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Channel Morphology Investigations Using Geographic Information Systems and Field Research

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Abstract.—Stream channels are integral to watershed function and are affected by watershed management decisions. Given an understanding of the relationships among channel and watershed variables, they may serve as indicators of upland condition or used in distributed rainfall-runoff models. This paper presents a quantitative analysis of fluvial morphology as related to watershed characteristics for two disparate sites in Arizona. Detailed geographic information system (GIS) analyses were combined with 297 cross-section surveys. Statistical relationships among GIS-based watershed and field-based channel variables are presented and explanations for discrepancies between sites are given.

Introduction

Watershed management has long focused on the effects of land use practices on runoff, erosion, and off-site impacts. The drainage network plays a critical role in watershed processes since it serves to route water across and out of a watershed. Furthermore, stream channels serve as critical habitat and migration corridors for many species of birds, animals, and fish. In the semi-arid Southwest, riparian communities are recognized for their importance to a wide diversity of species. Physically-based hydrologic models rely on channel morphologic estimates to improve their predictive capabilities (Feldman, 1995; Smith et al., 1995). Given that stream channels play important roles in the hydrologic response of a watershed and in the complexity and diversity of ecological systems, understanding their responses to watershed management and subsequent effects on water quality and peak and volume runoff is important.

One avenue for investigating a stream channel and its connectivity to the surrounding watershed is the assessment of its morphology (i.e., size and shape) with respect to upland characteristics. Historically, the size and scope of such analyses limited research into this area. Prior to recent advances in geographic information systems (GIS) and computer tools, large-scale geomorphic investigations were overly time consuming, imprecise, and impractical (Guertin et al., 2000). This is not to imply that significant advances in the understanding of channel dynamics were lacking, rather that data requirements and high overhead limited the practical range of such research (see Abrahams, 1984 for a technical review). The advent of GIS allows for the pursuit of detailed large-scale geomorphic analysis relating channels to their uplands.

In this study, detailed channel morphology surveys were carried out in two regions of eastern Arizona representing a wide range in watershed characteristics. GIS tools were created to characterize the areas contributing runoff to the survey sites. Field and GIS data were correlated to assess the relationships among watershed characteristics and channel morphology. Strong predictive relationships were derived from these data that illustrate the watershed factors responsible for dictating fluvial response. These relationships hold implications for watershed practices and may be useful for hydrologic modeling studies on ungauged or remote watersheds.

Description of the Study Areas

Stream channels included in this study were surveyed on the Apache-Sitgreaves National Forest of east-central Arizona and USDA-ARS Walnut Gulch Experimental Watershed, located in southeastern Arizona. Within the Apache-Sitgreaves, five small perennial streams were studied: the West, East, and South Forks of the Little Colorado River, the West Fork of the Black River, and it's tributary Thompson Creek. Basalt and andesite flows form rolling topography to the east of Mount Baldy, an extinct volcano within the Apache-Sitgreaves. The climate of the Mount Baldy area has been classified as moist to subhumid (Merrill, 1970). Mean annual precipitation is 76 cm at Sheep Crossing on the West Fork of the Little Colorado River, with half of the yearly precipitation falling during summer thunderstorms (Merrill, 1970). Although there are seasonal fluctuations in these streams, flow occurs

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year round. Elevation ranges from 2256 to 3474.5 meters (7402 to 11403 feet). Vegetation types in the study area range from open ponderosa pine forests at the lower elevations near Greer, Arizona, to spruce and fir forests on the upper flanks of Mount Baldy (Elmore, 1976). Vegetation cover consists of forests with small meadows on Mount Baldy and within the canyons, and large open meadows with patches of forest on the volcanic flows.

The Walnut Gulch Experimental Watershed is a relatively small (150 km^2) experimental watershed encompassing the town of Tombstone, Arizona. The watershed is heavily instrumented with rain gauges and various runoff measuring devices amidst rolling hills ranging from 1190 to 2150 m elevation. Climate within the region has been classified as semi-arid or steppe (Renard et al., 1993). Approximately 60%-70% of annual rainfall occurs during summer monsoon rainstorms, with the remainder primarily falling during winter frontal storms. Vegetation within the watershed is representative of the transition zone between the Sonoran and Chihuahuan deserts, and is composed primarily of grasslands and desertscrub communities.

Smaller in size than the Apache-Sitgreaves study area, Walnut Gulch is consequently more homogeneous with less complex hydrology and geology. Stream channels are ephemeral, and the majority of runoff occurs during summer monsoonal activity. While talus slopes in gorges and well-developed soils in meadows and forests are found with meandering well-formed streams on the Apache-Sitgreaves region, Walnut Gulch is typified by poorly developed soils with swales in its uplands and sandy-bottom washes with high transmission losses in larger channels.

Methods

Channel cross-section surveys were carried out on 233 stream reaches within Walnut Gulch and 64 within the Apache-Sitgreaves study areas. Separate sampling methodologies were imposed on the two study areas: a random sample design was used on Walnut Gulch, while uniform sampling was carried out on Apache-Sitgreaves. Channels with slopes greater than 6% were excluded from the Apache-Sitgreaves because they were deemed unsuitable for geometric assessment. Likewise, unstable channels undergoing rapid adjustments or actively degrading channels were not sampled.

In all cases, multiple cross-sections were surveyed within each stream reach to ensure that the reach geometry was adequately characterized. Three cross-sections at each sample point were surveyed, and the results averaged to determine a standard reach geometry composed of average channel width, depth, and cross-section area. High-resolution orthophotographs were used to geo-locate cross-section sites on Walnut Gulch, while a global positioning system (GPS) served to provide coordinate locations for survey sites in Apache-Sitgreaves. These sites were input into a GIS to allow for spatial analysis with other GIS data layers.

Comprehensive GIS databases were constructed for Apache-Sitgreaves and Walnut Gulch. Of primary interest to this study were the topography, soils, vegetation, and geology data. A high-resolution (10 m) digital elevation model (DEM) was constructed from low-level aerial photography for Walnut Gulch, while a USGS DEM (30 m) was built for Apache-Sitgreaves. It is recognized that GIS analysis is dependent on the scale and quality of the input data (Miller et al., 1999) and that mixing data sources confounds quantitative comparative analysis. However, for the purposes of this paper, wherein empirical relationships among watershed characteristics and channel morphology were determined, differences due to DEM sources are less significant than in process-based analyses and so are assumed to be negligible.

Using each of the channel survey points as outlets, subwatersheds were derived using flow direction and flow accumulation algorithms based on the DEM surfaces (ESRI, 1997). Watershed characteristics were derived for each of the 297 subwatersheds, including area, slope, maximum flow length, cumulative channel length, drainage density, perimeter length, basin shape, elevation change, dominant soil type, geology, and vegetation.

Stream channel morphology variables collected in the field were correlated to GIS analysis using standard statistical techniques. Simple and multiple regression analyses were used to determine the principle deterministic relationships in the Apache-Sitgreaves and Walnut Gulch study areas. In this way, similarities and differences in fluvial geomorphic response to watershed characteristics between the two regions were detected. This paper is concerned primarily with channel width and cross-section area. Channel width is of prime importance to rainfall-runoff modeling, and cross-section area represents the total response of a channel to upland and local conditions.

Results

Channel characteristics measured in the Apache-Sitgreaves study area were distinct from those measured in Walnut Gulch for watersheds with similar properties. Differences in hydrologic regime, soils, and vegetation are presumed to be responsible for the observed morphologic variability. Some variability may be attributed to cross-section survey error in both study areas; however, systematic error in sampling methods between the two regions was absent. Student t-testing at the 95% confidence level showed that the sample populations of channel width, depth, and cross-section area were significantly different from one another. These results are more substantial given that the watersheds surveyed in the two regions overlapped in size, shape, and other factors that govern hydrologic response.

Linear regression models were fit between the channel morphology measurements and the GIS-derived watershed characteristics for each survey point. These results were used to investigate watershed factors that contribute to channel forming processes. Channel morphology is a function of local (bed and bank material, vegetation) and watershed (hydrologic response, size, geometry) control. The purpose of this research was to investigate the watershed factors that influence channel formation; consequently local variables were not measured. While this decision is recognized as a limitation on analysis, some inferences regarding local control were made based on field observation.

A host of watershed variables, listed earlier, were used in the preliminary analysis. A subset of these variables was found to be related to channel morphology at both study sites: watershed area (Aw), elevation change (E), and maximum flow length (Lm). These variables are closely tied to runoff processes, which are in turn responsible for channel formation. Figure 1 shows some of relationships among channel properties and watershed area and the maximum flow length within a watershed.

Note that there is an offset between Walnut Gulch and Apache-Sitgreaves data points, while the slopes of the relationships for width and cross-section area are very similar. In general, channels on Walnut Gulch are wider

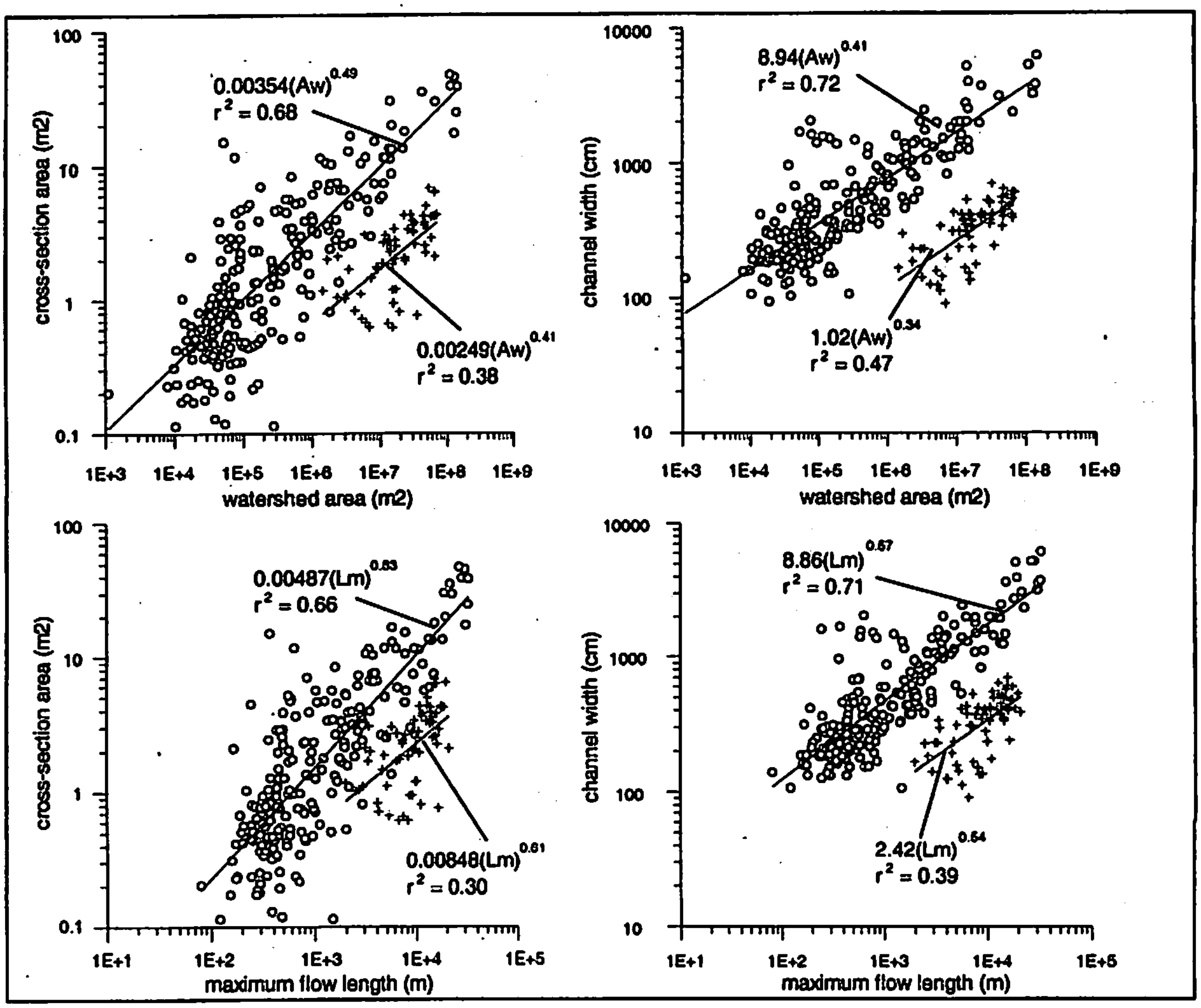

Figure 1. Relationships of channel width and cross-section area relative to watershed area and maximum flow length for Walnut Gulch and Apache-Sitgreaves study areas. Regression lines are shown to illustrate the offset and similarities in slopes between the two study areas.

and larger than on the Apache-Sitgreaves for similar watersheds, but channels on both areas increase in size at relatively the same rate. Recall that Apache-Sitgreaves data were collected on forested watersheds with perennial streams, while Walnut Gulch is a rangeland with ephemeral washes. Runoff on Walnut Gulch tends to be from flash floods and consequently more catastrophic. Furthermore, soils on Walnut Gulch contain less clay and are therefore less cohesive. These factors, in contrast to the stabilizing forces provided by vegetation and less violent runoff on Apache-Sitgreaves, combine to produce larger, wider channels on Walnut Gulch, thus creating the offset between the study sites. It is somewhat surprising, given these confounding factors, that the slopes of the relationships in figure 1are similar, implying that channels are increasing in size at approximately the same rate at both sites. Stream power, which is directly related to runoff volume and velocity and therefore channel excavation, appears to be increasing at similar rates on both study areas. Further research into runoff rates and hydraulic geometry is necessary to address this topic; unfortunately, while long-term gauging records are available for Walnut Gulch, a paucity of runoff data exists for Apache-Sitgreaves.

One of the goals of this research was to provide deterministic models for predicting channel morphology on ungauged basins for use in hydrologic modeling and hydraulic geometry research. Towards this end, simple and multiple regression models were developed to predict channel width and cross-section area. Results on both study areas were very promising when multiple regression techniques were used (table 1), but the Apache-Sitgreaves data contained greater variability than the Walnut Gulch data when related to a single watershed characteristic (figure 1).

Using multiple regression in the determination of channel morphology improved the predictive capability as illustrated by the high coefficients of determination (r^2) in those models shown in table 1. While the simple models work well on Walnut Gulch, models with high r^2 could not be found for Apache-Sitgreaves. Thus, it is suggested that the simpler models be applied on Southwest rangelands similar to Walnut Gulch, while the more complicated multiple regression models be employed on areas similar to Apache-Sitgreaves.

Conclusions

Stream channels within two areas of differing watershed and hydrologic characteristics (a rangeland and a forested area) were intensively surveyed and their contributing areas investigated with a GIS to determine the relationships among channel morphology and various watershed variables. Strong deterministic relationships for channel width and cross-sectional area were found for both areas. Variability in hydrologic response, soil cohesion, and vegetation, account for differences in the statistical models between the study sites. These statistical relationships should prove useful for future research into hydraulic geometry and rainfall-runoff modeling in the Southwest.

Table 1. A selection of linear regression models used in the prediction of channel width and cross-section area as a function of watershed properties.

Study area	Channel variable	Regression	r^2	RMSE
Walnut Gulch	area	1.82(Aw)+0.0028(E)+0.001(Lm)	0.91	3.54
Apache-Sitgreaves	area	5.69E-8(Aw)+0.0025(E)-3.54E-5(Lm)	0.88	1.04
Walnut Gulch	width	-9.73E-6(Aw)+2.11(E)+0.14(Lm)	0.84	506
Apache-Sitgreaves	width	2.94E-6(Aw)+0.344(E)+0.0071(Lm)	0.92	106

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Literature Cited

Abrahams, A.D., 1984. Channel networks: a geomorphological perspective. Water Resources Research 20(2): 161-188.

Elmore, F.H., 1976. Shrubs and Trees of the Southwest Uplands. Southwest Parks and Monuments Association. Tucson, AZ.

Environmental Systems Research Institute (ESRI), 1997. Arc/Info Ver 7.1 On-Line Documentation: watershed subroutine.

Feldman, A.D., 1995. HEC-1 flood hydrograph package. Chapter 4, Computer Models of Watershed Hydrology, edited by V. P. Singh, Water Resources Publications, Highlands Ranch, Colorado.

Guertin, D.P., S.N. Miller, and D.C. Goodrich, 2000. Emerging tools and technologies in watershed management. In this volume: Conference on Land Stewardship in the 21st Century: Contributions of Watershed Management, March 13-16, 2000, Tucson, AZ.

Merrill, R. K., 1970. The Glacial Geology of the Mount Baldy Area, Apache County, Arizona. Master's Thesis. Arizona State University. Tempe, Arizona.

Miller, S.N., D.P. Guertin, and L.R. Levick, 1999. Influence of map scale on drainage network representation. Proceedings of the 43rd Annual Meeting of the Arizona-Nevada Academy of Sciences Hydrology Chapter, April 17, 1999, Flagstaff, AZ. *In Press.*

Renard, K.G., L.J. Lane, J.R. Simanton, W.E. Emmerich, J.J. Stone, M.A. Weltz, D.C. Goodrich, and D.S. Yakowitz, 1993. Agricultural Impacts in an Arid Environment: Walnut Gulch Studies. Hydrological Science and Technology 9(1-4):145-190.

Smith, R. E., Goodrich, D. C., Woolhiser, D. A., and Unkrich, C. L., 1995, KINEROS- a kinematic runoff and erosion model, Chapter 20, Computer Models of Watershed Hydrology, edited by V. P. Singh, Water Resources Publications, Highlands Ranch, Colorado.