in a significant overall reduction in drainage density (Figure 5). Drainage densities were determined for each of the 39 subwatersheds used in this study, and their areas are plotted on the x-axis of Figure 5. Note the high variability in R_D at smaller watershed areas. This variability is due to localized differences in soils, topography, vegetation, and geology. Small-scale variability in channel definition is lost on the larger watersheds as average values tend to dampen smaller signals. Different erosional processes occur at different scales; at the finest scale, hillslope form is determined by sediment transport processes and by the production rate and availability of erodible materials. At progressively coarser scales, the watershed owes its form to a combination of processes operating on the finest scales and erosion and transport by smaller channels not depicted on the small-scale maps. Figure 5 underscores the need for detailed mapping and large-scale data on smaller watersheds. Note the dampening of the small watershed variability by the USGS data; many of the small, lower-order channels are not delineated on these maps, and the R_D values for those watersheds are therefore reduced. By removing the noise generated by small watershed variability, the overall picture of the watershed is significantly altered; here the USGS-based information appears to be more uniform across a range of scales than the aerial photography data.

The law of stream lengths can be used to illustrate the organization of stream patterns across a range of watershed scales: with increasing order (and therefore watershed area), there is a steady increase in both average and cumulative channel length (sum of all channel lengths within a basin). Linear regression models were fit between the cumulative channel lengths and watershed areas for the 39 subwatersheds at each of the map scales (Table 3). Strong power function relationships with high coefficients of determination (r^2)

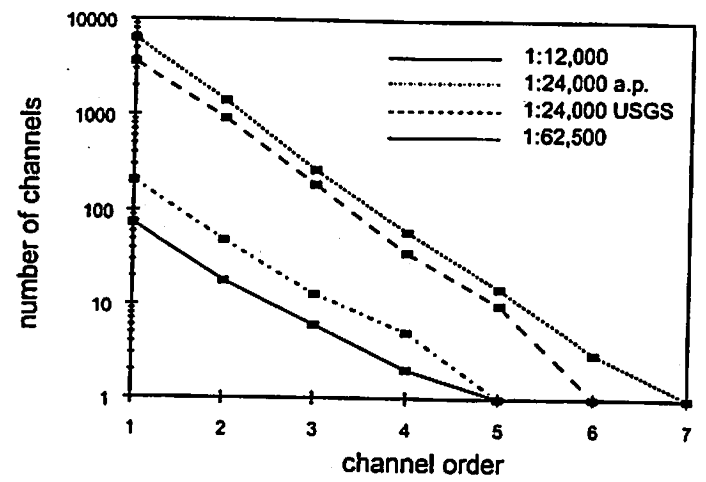

Figure 3. Number of stream channels by order as a function of map scale.

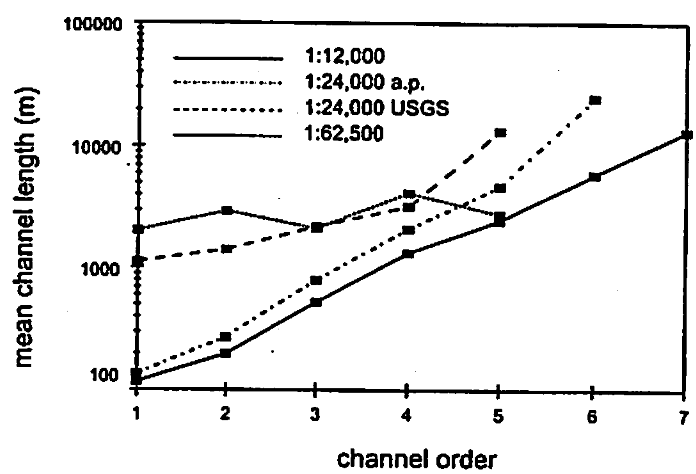

Figure 4. Average channel length by order as a function of map scale.

describe the increase in channel length with area (Figure 6).

All of the regression results presented in Table 3 were significantly different from one another. The principal separation between the results was the intercept, expressed as the coefficient in Table 3. The slopes of the lines, expressed as the exponent, are all similar. These results are perhaps indicative of the underlying drainage pattern structure and watershed routing efficiency.

Table 3. Linear regression models predicting cumulative channel length as function of watershed area expressed as power functions. Cumulative channel length = cA^b.

Map Source	Coefficient (c)	Exponent (b)	r^2
1:12,000	14.25	0.95	0.96
1:24,000 a.p.	10.93	0.92	0.89
1:24,000 USGS	3.99	0.93	0.97
1:62,500	2.11	0.95	0.86

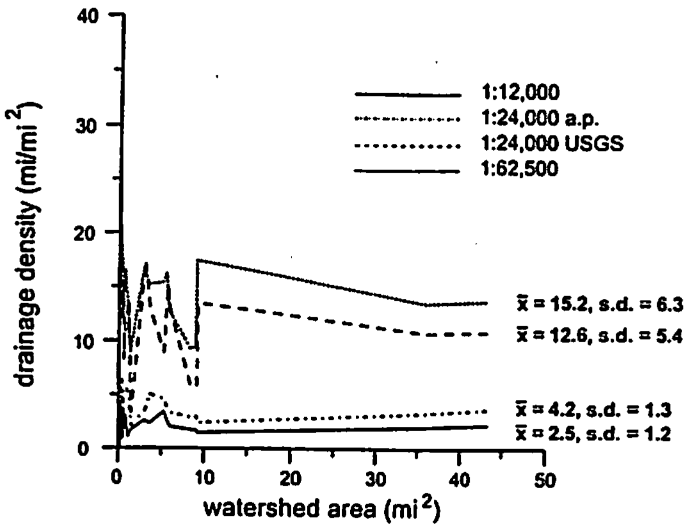

Figure 5. Drainage density as a function of watershed area and map scale.

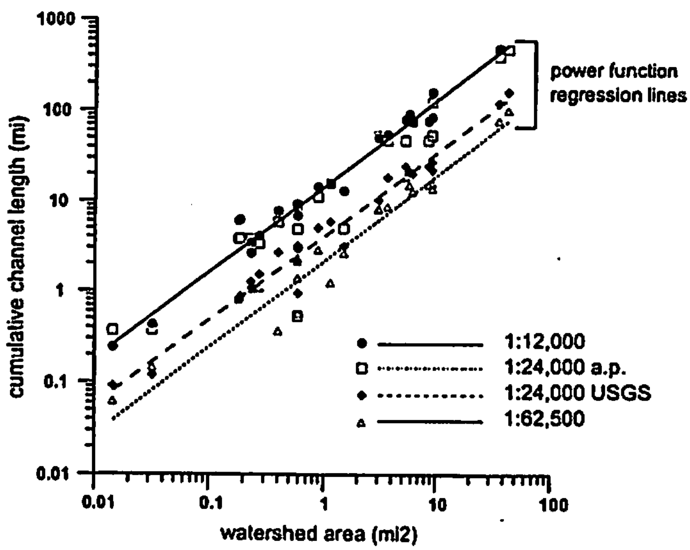

Figure 6. Cumulative channel length as a function of watershed area and map scale.

Conclusions

Four sets of maps and aerial photographs of different scales were used to delineate stream channels on the Walnut Gulch Experimental Watershed. Through GIS-based watershed and order analysis, it was demonstrated that the base scale significantly affects drainage articulation and basin characterization. Several reasons for differences in results are presented. The use of subjective guidelines for photo interpretation yields variable results even for the same base data. Base map scale restricts the amount of information that can be displayed on a given map. The original photo pixel resolution limits the amount of recorded information available for interpretation. When used for inter-basin comparison or watershed assessment, channel order analysis must be confined to maps constructed from similar data with similar techniques. Watershed area is perhaps better suited to studies involving scale issues in hydrologic and geomorphic analysis, and an approach for determining routing efficiency from watershed area is presented. Simple indices such as channel order are useful for watershed characterization and assessment, with the caveat that the techniques used to produce the results must be fully assessed before conclusions are drawn from the results.

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Volume 29

HYDROLOGY AND WATER RESOURCES IN ARIZONA AND THE SOUTHWEST

Proceedings of the 1999 Meetings of the

Hydrology Section
Arizona-Nevada Academy of Science

April 17, 1999, Northern Arizona University
Flagstaff, Arizona