Management of Landscapes Disturbed by Channel Incision

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GIS APPLICATIONS IN THE SPATIAL EXTRAPOLATION OF HYDROLOGIC DATA FROM EXPERIMENTAL WATERSHEDS

S. N. Miller, M. Hernandez, and L. J. Lane [1]

ABSTRACT

Geographic information system (GIS) technology and regression analyses were used to generalize the relationships between watershed parameters and measured cross-sectional for the entire digitized stream network on Walnut Gulch Experimental Watershed, Arizona, USA. Flood frequency analyses were conducted for runoff data from 16 runoff measuring flumes with areas ranging in size from 0.0018 to 148 km^2 and periods of record ranging from 15 to 28 years. The 10 year flood peaks (m^3/sec) were related to watershed area in a logarithmic form similar to that which describes the relationships between watershed area and channel width and depth. Equations for channel width and depth as a function of the peak discharge estimates were derived using two techniques to form a generalized hydraulic geometry for the measured cross-sections. GIS technology and the historic runoff databases for Walnut Gulch were used to extrapolate the hydraulic geometry to cover the entire stream channel network on the 148 km^2 Walnut Gulch Watershed. This synthesis of GIS thematic databases and hydrologic databases for subwatersheds ranging in scale from 10^{-3} to 10^2 km^2 represents a new and unique hydrologic application of GIS technology, one that will greatly enhance our ability to parameterize hydrologic models at the watershed scale.

INTRODUCTION

Hydraulic characteristics of a stream channel, such as width, depth, and velocity have been used to illustrate the relationship between channel morphology, peak runoff, and sediment load (e.g. Leopold and Maddock, 1953). Given that width, depth, and velocity are inter-related, a change in channel width or depth for a given velocity will result in an equivalent change in the other channel characteristic. This interaction is illustrated with generalized power functions given by Leopold and Maddock (1953):

$$w = aQ_x^b \quad (1)$$
$$d = cQ_x^f \quad (2)$$
$$v = kQ_x^m \quad (3)$$

where w = channel width, d = channel depth, v = mean velocity, Q_x = peak water discharge of the x-year runoff event, a,c,k are coefficients, and b, f, and m are exponents. Assuming that

$$Q_x = wdv \quad (4)$$

it follows that

$$b + f + m = 1 \quad (5)$$

and

$$a * c * k = 1 \quad (6)$$

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As illustrated by these relationships, a change in a given channel hydraulic characteristic must result in an adjustment of one of the other variables so that these relationships remain valid.

The understanding of flow and sediment transport in semiarid rangelands has been improved through research into fluvial geomorphology. Graf (1983) used channel cross-section profiles in the investigation of sediment yield from Southwest rangelands, focusing on the role of stream power changes in the downstream direction. A significant relationship between channel morphology and watershed area on Walnut Gulch was reported by Murphey et al. (1977). The influence of peak runoff on channel erosion and gully migration was investigated in semiarid rangelands using cross-section and peak flow data (Osborn and Simanton, 1986). Miller et al. (1996) measured 222 channel cross-sections at the bankfull stage on Walnut Gulch and found significant relationships between channel hydraulic characteristics and watershed variables. They reported that channel shape variables were related in a log-log fashion to watershed area (r^2 = 0.72 for width; r^2 = 0.68 for cross-sectional area), a conclusion that is supported here.

The objective of this study was to develop a generalized hydraulic geometry for the Walnut Gulch watershed and apply the results to the stream channels in the GIS. Having these data contained in a GIS would allow for the rapid parameterization of hydrologic models and aid in the ongoing hydrologic research in the Southwest. In this study, channel width and depth were measured for the channel segments immediately upstream of 16 runoff measuring flumes. The values of both Q_2 and Q_{10} were derived for each of the flumes from historical records using flood frequency analysis. Regression analysis was employed to correlate the measured channel variables with Q_2 and Q_{10}. Using results from a GIS analysis of the area contributing runoff to each flume, the hydraulic characteristics of the channel segments were related to watershed area. A GIS technique was used to extrapolate a generalized hydraulic geometry across the entire channel system of over 3000 individual channel segments, using watershed area as the common variable.

GENERAL DESCRIPTION OF THE STUDY AREA

The Walnut Gulch Experimental Watershed (Fig. 1) is located in the San Pedro River valley in southeastern Arizona (approx. 110°W, 31°45'N). The watershed is approximately 148 km^2 in size, with elevations ranging between 1190 and 2150m A.M.S.L. Vegetation within the watershed is representative of the transition zone between the Chihuahuan and Sonoran deserts, and consists primarily of shrub-steppe and grassland rangeland vegetation.

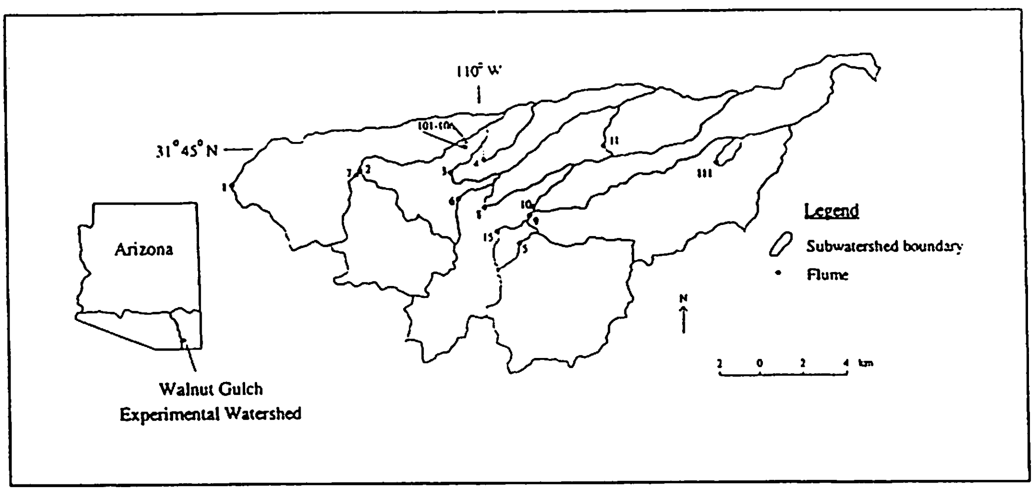

Figure 1: The USDA - ARS Walnut Gulch Experimental Watershed

The Walnut Gulch Experimental Watershed has served as a location for extensive investigations into the hydrologic behavior of semi-arid rangelands (Renard et al., 1993). A high-resolution geographic information system (GIS) exists for the Walnut Gulch watershed that includes thematic layers for soils, vegetation, and topography as well as a unique theme layer representing the channel network created in ARC/INFO[2] using 1:5000 digital orthophotographs (Miller, 1995). Channels wider than approximately 1m are represented in the GIS as polygonal features; smaller channels are captured as linear features. A digital elevation model (DEM) was created from 40m interval point attribute data. The DEM was improved by forcing the surface to fit the known stream locations. From this DEM a series of maps

[2] Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard 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.

representing the hydrologic characteristics of the watershed were derived, including flow direction and flow accumulation in each cell. Subwatersheds above the 16 flumes were delineated in the GIS using the results of the flow direction and flow accumulation maps.

Stream channels within Walnut Gulch are ephemeral, influent drainages, many of which have been recently incised (Lane, 1982). The majority of runoff occurs as a result of high-intensity, short-duration summer storms. The climate can be classified as semi-arid or steppe, with an average annual rainfall of 324 mm and an annual mean temperature in the city of Tombstone of 17.6°C (Renard et al., 1993). The underlying geology is that of a large alluvial fan, with groundwater levels ranging from a few meters to over 100m below the surface (Renard et al., 1993). Soils are typically well-drained, with some geologic control over runoff processes occurring as a result of faulting and near-surface bedrock (Breckenfeld et al., 1995).

An extensive network of rain gages and runoff measuring devices across the watershed allows for the quantification of temporal and spatial variability in rainfall and runoff events, which can be highly variable both in timing and volume. Runoff is measured from subwatersheds with a variety of gaging structures, including broad-crested V-notch weirs, H-flumes, and supercritical flow structures at various locations within the watershed (Fig. 1). Rainfall is measured by a network of 85 recording gages.

DATA COLLECTION

To relate flood frequency analyses with watershed characteristics, it was necessary to conduct a field research effort in conjunction with GIS investigations. The GIS was used to compute the areas contributing runoff to each of the flumes where cross-section profiles were surveyed. Data collected in the field were then related to the watershed area values acquired from the GIS and the measured values of peak runoff collected at the flumes (Tab. 1).

Table 1: Hydraulic variables measured and derived for channel segments above flumes

Flume ID	*Years of Record*	*Watershed Area (km^2)*	*Q_{10} (m^3/sec)*	*Channel Width (m)*	*Channel Depth (m)*	*Velocity (m/sec)*
63001	26	148	170	80.5	0.95	2.22
63002	28	112	259	37.6	0.97	7.10
63003	28	9.41	11.2	31.0	1.48	0.244
63004	24	2.27	12.6	20.9	0.74	0.804
63006	20	93.4	127	32.4	1.28	3.06
63007	16	13.6	62.7	20.9	0.75	4.00
63008	19	14.8	61.6	28.4	0.92	2.36
63009	15	23.9	72.8	38.9	0.73	2.58
63010	15	16.3	38.8	33.0	0.41	2.89
63011	19	7.82	65.0	64.2	0.58	1.73
63015	27	23.6	57.2	21.3	0.56	4.79
63101	17	0.0129	0.281	1.45	0.06	3.04
63103	17	0.0368	0.589	7.75	0.18	0.847
63104	17	0.0453	1.05	1.59	0.13	5.16
63105	17	0.0018	0.055	2.29	0.17	0.115
63111	20	0.53	8.61	22.1	0.29	1.36

Cross-section profiles of channel segments were surveyed above the flumes at 16 subwatersheds to characterize the stream profile closest to the flume (Fig. 1). Where possible, three cross-sections were measured: one at the uppermost portion of the reach; one in the approximate middle; and one close to the flume. A channel segment was defined as the upstream reach beginning above the obvious influence of the flume and ending at the first confluence of the main stem with a tributary.

Cross-sections were measured at the estimated level of bankfull discharge. Bankfull indicators, such as slope breaks, change in vegetation, change in surface soil characteristics, staining, and debris lines, were used to determine the maximum depth of flow. Channel cross-sections were measured using one of two methodologies depending on the size of the channel: smaller channels were profiled using a light line, line level, and tape; larger channels were surveyed using a total station in order to avoid complications with line sag and vegetation entanglement. Distance from the left bank (looking up-channel) and depth to the channel bed were taken at each break in slope. Average channel depth for the cross-sections were derived using a weighted average of the channel width for each portion of the cross-section. Average velocity was derived from Equation 4; values for channel width and depth were divided into the estimate of runoff. Summary totals for channel width, depth, and velocity were calculated as an average of the three cross-sections (Tab. 1).

RESULTS AND DISCUSSION

Using statistical methods, the field-measured hydraulic variables were related to the associated GIS-derived watershed area and the database-derived 2 and 10 year flood peak estimates derived from a flood frequency analysis (Tab. 1). Using regression analysis, it was found that Q_{10} is related to watershed area (A_w) by the power function

$$Q_{10} = 6.86A_w^{0.71} \qquad r^2 = 0.98; \qquad Se_{xy} = 0.07 \qquad (7)$$

where Q_{10} is in m^3/sec and A_w is in km^2.

Watershed area was also related to channel shape variables with regression analysis. Previous cross-section studies on Walnut Gulch (Miller et al., 1996) did not focus on stream channel segments immediately above the flumes measuring runoff. The advantage of this study is that it allows for the immediate correlation between channel shape and runoff, since little or no separation occurs between the measurement location and the flume. Channel depth and width both have a significant log-log relationship to watershed area and are predicted with a power function (Tab. 2).

Table 2: Power function relationships for peak runoff data, cross-sections, and watershed area.

Source of Estimate	*Width (m)*	*Depth (m)*	*Velocity (m/sec)*
Stream channel measurements as a function of GIS watershed data	$11.74A^{0.34}$ $r^2=0.83$; $Se_{xy}=0.04$	$0.38A^{0.22}$ $r^2=0.75$; $Se_{xy}=0.03$	n/a
Hydraulic geometry derived from regression between measured Q_{10} and cross-section data	$4.78Q_{10}^{0.47}$ $r^2=0.82$; $Se_{xy}=0.06$	$0.22Q_{10}^{0.29}$ $r^2=0.67$; $Se_{xy}=0.05$	$0.95Q_{10}^{0.22}$
Hydraulic geometry derived from the substitution of stream channel power functions into equation 7	$4.68Q_{10}^{0.46}$ $r^2=0.82$; $Se_{xy}=0.11$	$0.21Q_{10}^{0.31}$ $r^2=0.67$; $Se_{xy}=0.14$	$1.01Q_{10}^{0.21}$

The high coefficients of determination for these regression models imply a strong deterministic relationship between channel shape and watershed area. This is to be expected, since watershed area is closely linked to peak discharge (Eq. 7); an increase in discharge should correspond to a widening or deepening of channel form. In the sandy soils of Walnut Gulch, streams develop wide, shallow channels with increasing watershed area and runoff.

The channel shape characteristics of width and depth were related using linear regression analysis to the database-derived values for Q_2 and Q_{10}. It was found that the regression results were equally significant, implying that channel shape could be well predicted using either of the flood estimates. However, when Q_2 and Q_{10} were simulated using normal flow and Manning's equation with a roughness coefficient of 0.035, it was found that predicted values of Q_{10} were closely correlated to the observed values (Fig. 2), while values for Q_2 were consistently over-predicted unless an unreasonable roughness coefficient was used.

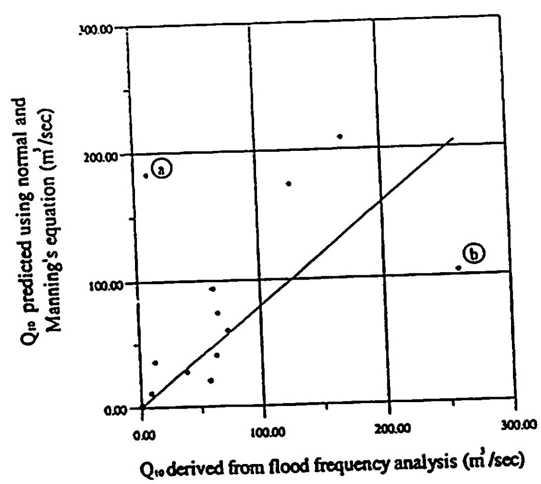

Figure 2: Comparison of Q_{10} values derived from flood frequency analysis and normal equation.

These observations suggest that the shape of channels on Walnut Gulch are formed by events similar in size to the 10-year event. There are two significant outliers within Figure 2: point (a) corresponds to subwatershed 63003; point (b) to subwatershed 63001. A significant percentage of the drainage area of subwatershed 63003 drains into ponds which contain and rarely release runoff. Since the channel was formed prior to the establishment of the ponds, the over-prediction of runoff may be attributed to the detention of runoff during events, which effectively decreases the contributing area. Runoff at subwatershed 63001, on the other hand, is under-predicted, perhaps owing to the large channel shape at the outlet, which may be formed by extreme events. It has been hypothesized that in semi-arid areas (such as Walnut Gulch), the concept of channel form as a function of discharge events may be less applicable than in humid regions, where the bankfull discharge typically corresponds to the 1-2 year event (e.g. Stevens et al., 1975; Leopold et al., 1964). In this study, however, we found good correspondence between bankfull stage and the 10-year event.

Power function relationships between Q_{10} and hydraulic characteristics were developed using two approaches (Tab. 2). In the first, measured values of width and depth were directly related with regression analysis to Q_{10}. In the second, equation (7) was solved for watershed area and substituted into the power function describing the relationship between channel measurements and watershed area. In this fashion, the hydraulic characteristics of a stream channel could be derived in the absence of measured values of Q_{10}. Due to the strong relationship between Q_{10} and watershed area (Eq. 7), both approaches yielded similar results, except that the second method produced regression relationships with a higher standard error (Tab. 2). In both cases, equations 5 and 6 were solved for k and m (Eq. 3) to create the power function relationship between velocity and Q_{10}. According to these hydraulic geometry relationships, channels on Walnut Gulch become proportionately wider relative to depth with increasing area and runoff: the higher value of the exponent indicates a stronger response to the independent variable (Fig. 3).

There is a remarkable degree of correspondence between the estimates of hydraulic geometry derived from field and GIS data and those extracted from the historical database. This considerable amount of consistency between methods demonstrates that the representation of hydraulic geometry is preserved when projected using GIS data derived from aerial orthophotography. Field-derived values also provide a validation for the values extracted from the hydrologic database.

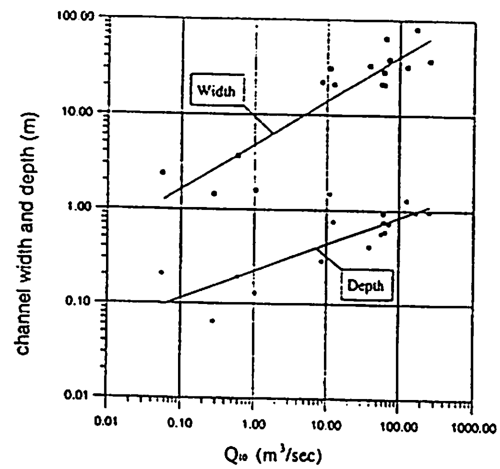

Figure 3: Hydraulic variables as a function of the 10-year peak flow

Estimates of hydraulic geometry are employed by numerous hydrologic models (e.g. Kineros - Woolhiser et al., 1990 and Smith et al., 1995; HEC-1 - Army Corps of Engineers - Feldman, 1995). The stream channel coverage within the GIS for Walnut Gulch was designed to be as compatible with potential hydrologic applications as possible. Estimates of channel width and depth were assigned to each channel segment across the watershed according to the area contributing runoff to that channel segment. These estimates were substituted into the power functions of Table 2, the results of which were included as variables in the supporting GIS database for the stream network coverage.

CONCLUSIONS

Hydraulic geometry estimates were obtained using field research and GIS techniques for the semi-arid Walnut Gulch Experimental Watershed. It was found that the bankfull channel shape was statistically determined by the 10-year runoff event. The generalized geometric relationships were extrapolated onto the entire stream channel network in the GIS database. This new ability to extrapolate hydraulic geometry values onto the Walnut Gulch channel sections within a GIS will allow for the rapid parameterization of hydrologic models requiring channel dimension data.

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