

LINKING GIS AND GEOMORPHOLOGIC FIELD RESEARCH
AT WALNUT GULCH EXPERIMENTAL WATERSHEDScott N. Miller¹, D. Phillip Guertin², and David C. Goodrich¹

ABSTRACT: Offering a significant savings in time and labor, geographic information systems (GIS) have improved the efficiency and repeatability of geomorphologic assessment and hydrologic model parameterization. The objective of this study was to couple field measurements, spatial data, and GIS analytical capabilities to improve our understanding of channel geomorphologic processes. A high-resolution GIS database was constructed for the USDA - Agricultural Research Service (ARS) Walnut Gulch Experimental Watershed (148 km²). Field measurements of channel characteristics (cross-sectional area, width, and depth) were taken at 222 sample points. To characterize the areas contributing runoff to each of the sample points a suite of GIS tools was developed in GRASS and ARC/INFO. A routine capitalizing on the arc-node topology of stream vector data was created to order the extensive channel network on Walnut Gulch. Relationships were derived between channel shape variables and watershed characteristics with robust predictive capabilities. Channel cross-sectional area and width were found to be significantly related to channel order, upstream watershed size, and maximum contributing flow length within a watershed. The ability to accurately and efficiently model channel characteristics in the southwestern United States offers the potential for improving the performance of hydrologic models as well as aiding the integration of hydrologic models and GIS.

KEY TERMS: GIS, channel morphology, hydrologic modeling, cross-section.

INTRODUCTION

Because of the time and degree of technical skill required for the completion of geomorphology studies, individual projects have historically been limited in size and scope. With the advent of geographic information systems (GIS), these technical problems have been assuaged. The GIS capability of storing large and diverse quantities of spatial data allows for the complex analysis of many sites to be carried out quickly, efficiently, and with a high degree of repeatability (Burrough, 1986). However, GIS-based projects often fail to integrate field-collected data with GIS spatial data. This project was designed to relate the GIS characterization of spatially distributed watershed characteristics with field measurements of point-attribute data (channel cross-section surveys). These data sets were related using statistical analysis to derive relationships between watershed characteristics and channel shape.

Watershed characterization based on geometric and physical properties was carried out in a GIS on 222 subwatersheds within the Walnut Gulch Experimental Watershed. At the same time a field measurement program was completed in which channel shape characteristics were measured at the outlet of each subwatershed. Statistical analysis between the two data sets showed a strong relationship between channel shape and watershed characteristics. It was shown that the derivation of hydrologic model parameters may be effectively carried out in a GIS on a large number of data points in a relatively short amount of time.

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With its long history of data collection and observational data, Walnut Gulch serves as an excellent location on which to conduct research into geomorphologic and hydrologic processes (Renard et al., 1993). Relatively little work, however, has focused on the characterization of the entire watershed. This lack of data has limited the ability to model landscape processes on a basin scale (Lane et al., 1994). Additionally, most of the research on the relationship between channel and watershed characteristics has been conducted on intermittent and perennial streams. A knowledge gap therefore exists for this type of data on aridland watersheds and the processes acting on ephemeral channel systems such as exist on Walnut Gulch (Osterkamp et al., 1983; Lane et al., 1994). Instead of limiting this work to a small section of the watershed, it was decided to characterize as much of the watershed as possible. Sample sites were located randomly across the entire 148 km² watershed within all soil types and many hydrologic conditions. Strahler ordering analysis (Strahler, 1952) and other measures of channel and watershed characteristics were utilized to describe the watershed as quantitatively and thoroughly as possible.

Analyses of basin characteristics have been carried out in a GIS environment for many years (Burrough, 1986; Garbrecht and Martz, 1995), but many of these processes were found to be incompatible or unworkable for the data collected during this project. Therefore, a suite of GIS analysis tools and ARC/INFO Macro Language (AML) programs were developed to facilitate the GIS investigation (trade names are mentioned solely for the purpose of providing specific information and do not imply recommendation or endorsement by the U.S. Department of Agriculture). Channel shape, required for hydraulic routing, cannot be accurately predicted (or extracted) from DEMs. Therefore a principle goal of this project was to develop a methodology for predicting channel shape from watershed characteristics that could be readily derived from commonly available GIS coverages. During this process, field research was synthesized with GIS applications and photogrammetry to more thoroughly describe the channel and geomorphologic characteristics than had previously been attempted.

SITE DESCRIPTION OF WALNUT GULCH

Located in southeastern Arizona (approx. 110°W, 31°45'N) and comprised of rolling hills and some steep terrain, the elevation of Walnut Gulch Experimental Watershed ranges between 1190 and 2150 m A.M.S.L. Some urbanization exists in and around the town of Tombstone, but cattle grazing and recreational activities are the major land uses. Vegetation within the watershed is representative of the transition zone between the Chihuahuan and Sonoran deserts, and is composed primarily of grassland and shrub-steppe rangeland vegetation.

Underlying Walnut Gulch is the geology of a high alluvial fan contributing to the San Pedro River watershed (Renard et al., 1993). Due to the enormous thickness and extent of the alluvial fill, the groundwater reserves are substantial, and can be found at depths ranging from 50 to 145 m (Libby et al., 1970). Some geologic control over the hydrology exists in the western regions of the watershed where metamorphic and orogenic activity has resulted in the fracturing and faulting of the bedrock. In 1994 the USDA Soil Conservation Service completed a detailed soil survey, finding that the watershed is dominated by 30 principle soil types (Breckenfield et al., 1995). Major soil units are Elgin-Stronghold (*Ustollic Paleargid*, *Ustollic Calciorthid*), Luckyhills-McNeal (*Ustochreptic Calciorthid*), McAllister-Stronghold (*Ustollic Haplargid*, *Ustollic Calciorthid*), and Tombstone (*Ustollic Calciorthid*).

The climate of Walnut Gulch can be classified as semiarid or steppe. Mean annual temperature in the city of Tombstone is 17.6 deg. C, with a mean annual precipitation of 324 mm. Annual precipitation is highly variable in both timing and total depth. Rain occurs mainly during two seasons: summer rains are the product of monsoonal, highly localized, convective storms; winter rains are generally low-intensity events that cover a larger proportion of the watershed. The majority of runoff occurring on Walnut Gulch is the product of summer storms, and is therefore episodic and of relatively high intensity (Renard et al., 1993).

FIELD DATA COLLECTION

A field measurement program was undertaken whereby 222 channel cross-sections were surveyed for morphometric assessment. To account for basin-scale variability, a large number of randomly selected points were used, and multiple measurements were taken at each site to account for local variability in channel shape. These randomly located sample point locations were pre-stratified by soil type using a GIS procedure: each major soil type was assigned a weighted proportion of the sample points based on the areal extent of the soil coverage. At each site 3 cross-section surveys were taken to characterize the channel section just above the outlet of the subwatershed. Width and depth were measured at breakpoints (changes in slope). The three surveys were then combined to determine the average width and depth for the channel segment, and these results were combined to derive average cross-sectional area.

A strict protocol was followed at each sample location in order to ensure proper measurement and consistency between sites. Upon arrival at a site, an inspection of the bank morphology, vegetation, and soil characteristics along the entire reach was completed to ensure that cross-sections were located where they would be most representative of the channel section. A site description was recorded in a log book for future analysis, and potential problems related to channel complexity and morphology were noted where applicable. Bankfull indicators, including slope breaks, changes in bed or bank materials, a shift in vegetative type, debris lines, and bank staining were noted in order to determine the bankfull depth (Osterkamp et al., 1983; Gordon et al., 1992; Harrelson et al., 1994). Wherever possible, evidence indicative of a constructive, rather than destructive process, was used to determine bankfull depth. In the southwestern United States channel processes are governed by rapid and violent runoff events, and many of the channels on Walnut Gulch are actively degrading. Channels that were clearly degrading and out of equilibrium were not subjected to channel measurement since an adequate determination of bankfull depth was not possible.

At each of the site locations a minimum of three cross-sections were surveyed. If the channel reach was complex, up to five cross-sections were measured to ensure adequate representation. At each of the cross-sections a light line was pulled level across the channel top at the bankfull depth. The line was leveled and pulled taught to reduce sag. Measurements of channel depth and distance from the left bank (looking upstream) were taken at each break in slope across the cross-section.

Channel width was more easily measured with precision than channel depth. Although determining the stage to which floodwaters rise proved difficult, the possibility for error was greater when measuring depth. This is due to a number of factors. First, depth was only measured at break points, which are to some degree subjective. Second, there was always a slight amount of sag in the line when it was stretched across a channel, lending a source of imprecision to the depth measurements. Third, more random deposition or scour of the stream channels tends to impact local channel depth measurements to a greater degree than width measurements.

GIS DATABASE DEVELOPMENT AND ANALYSIS

Given Walnut Gulch's history as a research site into various aspects of hydrology and natural resource management and its extensive rainfall and runoff database, it was decided that the GIS database would be created at a resolution not ordinarily attempted. Throughout the database development, an answer to a basic question was sought: what are the highest levels of precision and accuracy that could be achieved? There can be a tendency by GIS developers to overestimate the level to which data may be discretized. By attempting to create maps with a higher resolution than is allowable by the data, errors may be introduced, and a false level of analysis can be attempted (Burrough, 1986). Fortunately, data available for Walnut Gulch were of a quality that allowed for a very high level of resolution and positional accuracy.

Of particular relevance was the stream channel coverage. In many GIS studies, the channel network is derived from a DEM in a raster environment and then translated into vector data. Alternatively, channels may be digitized from USGS topographic maps, but channels drawn on these maps are partly based on DEMs. Traditional GIS technique dictates that the majority of channels be digitized as single vectors bisecting the channel position, with a few of the larger drainages characterized with two lines to illustrate relative width. Since a correlation was to be made in this study between channel shape and watershed variables, a channel network map was constructed whereby only the smallest channels were digitized as single vectors. Channels wider than approximately 1.5 meters were drawn as polygonal features. This highly detailed procedure relied on the 1:5000 orthophotographs as the base from which the stream positions and characteristics could be extracted. Most of the channels on Walnut Gulch were thus characterized in the GIS database as polygons, with associated width characteristics. In addition, where channel islands and bars were visible on the orthophotographs they were digitized. Thus, the channel network theme layer provides a detailed record of the channel system and its hydrologic characteristics as existed at the time (April, 1988) the aerial photographs were taken.

An important variable for the understanding of geomorphologic relationships is stream order. In this case the intensive channel network map was a drawback: because most of the channels were digitized as polygonal features it was not possible to automatically order the streams. To take advantage of GIS arc-node topology, the stream channels were vectorized. First, the map was translated into GRASS and rasterized with a one-meter resolution. The GRASS module "r.thin", which draws a parallel bisector through polygons, was executed on the stream map (Geographic Resources Analysis Support System, 1991). Upon completion of the vectorizing process, the maps were appended together and edited to remove spurious vectors created as a byproduct of the thinning process.

The vector stream channel map was then re-exported into ARC/INFO, which supports both vector and routing functions. An ordering routine was created that takes advantage of the "from" and "to" node data structure that ARC/INFO imposes on vector maps. All the streams first had to be oriented in the downward direction (i.e. pointing downstream). Once the streams were all pointing in the downstream direction, the ordering program was initiated. By assigning all vectors that had an open-ended "from" node an order value of one, it was possible to stimulate a cascading effect, whereby all vectors were assigned a stream order based on their relationship and connectivity to other channels.

A 10m resolution DEM provided the basis for the articulation of subwatersheds and the creation of many theme layers important to the statistical analysis of field data. Created from a large number of spot elevation points, contour data, and a thinned version of the channel network using the ARC/INFO tool "topogrid" (Environmental Systems Research Institute, 1994), the DEM was resolved to a 10 by 10 meter gridded surface. Using the "selectpoint" option within the "watershed" command in GRID, subwatersheds were delineated above each of the 222 channels surveyed in the field. From the DEM theme layers for flow direction and flowlength were created for each watershed. Watershed characteristics that were derived with the GIS included: watershed area; maximum flow length; average slope; elevation characteristics; and watershed shape variables.

STATISTICAL ANALYSIS

Descriptive statistics implied that stream order was significantly related to channel shape variables. An analysis of variance showed that significant differences exist for channel width, depth, and cross-sectional area between each stream order. Multiple analysis of variance proved average watershed soil clay content to have no influence on channel shape. Relationships between channel shape variables and watershed parameters were investigated using simple linear regression analysis. Having found strong relationships between these variable sets, multiple regression analysis was employed to further refine these relationships.

RESULTS

For the purposes of evaluating the relationship between channel morphology and the contributing area, the relationships describing the channel cross-sectional area were of primary interest, and deterministic models were derived using regression analysis. Channel cross-sectional area is a function of both channel width and average depth and thus reflects the total channel response to its hydrologic regime. Channel width can be extracted from a high resolution GIS such as exists for Walnut Gulch. Therefore, given a strong statistical relationship between cross-sectional area and watershed parameters, it would be possible to fully articulate channel geometry (width, depth, cross-sectional area) for all channels throughout Walnut Gulch. This ability to model channel shape accurately when a minimum of field data is available may benefit the application of a host of hydrologic models that incorporate hydraulic channel routing (i.e., HEC-1, Army Corps of Engineers- Feldman, 1995; the USGS DR3M model-Alley and Smith, 1982; KINEROS-Woolhiser et al., 1990).

Horton (1945) investigated the role of stream order on channel shape and hydrologic processes. He found that stream order was highly correlated to many watershed and channel variables, and that stream order could be used as a predictive tool for these variables. Strong relationships between stream order and channel shape were also found to exist on Walnut Gulch (Table 1). In this project, statistically significant differences were found to exist between the means of channel width, depth, and cross-sectional area for each step in stream order. Stream order, which is closely related to contributing area, was found to exert a strong effect on channel shape, and was used to stratify the data into subcategories for further analysis.

Table 1: Relationship of channel morphology variables to stream order.

Order / N	Average Width (cm)	Average Depth (cm)	Average Cross-Sectional Area (m ²)
1 / 58	279.65	26.32	0.802
2 / 65	404.32	34.57	1.47
3 / 40	563.03	40.10	2.54
4 / 26	960.39	54.94	5.63
5 / 20	1967.42	52.58	10.58
6 / 13	3329.99	79.69	26.21

Channel characteristics were related strongly and in a semi-log fashion to stream order. Average channel width, depth, and cross-sectional area were all directly related to order, with a break in the trend occurring between the fourth and fifth order channels, but only for channel width and depth; cross-sectional area maintains a semi-log relationship throughout each step in order. The average value for channel depth shows a decrease between channel orders four and five, which is out of trend for every other increase in order (Figure 1). However, there is a significant increase in channel width between the fourth and fifth order channels, effectively counteracting the decrease in depth so that the relationship between cross-sectional area and stream order remains consistent across each order. The overall effect on channel shape is an increase in the channel width:depth ratio, while the relationship of cross-sectional area to order (and, hence, upstream watershed area) remains consistent (Figure 1).

Statistical Properties of Channel Shape

Channel width appears to be more sensitive to the influence of watershed parameters than channel depth. Measured values of width have a large spread in their data, while the values for depth show a more central tendency with a lower variation. Without exception channel width proved to have a higher coefficient of determination than depth (e.g. $r^2 = 0.33$ for depth, and 0.72 for width when related

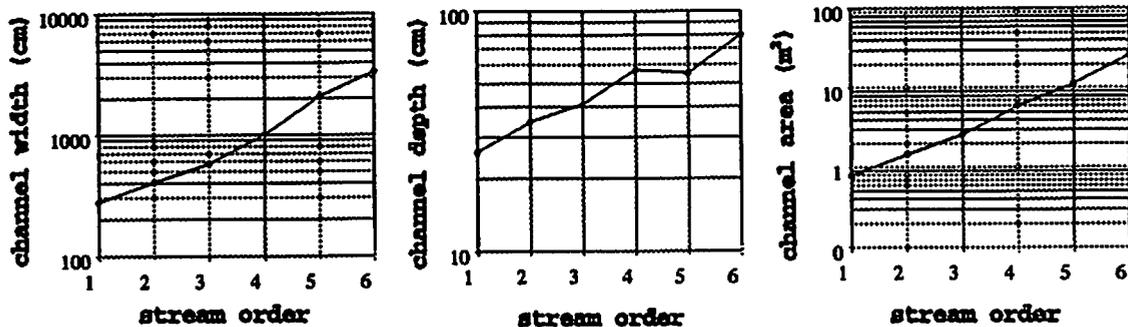


Figure 1: Semi-log plots of channel shape variables per stream order.

on a log-log basis to watershed area) when regression analysis was performed. In fact, depth proved to be resistant to any deterministic model based on the variables used in this study. Some of this resistance to forming a deterministic relationship may be a function of the difficulties associated with precisely measuring depth in the field. Fluvial characteristics are undoubtedly important to this tendency: as flow energy increases in a channel, the channel will adjust its shape to accommodate the increased level of power and erosive energy. This can be accomplished through the widening, and/or deepening of the channel. In the loosely consolidated soils of Walnut Gulch, the channels appear to respond to elevated flow energy by increasing their channel width proportionally more than depth.

Responding to the runoff they receive from uplands, stream channels constantly adjust their shape to achieve equilibrium with the flow volume. Changes in channel morphology may result in either degradation or aggradation, with a resultant change in the width:depth ratio, but the net effect is a change in the channel cross-sectional area. As such, the measurement and analysis of channel cross-sectional area is an effective method of illustrating the manner in which channels are responding to watershed characteristics.

A strong relationship exists between channel area and the maximum flow length within a watershed ($r^2 = 0.79$). Table 2 shows the results of regression models involving channel area. Long flow lengths within a watershed have been directly related to discharge (Leopold et al., 1964). With higher flows, the channel will become enlarged, either through bed scour or bank erosion, to accommodate the larger flows, resulting in an increased channel cross-sectional area. Following the same reasoning, a strong relationship between channel cross-sectional area and watershed area would also be expected. Data collected in this research support that logical extension. A log-log relationship ($r^2 = 0.68$) exists between channel cross-sectional area and watershed area. A strong relationship ($r^2 = 0.77$) exists between channel cross-sectional area and the watershed area:perimeter ratio, a measurement of the rotundity of a basin, and hence an indicator of basin response. Neither average watershed slope nor the relief ratio correlated strongly with channel cross-sectional area. The log of cumulative drainage length (total length of all channels in a subwatershed) had a moderate relationship to the log of channel cross-sectional area ($r^2 = 0.62$).

In order to improve on the relationships derived using simple linear regression, channel variables were related to watershed characteristics using multiple linear regression. Multiple regression analysis of channel cross-sectional area revealed the relatively strong role that channel order played in the determination of channel cross-sectional area. Systematic exploration of

the watershed data, using both stepwise forward and backward regression analysis, showed that channel area was heavily dependent on stream order and the area of and maximum flow length within the contributing watershed (Table 3). Depending on the subset of parameters investigated, it was possible to extract a significant regression model with a number of different independent variables. To avoid collinearity, multiple pools of data were used during the regression. Table 2: Results of linear regression analysis between channel area and watershed variables

Variable	Watershed Characteristic	r ²	Coefficient	Constant	Se _{yx}
channel area	maximum flowlength	0.79	0.001	1.83	3.46
log channel area	log watershed area	0.68	0.49	-2.44	0.34
channel area	area:perimeter ratio	0.77	0.03	0.17	3.60
log channel area	log cumulative channel	0.62	0.51	-1.38	0.40

analysis. For example, the relief ratio, a product of the maximum flow length and maximum elevation change, was considered separately from those two variables. The same separation was used for basin shape variables and watershed size. Note that a constant was not used in the analysis, and the equations were driven through the origin.

Table 3: Results of stepwise backwards multiple linear regression analysis for channel cross-sectional area as a function of watershed variables.

Case	Regression Model	r ²	Se _{yx}
1	Ca = 0.686(So) + 0.065(Aw) + 0.909(Lm) - 0.006(h)	0.849	3.36
2	Ca = 0.40(So) + 0.009(Aw) + 0.821(Lm) - 0.006(h)	0.851	3.35
3	Ca = 0.72(So) + 0.095(Aw) + 0.001(Lm) - 0.007(h) -	0.851	3.34
4	Ca = 0.616(So) + 0.001(Lm) + 0.001(S)	0.849	3.42

where: Ca = channel cross-sectional area (m²); So = stream order; Aw = subwatershed area (m²); Lm = maximum flow length (m); h = relief (m); Dl = sum of drainage lengths (m); S = basin slope.

CONCLUSIONS

Strong statistical relationships were derived between channel variables measured in the field, such as width, depth, and cross-sectional area, and a host of watershed parameters, including channel order, watershed area, shape, drainage properties, and elevation characteristics that were defined using a GIS. Channel cross-sectional area was related in a deterministic manner to multiple watershed variables, yielding models with strong coefficients of determination (r² > 0.84). Channel shape (and, hence, bankfull stage) may thus be predicted from watershed characteristics readily extracted from common GIS coverages.

Field data was successfully integrated with GIS-derived results. Channel cross-sectional area and other field-measured channel morphometric parameters were found to be strongly related to watershed characteristics extracted from a high-

resolution GIS. It is preferable to collect field data when developing parameters for application in hydraulic routing models, but field collection can be costly and time consuming. The channel coverage created for Walnut Gulch contains information on channel width. Using the values for width that can be extracted for the GIS, in conjunction with the developed regression models, values for channel depth and cross-sectional area may be calculated for all channel segments within the watershed. Relationships developed upon verification outside Walnut Gulch have the potential to overcome the inability of DEMs to parameterize channel cross-section properties. In this fashion hydrologic models can be parameterized using a GIS to aid in the understanding of hydrologic processes in the southwestern United States.

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