AN ANALYSIS OF CHANNEL MORPHOLOGY AT WALNUT GULCH

LINKING FIELD RESEARCH WITH GIS APPLICATIONS

by

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A Thesis Submitted to the Faculty of the

SCHOOL OF RENEWABLE NATURAL RESOURCES

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE
WITH A MAJOR IN WATERSHED MANAGEMENT

In the Graduate College

THE UNIVERSITY OF ARIZONA

1995

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ACKNOWLEDGMENTS

I would like to express my gratitude to many who were instrumental in helping me to finish this project. Special thanks go to Phil Guertin, who caught me in the hall one day and asked if I might be interested in something called GIS. It was that meeting that propelled me down this avenue of research, with a little push from Dr. Bill Bull, who stimulated my interest in geomorphology. Thanks also to Phil for his invaluable guidance and help with the study throughout.

Dave Goodrich was responsible for allowing me to become a part of the Southwest Watershed Research Center, for which I am grateful, as well as to his great help in the completion of this project. Waite Osterkamp provided unique insight and not a small amount of geomorphology experience to this project. Specifically, his help in outlining a field research plan and survey methodology can not go unnoticed. Thanks also to other members of the SWRC staff who aided in this project, including Leonard Lane, Jeffry Stone, Bisher Imam, John Masterson, and Rose Shillito.

I would be remiss in mentioning the SWRC without thanking that institution for funding my research and providing critical expertise and resources. This project was a cooperative effort between the ARS and the School of Renewable Natural Resources of the University of Arizona. The Advanced Resource Technology Lab was instrumental in the completion of this project, and ART lab faculty and staff provided excellent guidance and solutions to technological issues that arose during the course of this work.

The final member of my committee, Pete Hawkins was instrumental in helping me to frame my understanding of the results, as well as providing his unique brand of humor during my time as a Master's candidate. I am also grateful to Lloyd Gay, who extended his confidence to me by accepting me into the watershed management program and helped me considerably as I was deciding on a project.

I would also like to thank Tom Potter and Barbara Ball for their patience and understanding as they (mostly painlessly) guided me during my first foray into GIS and ARC/INFO. I would not have wanted to undertake a project such as this without Craig Wissler's help, as his exhaustive knowledge of ARC cleared away many of the obstacles I faced. Rob Murphy and Ani helped me complete my field research in a timely manner, and provided needed help and good humor during long days on Walnut Gulch.

Last, and perhaps most important, I would like to extend my appreciation for the patience and long hours of listening given me by Jen Bonini. Especially during the last months of this project, Jen injected no small measure of peace and rationality into my life.

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ABSTRACT

Geographic information systems (GIS) have improved our ability to accurately model and assess landscape parameters and processes. These systems offer a significant improvement in time and manpower needed to complete landscape studies. Too often, however, GIS projects have relied heavily on data that has not been integrated with field work or represents an abstraction of reality. A high-resolution database was constructed for the Walnut Gulch Experimental Watershed. New methods for delineating channels and acquiring data were developed to promote field integration. Simultaneously, a field measurement program of over 200 channel cross-sections was undertaken on the same area. The results from the GIS analysis and field research were integrated using statistical analysis. Strong deterministic relationships were derived between channel shape variables and watershed parameters. Channel shape was found to be influenced strongly by channel order and several watershed parameters, principally watershed size and the maximum flow length within a watershed.

INTRODUCTION

Problem Statement

Historically, the representation and analysis of spatial information has been constrained by technical problems concerning the difficulty of accurately displaying, storing and retrieving large amounts of data. Classical cartographic techniques enabled a researcher to delineate two-dimensional information but did not satisfactorily support three dimensional analysis or the integration of multiple map layers. With the advent of Geographical Information Systems (GIS), these problems were lessened. No longer are researchers required to derive measurements by hand from cartographic information using a time-consuming and somewhat imprecise methodology. A GIS allows a skilled user to interpret digitally stored data and withdraw relevant information by manipulating that data using computer technology. In this way quantitative analyses, such as watershed and hydrologic modeling, can be carried out rapidly and accurately on thematic map layers.

This paper presents the results of a project that utilized emerging GIS technology to apply established watershed and channel morphometric analyses on a large-scale, high-resolution database. A quantitative geomorphic study of channel cross-sections was undertaken on Walnut Gulch, information from which was integrated with the GIS developed for the Southwest Watershed Research Center of the United States Department of Agriculture's Agricultural Research Service (ARS). This GIS database was developed with a scale and resolution not usually attempted (Burrough, 1986), GIS map layers needed to complete the watershed analysis were created using innovative mapping techniques. Statistical analysis provided the mathematical link between data stored in the GIS and that collected in the field.

Walnut Gulch serves as an excellent place on which to conduct primary research, due in large measure to the long history of research that has been completed on the watershed. It is a well-gaged watershed with much historical data. Relatively little work, however, has focused on the characterization of the entire watershed's geomorphologic characteristics, limiting the ability to model landscape processes accurately (Lane et al., 1994). Rather than focusing on a small section of the watershed as other past research, this project encompassed the entire watershed. Relationships were developed between watershed and channel parameters, which may in turn serve as indices for hydrologic modeling and simulation. Procedures, including Strahler ordering analysis (Strahler, 1952), analysis of the bifurcation ratio (Horton, 1945), and analysis of channel morphology, were utilized to describe the watershed as thoroughly and quantitatively as possible. In so doing, field research was synthesized with computer applications and photogrammetry to more thoroughly describe the channel and geomorphic characteristics of Walnut Gulch than had previously been attempted.

BACKGROUND

During the period from the mid-1940s through the 1970s considerable original research focused on the development of geomorphometric relationships (Horton, 1945; Leopold and Maddock, 1953; Strahler, 1957; Schumm, 1960; Flint, 1974). Concepts such as the bifurcation ratio (Horton, 1945) hydraulic geometry (Leopold and Maddock, 1953), and ordering analysis (Horton, 1945; Strahler, 1952) were developed in order to link various watershed characteristics, and thus attempt to interpret the relative stability of an area. Although some relationships have proven to be generally consistent for a wide range of watersheds, they are most successful when applied on watersheds with similar characteristics to those on which the relationships were developed. Since the middle part of this century there has been a wealth of research on these subjects, but relatively little has focused on the semi-arid regions of the southwestern United States.

Compounding this discrepancy, much of the primary research on channel geometry and hydrologic relationships has been developed on perennial and intermittent streams. These facts illustrate the importance of carrying out primary research on Walnut Gulch rather than relying on previous research that may be inapplicable due to differences in climate and hydrologic response. A general location map of Walnut Gulch is presented as Figure 1. It was pointed out by Heede (1975) that a paucity of data exists for small watersheds, which has limited the understanding of small watershed and channel processes. To redress this inequity, it was decided that small channels would not be subjectively excluded from this study.

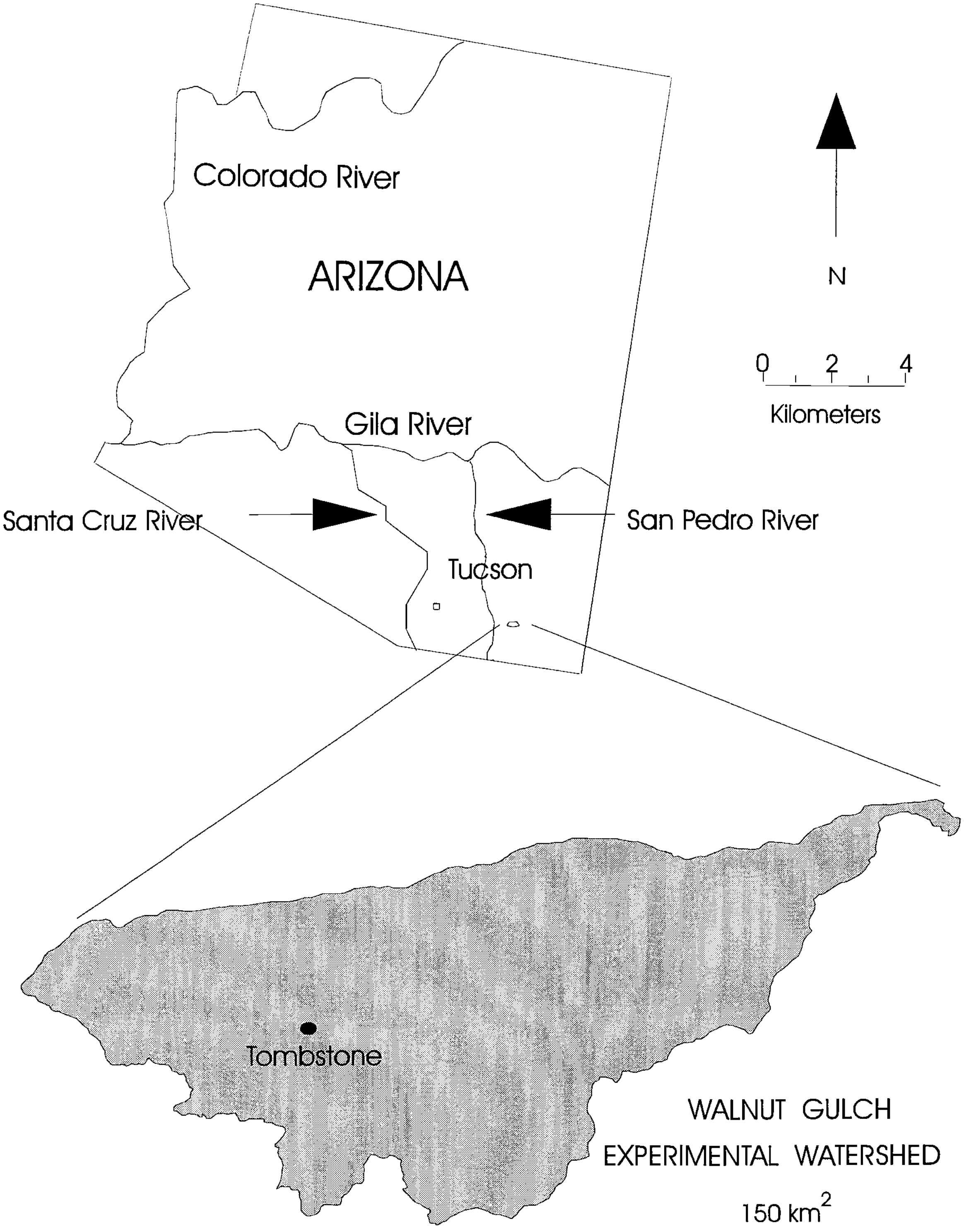


Figure 1. Location of Walnut Gulch Watershed

There were two principle thrusts of this work; an exercise in GIS analysis of small watersheds, and a field research program investigating channel shape and geomorphic relationships. Altogether, it was a synthesis of a large-scale GIS application and field research. As such, there were multiple objectives, each associated with a principle component of the research. GIS analysis can inadvertently be disassociated from actual hydrologic processes through the simplification of a basin and the construction of assumptions that allow the use of computer-based models. This abstraction of reality can hinder the development of working models and serve to remove the researcher from actual landscape processes. A goal of this project was to develop new GIS techniques that could be integrated successfully with field research and reduce the abstraction of reality common to computerized mapping. To realize this goal, an associated objective was put forth: to create a high-resolution, highly accurate representation of Walnut Gulch within a GIS environment which would aid in the development of models and improve our understanding of surface processes acting on Walnut Gulch.

Analyses of basin characteristics have been carried out using GIS for many years (Burrough, 1986). Unfortunately, there were several impediments to the direct application of much of the developed methodology to this project. Many of the established techniques were created to suit specific data types, and the GIS used at Walnut Gulch was not constructed in the same format. Additionally, the creation of speed-optimizing techniques and the upgrade of existing approaches proved to be necessary due to the combination of the large number of data points in the sample design and the high resolution of the database. As a contribution to the rapidly growing field of GIS, the development of new techniques and the upgrading of older methodology was another objective of this project.

Increasingly, models and equations are being used to apply hydrologic information from basins with available data to areas where such data has not been collected. Such models are also used to appraise the health and stability of gaged and ungaged regions. However, in order to adequately model or appraise a basin, its characteristics must be quantified and statistical relationships drawn between hydrologic variables. Through such analysis understanding is gained of the hydrologic principles and their natural variability within a basin. The final objective of this study was to quantify channel and watershed variables and develop relationships between them. It was hoped that a more thorough understanding of hydrologic and landform principles operating on Walnut Gulch would be derived from this study.

Objectives

There were four principle objectives associated with this project:

1. To develop a high resolution GIS with innovative techniques that could be used for assessment of hydrologic parameters and aid in the development of deterministic models.

An accurate representation of the channel network and the shape of interior reaches was of primary importance;

2. To develop new techniques and enhance established methods of data acquisition and creation of a GIS database;

3. To derive deterministic relationships between channel shape variables and watershed parameters. These relationships serve to illustrate the interrelated nature of watershed variables and can be used to parameterize hydrologic and watershed models; and

4. To successfully integrate and relate results of field research with data extracted from the GIS.

Approach

Since this study combined field research with GIS analysis, it was composed of three distinct research phases: 1) the development and use of a GIS; 2) the execution of field research; and 3) the statistical analysis of geomorphic variables retrieved from the first two phases of the project. This distinction should not imply, however, that the first two phases were executed without respect to one another. Quite to the contrary; map layers within the GIS were designed with the field research in mind, and the field research design was developed within a GIS framework. It would be folly to attempt to integrate point-specific information with a GIS without a prior understanding of the database into which it would be integrated.

GIS DEVELOPMENT

At the commencement of this project, no attempt had been made to construct a GIS database for the Walnut Gulch Experimental Watershed. Since Walnut Gulch serves as a fertile ground for research into various aspects of hydrology and natural resource management, it was decided that the database would be created at a resolution not normally attempted. Certain map layers (also referred to as "theme layers" or "coverages") were necessitated by this particular project, but many were created specifically for research conducted by Agricultural Research Service (ARS) staff. Throughout the database development, an answer to a basic question was sought: what is the highest level of precision and accuracy that can be achieved within the database and serve to maximize the resolution?

There can be a tendency by GIS developers to over-estimate the level to which data may be discretized (Jenks, 1981). 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, available data for Walnut Gulch was of a quality that allowed for a very high level of accuracy and precision, and should not hinder future GIS investigations. First, the nature of the data and its intended use were investigated. Second, its background and potential liabilities were outlined. Finally, a decision was made as to what level the data could be resolved. When integrating different theme layers, the lowest level of resolution among map layers will used. To accommodate the use of the lowest common denominator, it is important to resolve each map layer as closely as possible to each other. However, simply creating a map at a high resolution does not improve its fundamental quality and can lead to problems in later analysis. Therefore, there are conflicting interests that must be considered during database development: each of the theme layers should be created at as high a resolution as possible, but proper understanding of the data's properties should limit the amount of refinement so as to minimize errors.

For the purposes of this investigation, four elementary theme layers were required: soils, stream channels, elevation, and roads. These maps were synthesized during the investigation, so it was important from the onset of research to create them in concert. Therefore, the raster maps of soil units and surface elevation were both created using a ten-meter grid-cell resolution. The roads coverage and hydrology were drawn from 1:5000 orthophoto maps, which allow for a very high level of precision and accuracy. Stream channels were traced by hand and have greater than one meter's accuracy and resolution.

FIELD RESEARCH

Since the preponderance of research into southwest rangelands and channel geometry has focused on high order channels, this project sought to investigate all sizes of watersheds and stream orders present in Walnut Gulch. A goal of this project, the development of a deterministic model of geomorphic variables, required that the sample design be completely random. Therefore, sample points were located randomly across the entire watershed without respect to channel size or sub-basin area. By using a large number of points in the sample set, replication was achieved for important watershed and hydrologic parameters.

At each sample point either three or five cross-section surveys were made, depending on channel complexity. Variability in channel shape can be due to large-scale variables such as basin characteristics, and small-scale natural fluctuations within a channel section. The sample scheme sought to capture basin-scale variability by sampling a large number of points across the entire watershed. Regional variability was accounted for through the execution of cross-sections along each channel link. Microtopographic changes in channel shape were captured as well, although anomalous sections were avoided that did not adequately represent the regional topography.

Benefits

With the development of a GIS database for Walnut Gulch, possibilities for intensive research using this powerful tool have been opened to future researchers. Since the database is of a high resolution and quality, watershed and hydrologic analysis will be expedited on this unique experimental watershed. One of the greatest benefits of a GIS is the upgrade in speed and accuracy of basin characterization it provides over traditional methods. Throughout this project, such analyses were explored and refined on the Walnut Gulch database. Certain problems encountered in their application were solved, and subroutines written to allow for greater speed and improve user-compatibility. These investigations and the routines developed for basin analysis should prove useful for future applications on Walnut Gulch and other basin systems.

From the examination of basin characterization and the investigation of channel geometry and topographic relationships, a more refined understanding of channel processes has been developed. Data withdrawn from this study should be applicable to hydrologic and erosion modeling and allow for high-resolution parameterization of such models.

LITERATURE REVIEW

Since the middle of this century, considerable work has been completed on the statistical relationships between watershed variables. From this work, various procedures have been developed for the quantification of drainage basins, Horton (1945), Strahler (1952), Leopold and Maddock (1953), Hack (1957), and Schumm (1960), were primary investigators who inferred relationships between watershed parameters. Scientific observation of the basic similarity between many stream systems did not begin in this century: in the 1800's Playfair noted the "nice adjustment" of stream systems to their geological setting, as well as the basic similarity that seems to exist between basins (*in* Horton, 1945). Playfair's understanding of stream systems was founded strictly on empirical observation. Not until the seminal work of Horton in 1945 was a thorough quantification made of basin characteristics.

Stream Order Analysis

Stream ordering analysis has been used to illustrate the similarity of different stream systems. Strahler (1957) outlined the power function relationship that exists between stream order and the number of streams per order. He and other researchers (Horton, 1945; Leopold and Maddock, 1953; Schumm, 1956; Flint, 1974;) have demonstrated the similarity between drainage basins by showing that representative functions can be satisfactorily applied over a wide range of basins. Shreve (1966) took that assumption a step farther by introducing the random topology model. Shreve predicted with an abstract model many of the relationships illustrated by earlier workers, showing the adherence of a number of independent stream systems to a statistical order.

In order to describe drainage basin characteristics either dimensional or dimensionless ratios may be employed. Dimensionless ratios, such as those which describe drainage basin shape, have the advantage of allowing the researcher to assess similarities irrespective of basin size (Dunne and Leopold, 1978). Dimensional analysis, on the other hand, utilizes length factors as a foundation for geometrical comparison. Towards this end, power functions have been developed to illustrate the inherent relationship between many geometric properties of a drainage basin.

Stream ordering analysis as defined by Horton (1945) and updated by Strahler (1952) relies on the development of power relationships between geometrical properties. A series of laws in which the relationship of stream order and length to basin morphology was outlined by Horton (1945). Stream ordering, as modified by Strahler (1952), dictates that the smallest streams, into which no other streams enter, are designated as being of the first order; where two first order streams merge, a stream is designated second order; where two second order streams flow together, it becomes a third order; and so on. It is presumed that order number is directly proportional to channel dimensions, as well as watershed size and channel discharge (Strahler, 1964).

In any basin the number of first order streams will be greater than the second order, which in turn will be greater than third order, and so on. The bifurcation ratio, wherein the number of segments of a given order is divided by the number of streams of the next higher order, tends to be constant throughout a stream basin, although it will generally not be the same for each step (Strahler, 1952 and 1957; Leopold et al., 1964). It is predicted that higher bifurcation ratios will exist in mountainous or highly dissected terrain (Horton, 1945), and that the ratio is highly stable from one region to another (Schumm, 1956; Strahler, 1957).

Other researchers have focused on the behavior of drainage systems as a function of stream order. For example, stream order has been found to be an important factor in controlling interior drainage link lengths and drainage areas (Ghosh and Scheidegger, 1970; Scheidegger, 1968), stream gradient (Flint, 1974), and stream meandering (Stall and Folk, 1967; Smart and Surkan, 1967). Channel meandering is related to channel size (Williams, 1986), a relationship that further buttresses the concept that stream order is directly proportional to stream discharge, and hence channel size (Strahler, 1964). Stream order acts as a surrogate for increasing channel size, since the combination of multiple side channels into the main channel increases the volume of flow through that main channel. Consequently, relationships between channel flow and geomorphological parameters tend to be highly correlated with stream order (Strahler, 1964). As such, stream order has been used as a treatment in many statistical models relating geomorphological variables (Dunne and Leopold, 1978).

In his impressive paper describing quantitative morphology, Horton (1945), also delineated several rules governing the relationship of streams to their environment:

(1) *Law of stream numbers:* The number of streams of different orders in a given drainage basin tend to closely approximate an inverse geometric series in which the first term is unity and the ratio is the bifurcation ratio. This relationship can be expressed by the power function:

$$N_o = R_b^{s-o} \qquad (1)$$

where

N_O = the number of streams of a given order;
R_b = the bifurcation ratio;
s = the order of the main stream, and;
o = the order of a given class of tributaries.

(2) *Law of stream lengths:* The average length of streams of each of the different orders in a drainage basin tend to closely approximate a direct geometric series in which the first term is the average length of streams of the first order. The mathematical expression for this law is:

$$L_a = L_1 * R_1^{u-1} \qquad (2)$$

Where

L_a = the average stream lengths of first order streams;
L_1 = the stream length of a given stream order;
R_1 = the length ratio of successive stream orders;
u = a coefficient.

(3) *Law of stream slopes:* An inverse geometric series governs the relationship between order and average slope.

Hydraulic Geometry

Power function relationships have been found which directly correlate various watershed variables, including relationships between discharge and the width and depth of a given channel (Leopold and Maddock, 1953), length of channel and drainage area (Hack, 1957), and channel width-depth ratio and sediment class (Schumm, 1960). Schumm (1956) described the law of area, stating that basin area increases exponentially with stream order. It has also been observed that as drainage area increases, the contributing area's drainage density drops in an exponential manner (Strahler, 1957). Osterkamp and Hedman (1977), described the relationship between width of stream channels and their relationship to discharge.

These underlying postulates: that stream systems in similar geologic and climatic regimes will be statistically the same; that a quantitative analysis of a drainage basin can be made through direct observation of geomorphologic characteristics; and that relationships between those factors can be successfully derived, have formed the basis for a great deal of work in geomorphology and hydrology. Unfortunately, much of that work has focused on areas outside the desert southwest.

In their classic scientific work, Leopold and Maddock (1953) explored the empirical relationships between channel form and mean annual discharge. Exponential equations describing stream discharge were developed:

$$W = aQ^{b} \tag{3}$$
$$D = cQ^{f} \tag{4}$$
$$V = kQ^{m} \tag{5}$$

where

W = width of the channel, in feet;
D = mean channel bankfull depth, in feet;
V = mean channel velocity, in feet per second;
a, c, k = coefficients, and;
b, f, m = exponents.

By solving the continuity equation:

$$Q = WDV \tag{6}$$

it was shown that

$$ack = 1 \tag{7}$$

and that

$$b + f + m = 1. \tag{8}$$

It was further postulated that any data set would fit these basic relationships (Leopold and Maddock, 1953). Channel geometry has been used for indirectly estimating streamflow. Based on the concept that channel form is controlled primarily by stream discharge, although soils, vegetation, and management may play important roles in channel development as well. This work serves as a natural extension to the study of hydraulic geometry originated by Leopold and Maddock (1953). Because of variability in recording and the possibility for measurement errors, Hedman and Osterkamp (1982) focused on the relationship between streamflow and channel width. By re-arranging equation (3),

$$Q_v = a W^b, \qquad (9)$$

where

Q_v = measure of streamflow (L^3 / sec.);
a = a coefficient;
b = an exponent, and;
W = channel width, (L).

Hedman and Osterkamp (1982) reported relationships between streamflow and channel width for areas with similar climates in the western United States. Many of the cross-sectional surveys analyzed by Hedman and Osterkamp (1982) were taken on ephemeral stream channels, such as exist in Walnut Gulch. By taking into account the shear stress distribution within the channel, Osterkamp et al. (1983) further explored the relationships governing streamflow and channel geometry and derived the exponents for the width, depth, and velocity factors used in hydraulic geometry equations 3-5. Other researchers have found the variables of width and depth to display a large variance, while cross-sectional area displays a strong relationship to flow distance (Dunkerly, 1992). Dunkerly (1992), from investigations into ephemeral stream channels, showed that estimates of discharge based on channel geometry display a log-linear relationship to flow distance. In order to provide an index applicable to ungaged sites, Wharton et al. (1989) investigated the relationship of discharge to channel capacity and reported a high correlation between the two variables.

Channel measurements and their geometric relationships can be applied to planning-level and basin-scale models (Allen et al., 1994). Using relationships between channel dimensions and discharge, Allen et al. (1994) showed that channel geometry serves as an adequate method for parameterizing basin-scale planning models. Furthermore, recent basin-scale modeling has been developed that incorporates channel dimension data (Arnold et al., 1993; Baun and Snowden, 1988).

Previous Research on Walnut Gulch Experimental Watershed

Issues of scale are prevalent in research on the subject of morphometry. Large-scale maps and photography contain a greater amount of detail and information than do their smaller-scale equivalents. Consequently, information gathered from differently-scaled data sources is bound to yield different results. The effect of scale on Strahler ordering analysis was demonstrated by Lane (1994) in studies completed on Walnut Gulch. A greater percentage of lower order streams are picked up on large-scale maps, resulting in changes in the bifurcation ratio, drainage density, and all length measurements pertaining to channel geometry. Horton-Strahler drainage net analysis has been completed on Walnut Gulch on both 15 and 7.5 minute quad sheets, as well as on 1:12000 photo-mosaics.

Computer Analysis of Geomorphologic Data

With the increasing reliance on computers in natural resource management, studies have been undertaken which attempt to utilize the power of computer applications on proven geomorphologic techniques. GIS applications have been created to extract and model hydrologic parameters (Van Blargen and Ragan, 1991). Theme layers of watershed variables necessary for the articulation and derivation of hydrologic variables, including those of channel characteristics, land surface models, and soils, may be input into a GIS (Burrough, 1986).

Watershed characteristics may be entered manually into a GIS or derived from combination of data layers. For example, watershed delineation within a GIS is rapid and accurate, although dependent on the choice of algorithm within a given geomorphic terrane. Triangular irregular networks (TIN) (Jones et al., 1990; Tachikawa et al., 1994), digital elevation models (DEM) (Moore et al., 1991), and contour-based information (Moore et al., 1988) have been used to model watersheds and their geometric characteristics. Stream ordering analysis also may be accomplished within a GIS system (Lanfear, 1990). Drainage basin characteristics, such as slope, channel slope, basin relief, and shape characteristics have all been derived from watershed maps within a GIS using processing algorithms (Eash, 1994; Burrough, 1986; Cowen, 1993; Bhaskar et al., 1992).

Digital Elevation Models (DEMs) have been used to generate hydrologic and topographic surfaces for input into hydrologic modeling routines (Moore et al., 1991).

Contour information contained in the Walnut Gulch GIS was captured in this fashion, although no stream network generation was accomplished. When generating surfaces for modeling purposes, it is important to have as well-articulated a surface as possible without overtaxing the system requirements of the computer (Burrough, 1986). Moore et al. (1991) pointed out the necessity of high-quality data input for hydrologic simulation in the GIS environment. Parameterization of a GIS, such that stream channels are represented not just as linear features but as three-dimensional entities would conceivably allow a greater articulation of the surface over which hydrologic simulation will be generated.

Model development to simulate hydrologic and erosion processes is currently being undertaken in which geomorphological and hydrological variables will be input into the models directly from a GIS (Srinivasen and Arnold, 1994; Tarboton, 1991; DeVantier and Feldman, 1993; Muzik and Pomeroy, 1990; Hoover et al., 1991; Djokic and Maidment, 1992; Sasowsky and Gardner, 1991). Of paramount importance to all these models is the correct registration and resolution of ground data as represented in the GIS.

METHODS

Site Description of Walnut Gulch

Administered by the ARS since its creation in 1957, the Walnut Gulch Experimental Watershed is located in southeastern Arizona in the scrub-grassland that surrounds the city of Tombstone (figure 1). Comprised of rolling hills and some steep terrain, the elevation of Walnut Gulch ranges between 1190 and 2150m MSL. Due to the presence of the town of Tombstone, there is urbanization within the watershed boundary, but it is relatively limited in scope. Cattle grazing and recreational activities are the major land uses. There is evidence of mining activities throughout the hilly areas on the southwestern portion of the watershed.

Vegetation within the watershed is representative of the transition zone between the Chihuahua and Sonoran deserts, and is composed primarily of grassland and scrub rangeland vegetation (figure 2). According to Hastings and Turner (1965), approximately 95% of the watershed was covered by grasslands at the turn of the century, whereas only one-third is grassland today.

Underlying Walnut Gulch is the geology of a high alluvial fan contributing to the San Pedro River watershed (Renard et al., 1993) (figure 3). Similar to the present-day mountains on the southern border of the watershed, the alluvium is of Cenozoic age, very thick (greater than 400m in depth) and coarse-grained (Breckenfield et al., 1995). Due to the enormous thickness and extent of the alluvial fill, the groundwater reserves are

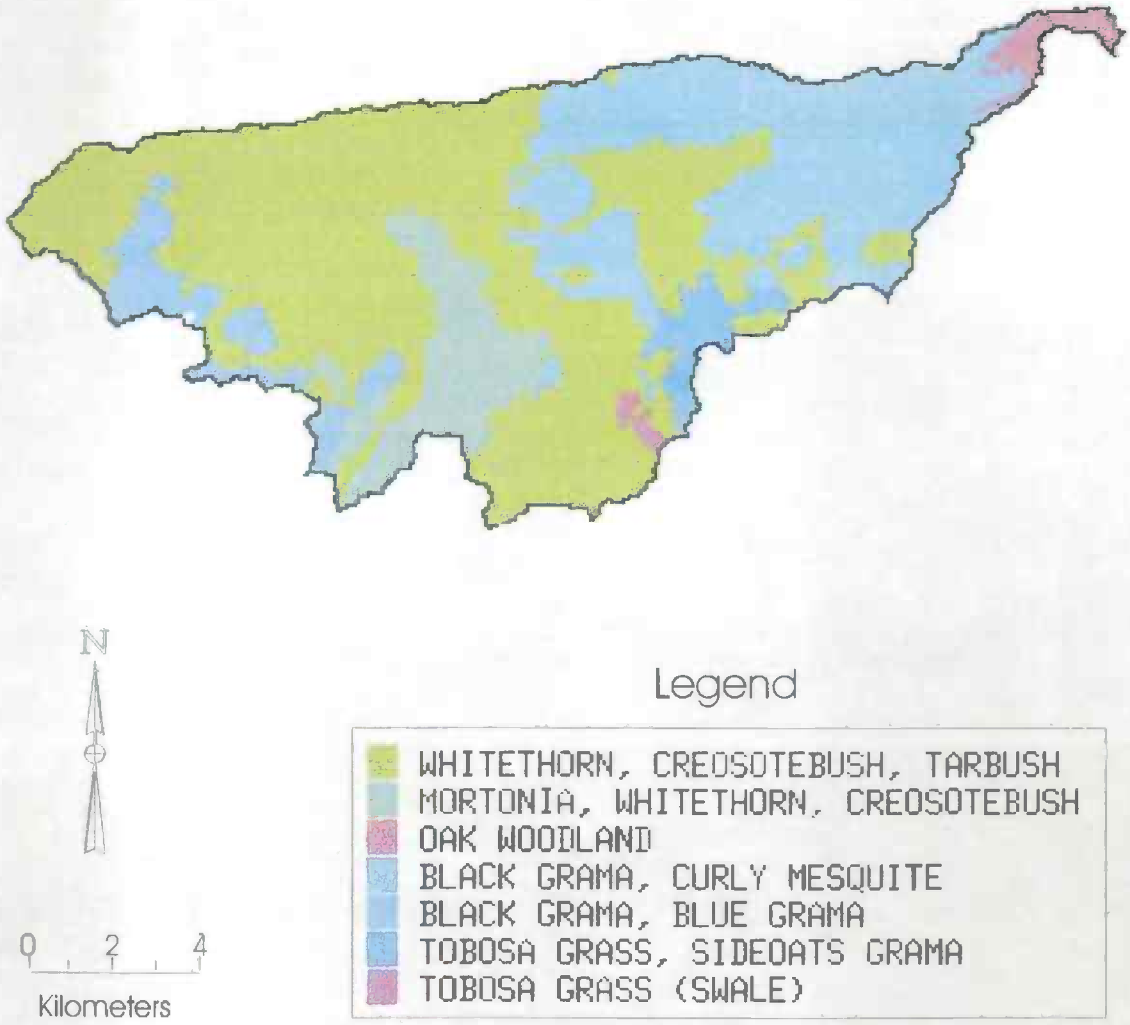


Figure 2: Vegetation map of Walnut Gulch

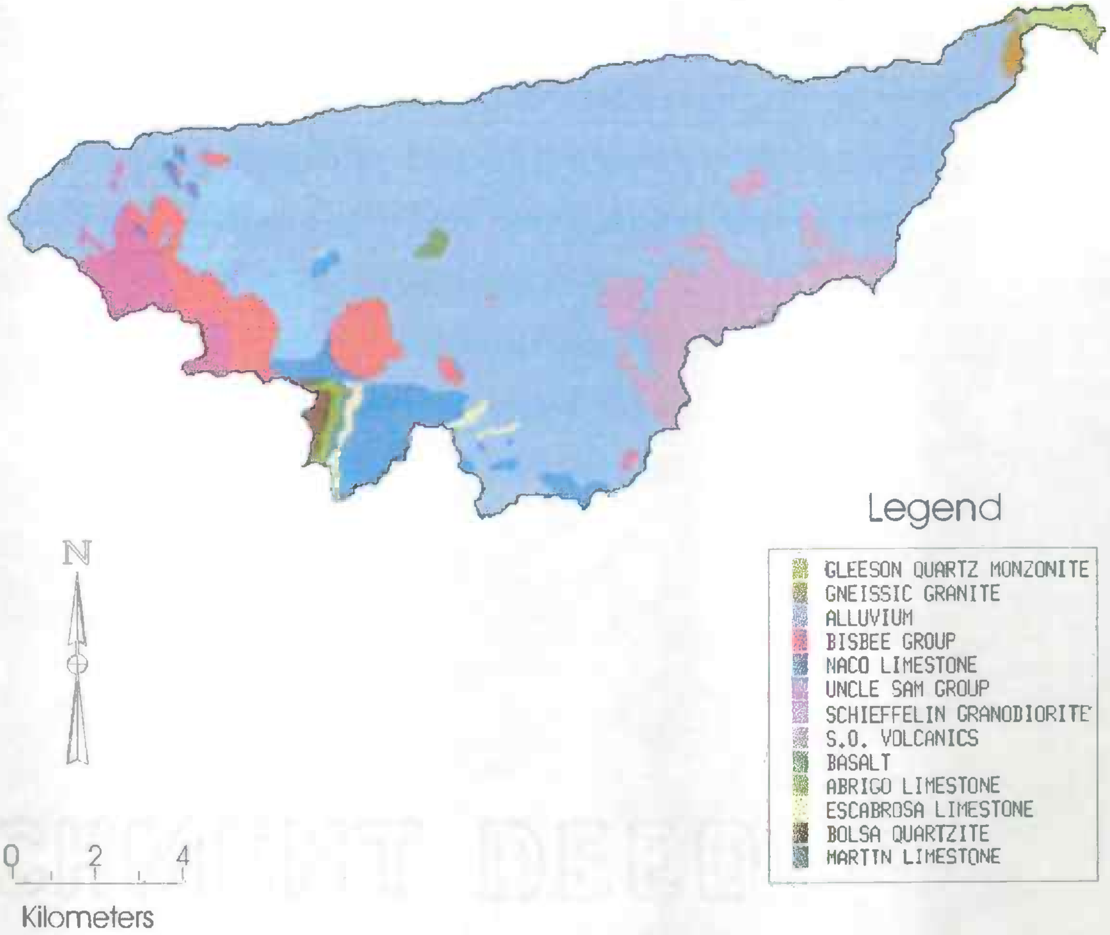


Figure 3: Geology of Walnut Gulch

substantial, and can be found at depths ranging from 50 to 145m (Libby et al., 1970). In the mountainous regions of the watershed, the geologic material is more indurated, and in some places form complete sections. Several types of limestone, as well as granite and quartzite are present within the watershed (Libby et al., 1970). Most of the geology in these regions has been subjected to minor metamorphic events, including folding, thrusting, and compression, resulting in the presence of copper and gold deposits.

Soils within the watershed boundary are highly influenced by the presence of large deposits of limestone. A high percentage of the upper horizons are composed of gravel (up to 60%), while the lower horizons are generally less gravely (Renard et al., 1993). The SCS revisited Walnut Gulch in 1994 for the purposes of completing an updated soil survey, the results of which indicate that there are 30 soil map units within the watershed (Breckenfield et al., 1995) (figure 4). As indicated on table 1, the 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 has been 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. However, annual precipitation is highly variable, both in timing and amount. 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

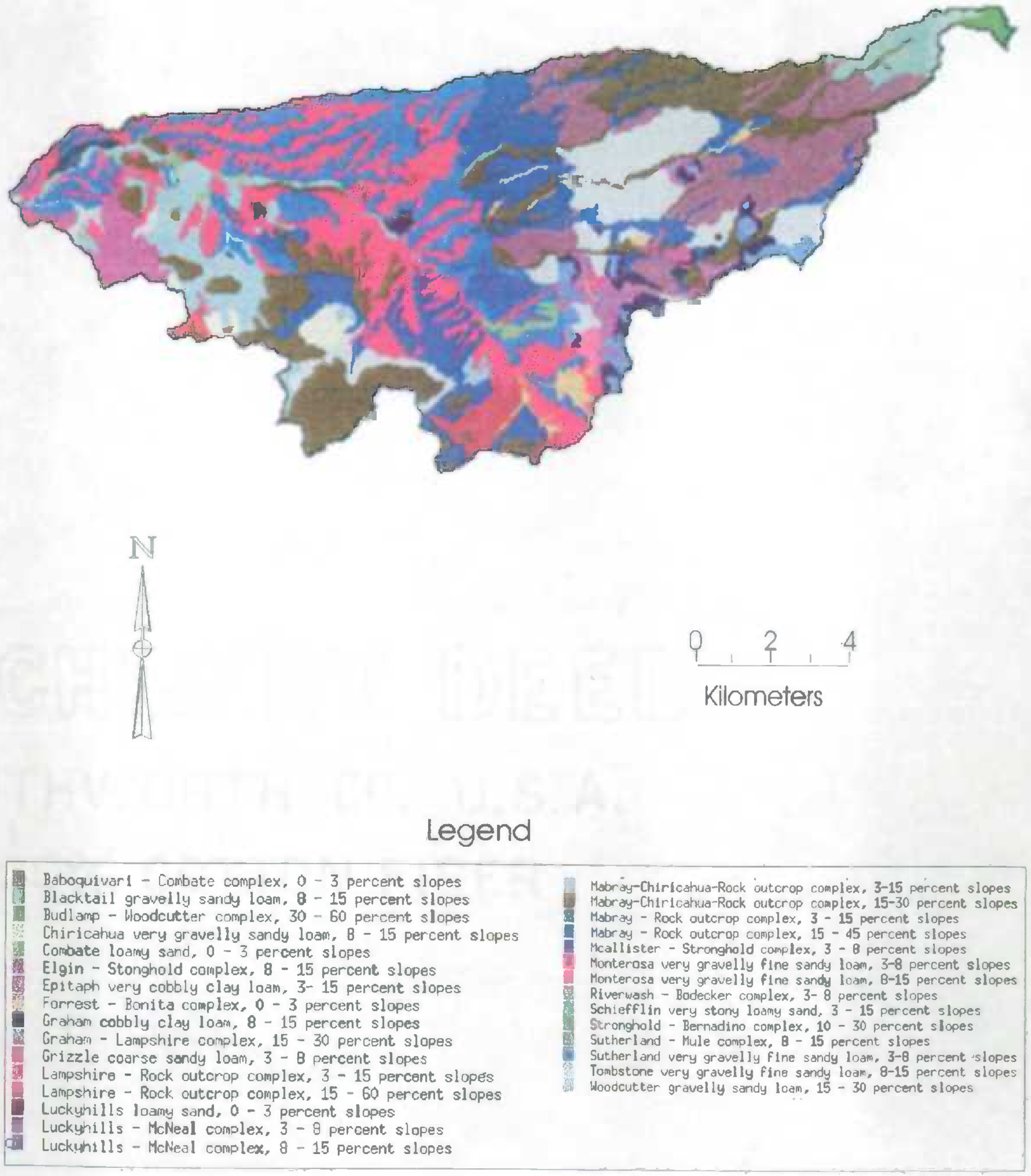


Figure 4: Soil unit map of Walnut Gulch

Table 1: Soil map unit areas of Walnut Gulch

Soil Code	Soil Map Unit Name	Area (hectares)
1	Baboquivari - Combate complex, 0 - 3 percent slopes	542.7
2	Blacktail gravelly sandy loam, 8 - 15 percent slopes	245.1
3	Budlamp - Woodcutter complex, 30 - 60 percent slopes	64.7
4	Chiricahua very gravelly sandy loam, 8 - 15 percent slopes	147.0
5	Combate loamy sand, 0 - 3 percent slopes	106.4
6	Elgin - Stonghold complex, 8 - 15 percent slopes	1504.1
7	Epitaph very cobbly clay loam, 3- 15 percent slopes	241.7
8	Forrest - Bonita complex, 0 - 3 percent slopes	140.1
9	Graham cobbly clay loam, 8 - 15 percent slopes	284.3
10	Graham - Lampshire complex, 15 - 30 percent slopes	244.0
11	Grizzle coarse sandy loam, 3 - 8 percent slopes	81.3
12	Lampshire - Rock outcrop complex, 3 - 15 percent slopes	358.5
13	Lampshire - Rock outcrop complex, 15 - 60 percent slopes	26.6
14	Luckyhills loamy sand, 0 - 3 percent slopes	67.7
15	Luckyhills - McNeal complex, 3 - 8 percent slopes	3072.8
16	Luckyhills - McNeal complex, 8 - 15 percent slopes	1082.1
17	Mabray - Chiricahua-Rock outcrop complex, 3-15 percent slopes	305.4
18	Mabray - Chiricahua-Rock outcrop complex, 15-30 percent slopes	189.9
19	Mabray - Rock outcrop complex, 3 - 15 percent slopes	780.3
20	Mabray - Rock outcrop complex, 15 - 45 percent slopes	123.0
21	Mcallister - Stronghold complex, 3 - 8 percent slopes	1357.5
22	Monterosa very gravelly fine sandy loam, 3-8 percent slopes	274.2
23	Monterosa very gravelly fine sandy loam, 8-15 percent slopes	43.5
24	Riverwash - Bodecker complex, 3- 8 percent slopes	170.9
25	Schiefflin very stony loamy sand, 3 - 15 percent slopes	393.3
26	Stronghold - Bernadino complex, 10 - 30 percent slopes	759.7
27	Sutherland - Mule complex, 8 - 15 percent slopes	182.4
28	Sutherland very gravelly fine sandy loam, 3-8 percent slopes	674.1
29	Tombstone very gravelly fine sandy loam, 8-15 percent slopes	1275.4
30	Woodcutter gravelly sandy loam, 15 - 30 percent slopes	61.9

runoff occurring on Walnut Gulch is the product of summer storms, and is therefore episodic and of relatively high intensity (Renard et al., 1993).

GIS Coverage Creation

All of the maps used to describe Walnut Gulch were created in the GIS package ARC/INFO (ARC) by the author, using the editing package ARCEDIT and a combination of ARC utilities. Primary coverages include polygon maps for soils, range site, vegetation, geology, utilities, subwatersheds, and stream channels (a combination of vector and polygon topology); point coverages include those for flumes, rain gages, and stock pond locations; a vector map was created for the roads. Additionally, a digital elevation model (DEM) was created from spot elevation, contour, and stream channel data using the ARC utility "topogrid" (ESRI, 1994).

THEME LAYER DEVELOPMENT

Geology and vegetation data were transcribed into digital form from 1:24000 rectified maps. Polygon boundaries of these maps were originally hand-drawn by ARS staff, and have a relatively high error associated with their placement.

Several iterations of soil maps were created before the final map was acceptable. Originally, data was digitized directly from polygonal features inscribed on 1974 NHAP photographs. Photos from this time period were only partially rectified, which resulted in a rather severe distortion over the hilly regions of the watershed. Additionally, the photo base was of poor quality; several of the photographs were overexposed, while others were washed out. In general, it was problematic to accurately digitize the original line work. Due to these restrictions in data quality, it was decided that the data would be transcribed from the NHAP 1:24000 photos onto 1:5000 orthophotos. The transcribed line work was then digitized and served as the basis for the final soil map. There are 9 additional soil maps, representing more precise original work by the United States Soil Conservation Service (SCS) on individual 1:5000 orthophoto sheets, which were digitized and serve as local regions with higher resolution.

Since the range site map is a capability map based on soils, it was created from the soil map by reclassification (figure 5). Roads were digitized directly from the 1:5000 orthophotos (figure 6). Point attribute information, such as rain gages and flumes, were imported into ARC from text files supplied by the ARS which contained x- and y-coordinate location and supporting attribute identification.

In order to more fully understand the channel geometry and stream network of Walnut Gulch, a theme layer was constructed at extremely high resolution of the surface channel network (figure 7). Orthophoto sheets with a 1:5000 scale provide photographic coverage of the entire watershed, and from this photo base stream channels were delineated. After placing one of the transparent mylar orthophotos on a light table, a sheet of one-sided clear mylar was placed over the photo, and both sheets were secured

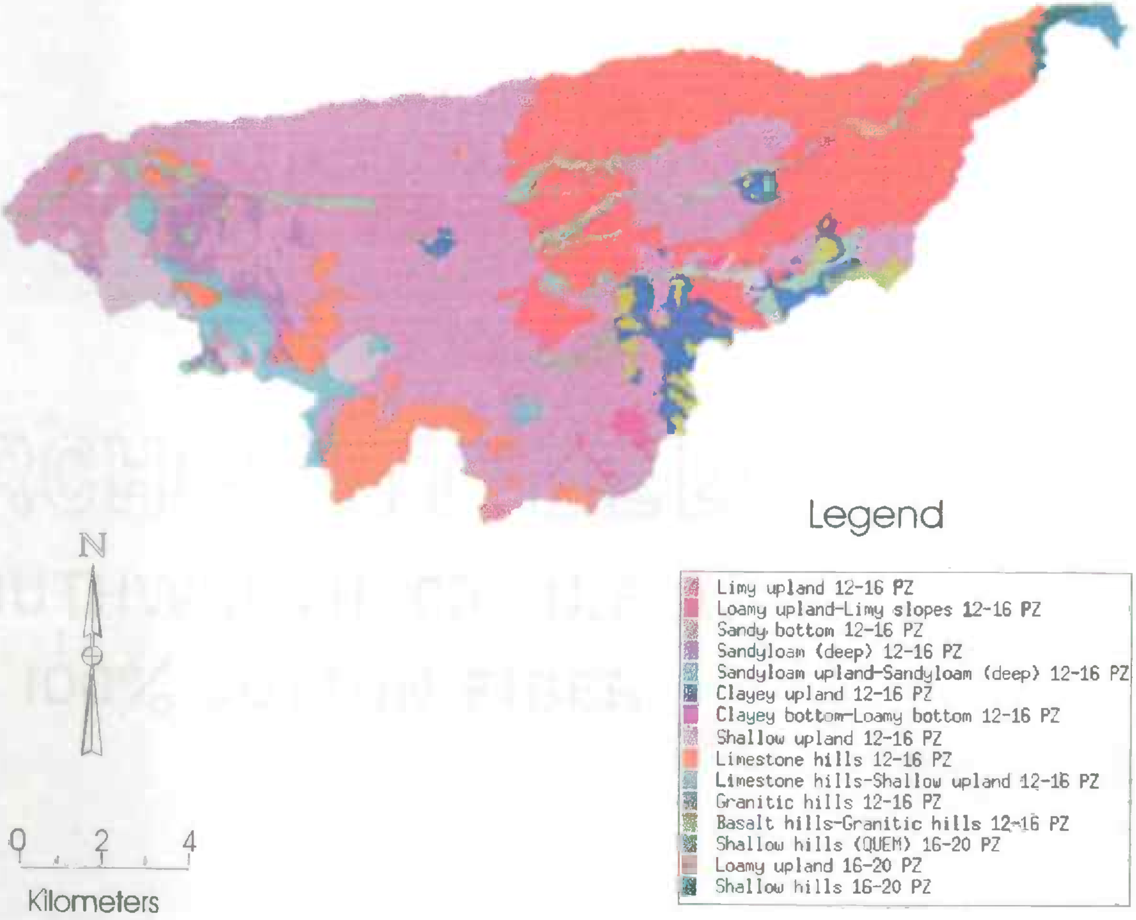


Figure 5: Range potential map of Walnut Gulch

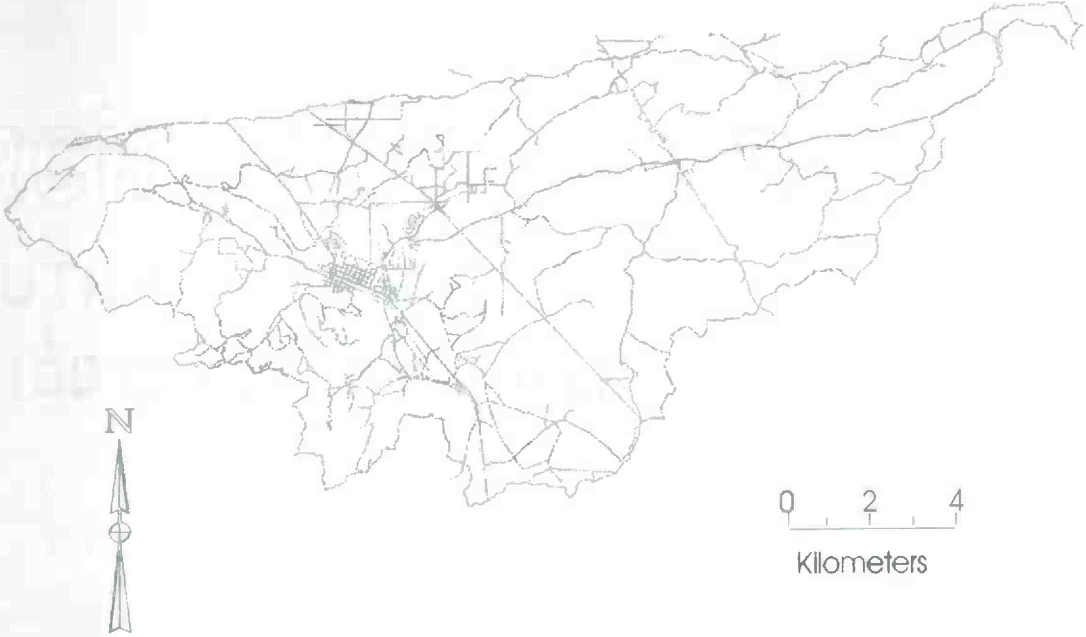


Figure 6: Road map of Walnut Gulch

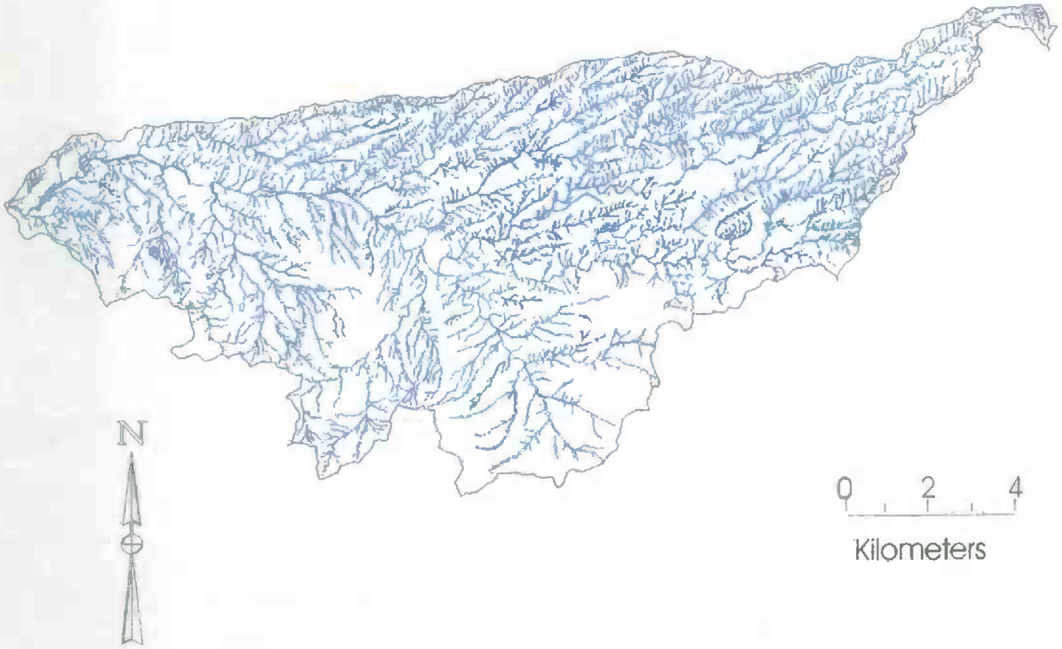


Figure 7: Channel system on Walnut Gulch

in place. By shining a light through the two layers of mylar, it was possible to accurately assess channel edges and reproduce them on the covering sheet of mylar.

Channels were traced on the covering mylar using fine-tipped colored pencils. Different colors were used to indicate the type of channel being delineated. Five basic channel types were delineated with different colors: swales, ponds, alluvial fans, channels less than 1.5 meters in width, and channels wider than 1.5 meters. There were three criteria used to determine channel type: channel form, vegetation changes, and soil characteristics. Channel surfaces may be entirely, partially, or not covered with vegetation. Additionally, a channel surface may be covered with soil or channel debris. Landscape features such as these show up clearly on high-resolution photographic imagery and were used to characterize the channel boundaries and type.

Swales may be separated from incised channels by the presence of vegetation within the channel boundaries, the lack of visible soil surface material, and their wide, shallow appearance. With the onset of incisement, vegetation is scoured from a channel bottom, exposing soil materials and further defining the channel. Higher photo reflectance is the result, which leads to a recognizable difference in channel type. Additionally, because differences in surface material between the channel and surrounding area, it is somewhat easier to define the edges of incised channels. Swale boundaries were judged on the basis of vegetation and slope changes. Within the swale boundaries, vegetation is highly influenced by the presence of additional water. Grasses and brush may flourish within the swale relative to the surrounding area. Where the vegetation change occurs there may also be a recognizable change in slope and soil, further defining the channel.

Incised channels wider than 1.5 meters were defined as polygonal features, with their channel islands and bars also delineated. Channel islands were defined using the same basic criteria used to delineate the channel boundaries: where surface reflectance and/or vegetation changed within the channel in a noticeable pattern, it was defined as a channel feature. Channels less than approximately 1.5 meters wide were represented in a more typical GIS fashion: as single lines which bisect the approximate channel boundaries. Figure 8 shows the level of detail that was achieved using this methodology. Multiple channel islands and braided channels are present, as is visible on the blown-up portions of the map. Notice that channels are represented both as linear and polygonal features, with channel definition represented with a high level of precision.

Alluvial fans were identified primarily by their combination of triangular form and soil characteristics. Often, channels emerge from side-slopes onto alluvial fans, resulting in the subsequent disintegration of the channel form. This characteristic: the devolution of channel boundaries upon emergence from incised hillslopes, was the primary factor in defining the alluvial fans.

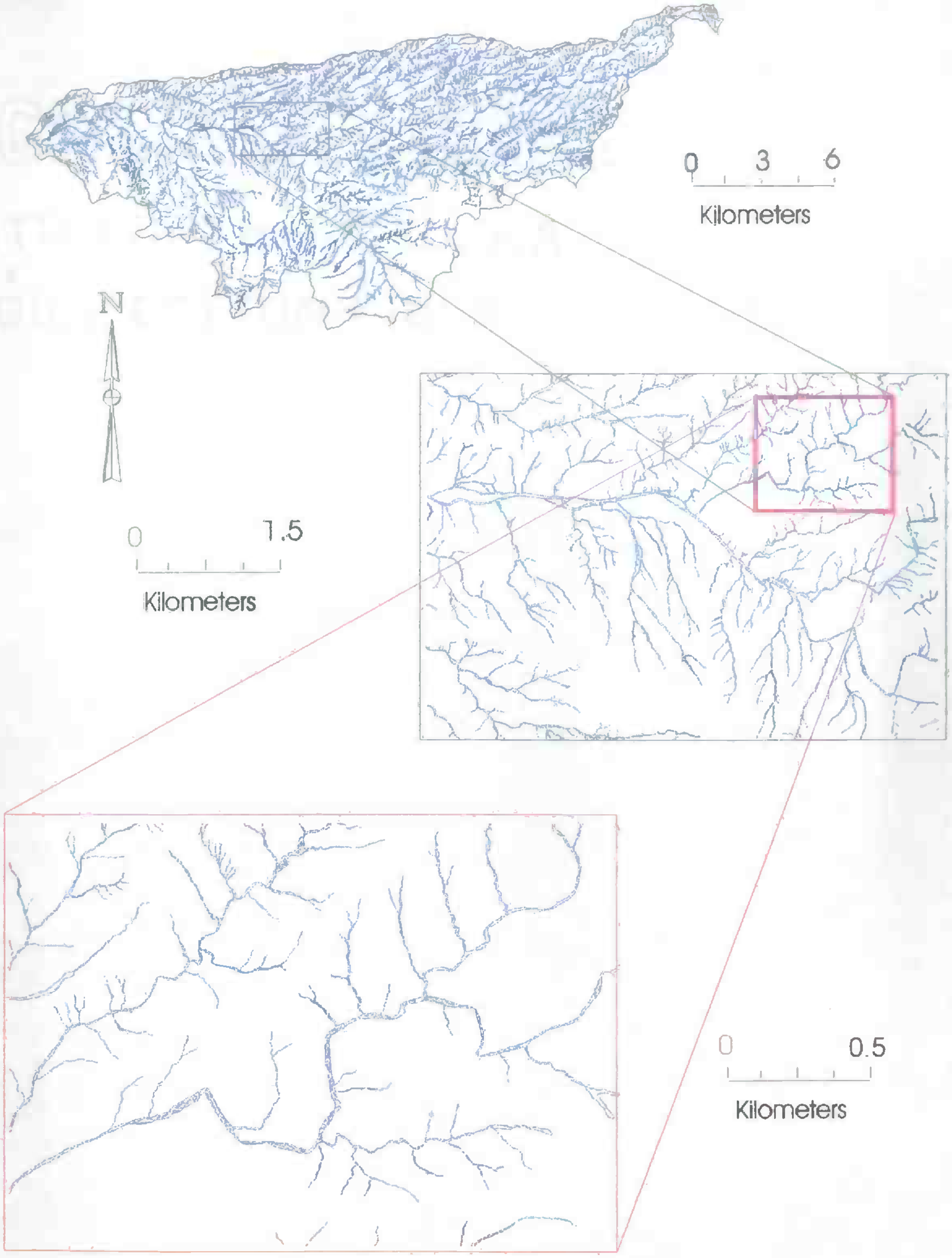


Figure 8: Stream channels represented at different scales

Sample Point Designation

To account for basin-scale variability, a large number of randomly sampled points was required. These points were to provide a representative sample distribution across the watershed. More points than necessary were created for the original sample design, since it was anticipated that, due either to human impact or other environmental variables that would change the hydraulic characteristics of a site beyond that which would be expected under natural conditions, some points would be inappropriate for sampling and discarded from the study. Of the original 300 points, 222 were ultimately used in the analysis. Figure 9 shows the distribution of sample points across the study area.

ROLE OF SOILS

One of the original postulates of this research was that soil type would play an influential role in determining stream channel characteristics. To account for this assumption, the sampling design was pre-stratified by soil type. The soil types described in the SCS soil survey (Breckenfield et al., 1995) were first lumped into distinct groups so as to more appropriately partition the watershed. Soil map units were reclassified according to similarities in texture, slope classes, and soil series. Since the soils were mapped at the association level, each soil map unit contained multiple series, with considerable overlap between the different units. Where such overlaps were extensive, the soils were merged to create a lumped soil map. From the original 30 soil

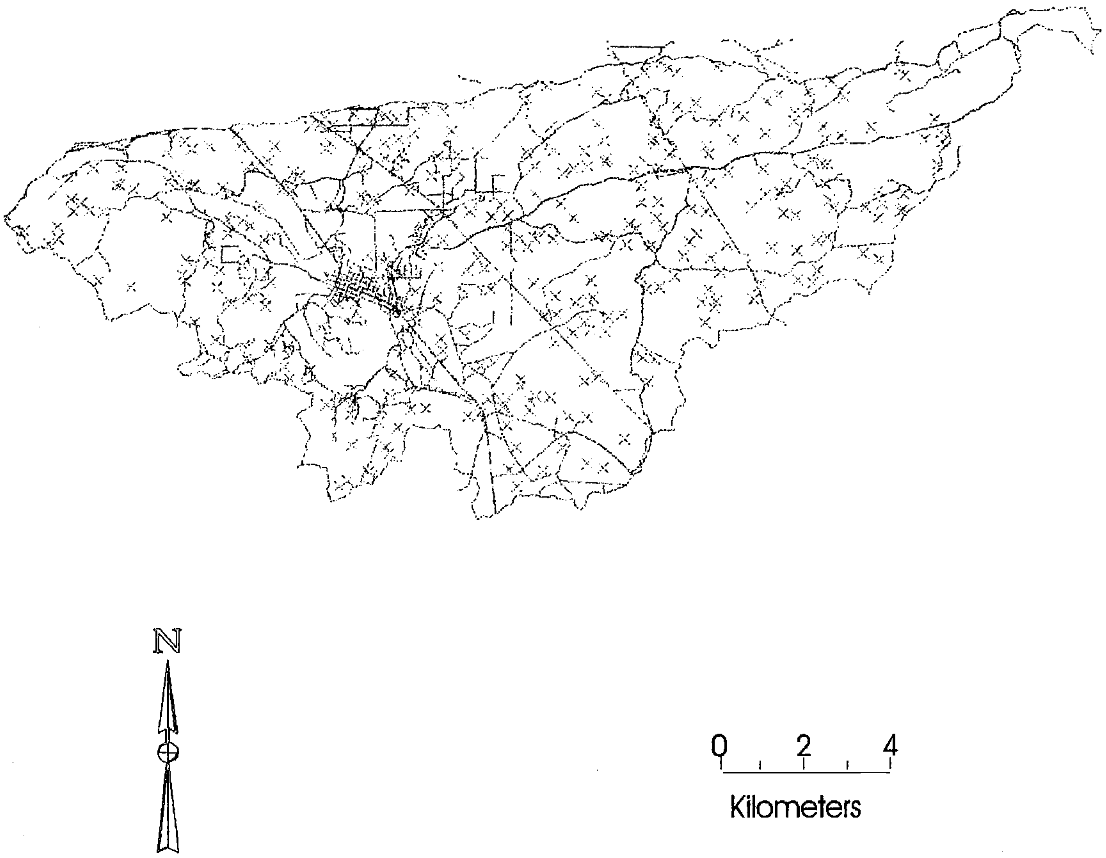


Figure 9: Sample points for field research

types, a final map containing 21 soil classes was created. The results of this reclassification can be seen in table 2.

Having set up the remap table, it was then possible to utilize reclassification routines in ARC to create a new lumped soil map. From this map, areal extents of each of the new soil classes were determined by analyzing their polygonal attributes. This information was then exported into a spreadsheet to determine the number of points needed for each soil class. For the purposes of pre-stratification, the total number of potential points (300) was multiplied by the percent cover of each reclassified soil type to determine the number of points that would fall within that particular soil class.

POINT GENERATION

A random number generator was employed to derive the appropriate number sample points within each of the 21 soil classes. The resultant x- and y- coordinate pairs were imported into an ARC/INFO point coverage, which was draped over the hydrology theme layer. In some cases the sample points fell directly on top of a stream channel. In most cases, however, the sample point fell close to, but not on a channel link. In those cases, the sample point was moved to the closest channel link. In this manner the 300 sample points were adjusted to their final positions for the field survey.

It should be noted that the soil map used in the pre-stratification process was later found to be flawed and rejected. Drawn from 1:24000 scale photos with soil boundaries

Table 2: Reclassification of soil map units based on compositional similarities

Soil code	Soil map unit name	Lumped soil group
1	Baboquivari - Combate complex, 0 - 3 percent slopes	1
2	Blacktail gravelly sandy loam, 8 - 15 percent slopes	2
3	Budlamp - Woodcutter complex, 30 - 60 percent slopes	3
4	Chiricahua very gravelly sandy loam, 8 - 15 percent slopes	4
5	Combate loamy sand, 0 - 3 percent slopes	5
6	Elgin - Stonghold complex, 8 - 15 percent slopes	6
7	Epitaph very cobbly clay loam, 3- 15 percent slopes	7
8	Forrest - Bonita complex, 0 - 3 percent slopes	8
9	Graham cobbly clay loam, 8 - 15 percent slopes	8
10	Graham - Lampshire complex, 15 - 30 percent slopes	9
11	Grizzle coarse sandy loam, 3 - 8 percent slopes	10
12	Lampshire - Rock outcrop complex, 3 - 15 percent slopes	11
13	Lampshire - Rock outcrop complex, 15 - 60 percent slopes	11
14	Luckyhills loamy sand, 0 - 3 percent slopes	12
15	Luckyhills - McNeal complex, 3 - 8 percent slopes	12
16	Luckyhills - McNeal complex, 8 - 15 percent slopes	12
17	Mabray - Chiricahua-Rock outcrop complex, 3-15 percent slopes	13
18	Mabray - Chiricahua-Rock outcrop complex, 15-30 percent slopes	13
19	Mabray - Rock outcrop complex, 3 - 15 percent slopes	13
20	Mabray - Rock outcrop complex, 15 - 45 percent slopes	13
21	Mcallister - Stronghold complex, 3 - 8 percent slopes	14
22	Monterosa very gravelly fine sandy loam, 3-8 percent slopes	15
23	Monterosa very gravelly fine sandy loam, 8-15 percent slopes	15
24	Riverwash - Bodecker complex, 3- 8 percent slopes	16
25	Schiefflin very stony loamy sand, 3 - 15 percent slopes	17
26	Stronghold - Bernadino complex, 10 - 30 percent slopes	18
27	Sutherland - Mule complex, 8 - 15 percent slopes	19
28	Sutherland very gravelly fine sandy loam, 3-8 percent slopes	19
29	Tombstone very gravelly fine sandy loam, 8-15 percent slopes	20
30	Woodcutter gravelly sandy loam, 15 - 30 percent slopes	21

inscribed on them, these maps were only partially rectified, and errors due to photographic distortion were significant. Consequently, the soil polygons were judged to have been created from faulty data, and the soil map was entirely recreated. The re-creation of the soil theme layer significantly altered the distribution of soil types underlying the sample points. Of the 222 sampled points, 150 had their underlying soil types change when the soil map was updated. However, when the soil categories are lumped together to provide a better distinction between soil categories, the change in soil becomes less distinct, and the number of differing sample points drops to 103.

The change in soil type is particularly significant in the larger stream channels. When the soil polygons were transferred onto the 1:5000 orthophotos, it was easier to pick out the upper reaches of the stream channels, and the soils representing channel beds and alluvial material increased significantly (soil types 1, 5, and 24). Of the changes reported between the two soil maps, 29 were caused by the extension of channel bed material into the uplands of the watershed.

ELIMINATION OF DATA POINTS

Statistical Reasons

Investigation into the statistical distribution of channel geometry data revealed that swales could not be evaluated with incised channels. The values of the swales' width and depth did not relate to those of the incised channels, and served to introduce a bias and exaggerate the variance. Therefore, swales were excluded from the final analysis. Since a small number of swales was measured in the field, it was infeasible to analyze them separately. Three points were removed from the analysis because they introduced a severe bias or overly contributed to a variable's standard deviation. All three points were first-order channels, these anomalous readings were most probably the result of recording errors. Future research into the morphology of swales and their response the hydrologic and topographic variables would serve to make this study more comprehensive.

Field Problems

Several data points were found to have been significantly altered by human activity and discarded from the sample collection. Many of the sample points near and within the town of Tombstone were located in channels with disturbed hydrology from construction and channel improvement projects. These sample points were removed from the sample population because they were not representative of the overall distribution of channels. Some reaches could not be located in the field, and could therefore not be included in the study. These were few in number because of the high quality of field maps used in the investigation, but in some areas with rugged topography it proved impossible to ensure an accurate field location. Following Osterkamp and Hedman (1977), unstable reaches or those dominated by geologic control were not sampled. Ultimately, a final sample size of 222 was used in the analysis.

Field Work

In order to expedite travel to each sample point location, large-scale maps were created to detail road, stream, contour, and site information surrounding each data point (figure 10). Of primary concern was the accurate placement of site locations in the field. Because the GIS maps were created at a very high resolution, it was possible to place a specific location in the field within a few meters. Although the sample locations are herein referred to as "points", measurements of geomorphologic information focused not on particular points on a stream channel, but on interior drainage links. At each site, procedures demonstrated by Osterkamp et al. (1983), Gordon et al. (1992), and Harrelson et al. (1994) were followed. The closest channel link to a sample point, defined as a channel section between two channel confluences (Leopold et al., 1964) was subjected to the survey methodology described in the next section.

INITIAL SURVEY

Upon arrival at a site, an initial inspection of the stream link was completed. The length of the channel was walked and the bank morphology, vegetation, and soil characteristics were examined. This was done to ensure that cross-sections were representative of the entire channel link. A site description, including vegetation type and channel characteristics, was recorded in a log book, with references to potential problems and channel complexity. Bankfull and channel-top indicators, including changes in

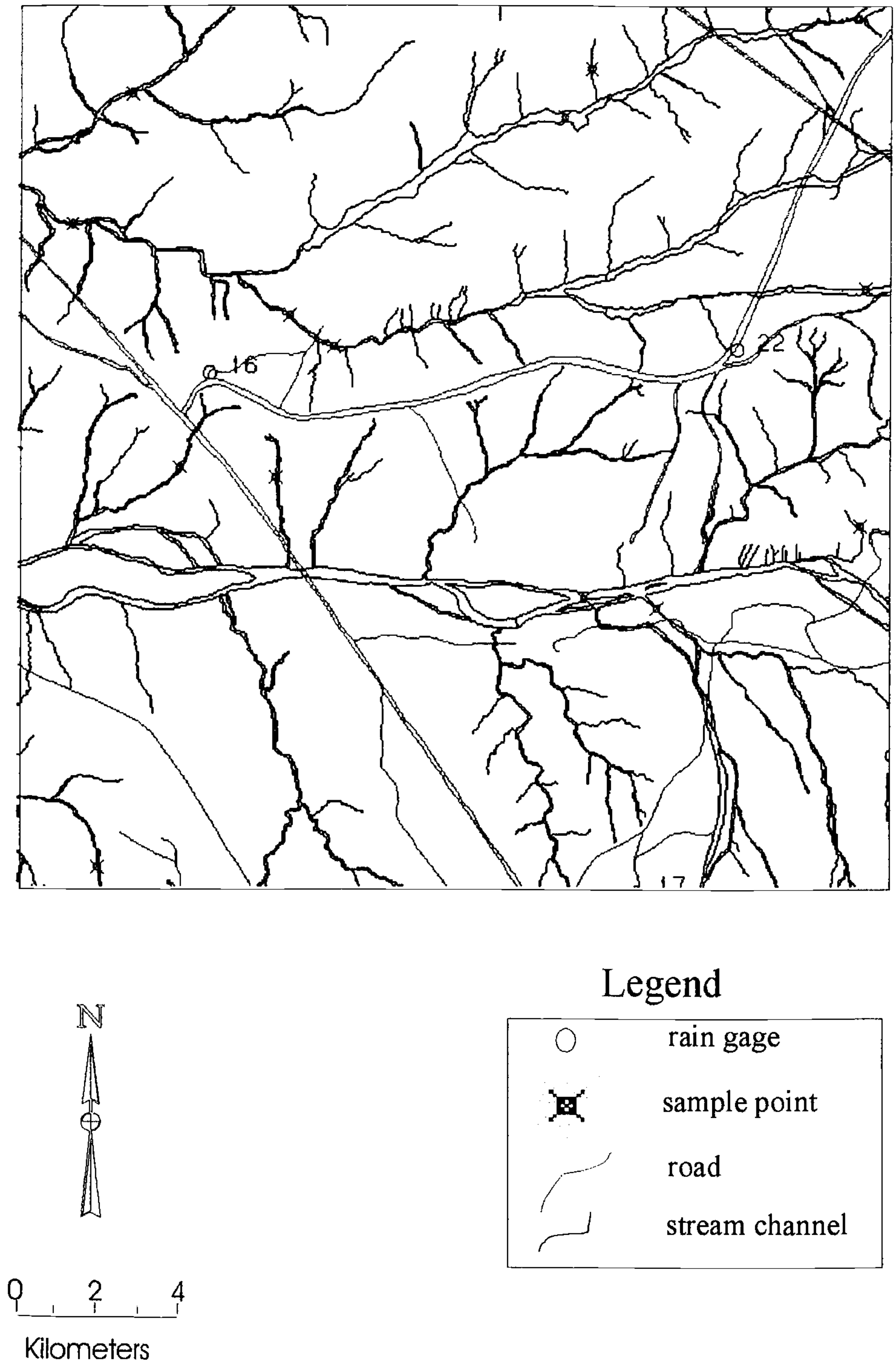


Figure 10: Field-scale map of sample locations near flume 6

slope, change in vegetation or bank materials, debris lines, and bank staining were utilized to determine the proper location and placement of the cross-sectional survey.

There are, of course, many changes in slope along a cross-sectional profile, but the most significant change, that from a steep-walled to a flat profile, indicates the point at which bankfull width could be marked. It was important to note the presence or absence of channel terraces; some cross-sections displayed a series of terraces and channel islands which affected the surface significantly, but did not serve as indicators of bankfull depth. To gauge the difference between terrace and floodplain formation, other factors were assessed, especially sediment and vegetation changes.

Ephemeral channels, as found on Walnut Gulch, are subject to relatively rapid and violent runoff events and generally do not contain significant vegetation within the channel profile. The presence of vegetation on the bank can therefore serve as a primary indicator of the dominant flood stage. The type and variety of vegetation present on the bank is also important. Whereas rabbitbrush (*Chrysothamnus nauseosus*) and some grasses may survive in the relatively high-moisture soils of channels, desert plants such as creosote (*Larrea tridentata*), prickly pear (*Opuntia sp.*), and yucca (*Yucca sp.)* cannot survive consistent exposure to flood waters. The demarcation present between vegetative zones can serve as a useful reference to bankfull stage. Additionally, larger plants and trees hold the banks in place and also serve as indicators of flood stage. Trees such as desert willow (*Chilopsis linearis*), mesquite (*Prosopis sp.*), hackberry (*Celtis pallida*), and walnut (*Juglans major*) all served at times to delineate channel width.

Bank and bed materials change significantly between the channel exposed to consistent flood events and the areas outside of the dominant channel processes. A clear change in particle size (either from coarse-to-fine or vice-versa) can be indicative of a change in hydraulic processes acting on the surface. Abrupt changes in soil type at survey locations were often associated with a break in slope. Changes in soil texture were especially noticeable at the edges of swales. Within the swale boundary, fine materials, including clays, were generally present, while outside the boundaries of flow, desert pavement may exist. Where this occurs, there was usually a marked change in vegetation from grasses and forbs to desert shrub.

Debris lines and staining on the channel bank were especially useful when surveying relatively small first and second order streams. In such small streams, channel processes may not have yet fully developed the classic channel shape, and the channel may appear on a continuum between a steep-walled arroyo and discontinuous, indistinct flow path. In such cases, the presence of scour lines may coincide with debris lines at the base of vegetation. Where such debris lines or escarpments run continuously it is possible to draw an accurate representation of bankfull stage.

Wherever possible, evidence indicative of a constructive, rather than destructive, process was used. Escarpments were particularly avoided, unless used in conjunction with other evidence, due to the concern that undercutting had caused the demarcation. Constructive landforms, such as floodplains and terraces, indicate that the system is in dynamic or quasi-equilibrium, and the channel may be assumed to be representative of the area from which it was taken (Osterkamp, 1995). Such constructive landforms were not always in evidence, and if there was little or no credible constructive evidence, the channel was assumed to be in disequilibrium and discarded from the sample design.

CROSS-SECTION SURVEYING

For the purposes of this survey, the concept of bankfull stage was employed, wherein the major break in slope from channel to floodplain served as the primary marker for flow. The representation of bankfull stage as the expected depth of a 1.5 year return flow (Dunne and Leopold, 1978) may have limited application in a semi-arid climate due to the intermittent behavior of rainfall and ephemeral response of drainage networks. However, the dominant flow regime may best be reflected by the channel geometry at bankfull stage, specifically as a measure of the average depth and width of a channel (Osterkamp et al., 1983). Some degree of subjectivity was present in the definition of channel shape, since the channels at Walnut Gulch do not follow a consistent morphology. With channel morphology due to inconsistent runoff, bank indicators were often indistinct.

Once the stream link was inspected and a thorough visual analysis of the channel morphology completed, cross-section surveys were established at three points along the link's length and marked on the field map. If the section was particularly inconsistent in morphology, an additional two cross-sections were taken. At each cross-section, a pin was inserted into the channel bank at bankfull depth. From that pin, a light kite string was drawn perpendicular across the channel. Using a line level, the string was leveled and secured against the other bank with another pin such that the line intersected the ground level to the first pin. The line was pulled as tight as possible to eliminate sagging. A fiberglass measuring tape was drawn across the channel next to the kite string and also pulled tight. Using the convention that the origin of the cross-section was the pin on the left side while facing upstream, depth measurements were taken at each change in slope across the section and recorded on a data sheet (table 3). This procedure was then repeated for the other cross-sections at that sample point.

Data collected for each cross-section was imported into spreadsheet format and analyzed to derive the average channel width and depth for the stream section. Average channel width was found by applying the formula:

$$\overline{W} = \frac{w_1 + w_2 + \cdots + w_n}{n} \tag{10}$$

where,

$\overline{W}$ = average width of channel link (cm),
w_n = channel cross-section width (cm),
n = number of cross-sections measured along the channel link.

In order to determine the average channel depth at each point, a weighted average of depth based on the distance between slope breaks was used. An inspection of table 4 shows that width and depth measurements were recorded at each break in slope along the

Table 3: Sample geomorphologicic field notes table, site no. 321a

Site no.	Location marked on topo sheet?	Distance from top left. X coord (m)	Distance down from tape. Y coord (cm)
321 A	y	0.87	20.1
		1.39	31.6
		3.68	34.7
		4.27	29.8
		6.79	24.9
		7.36	16.5
		9.07	0.0

Table 4: Sample spreadsheet used to derive channel width and average depth from a cross-section survey, site no. 321a.

Break point	y_p	x_p	d(x)	k	$\bar{y}$	$k\bar{y}$	W/D	A_c
	0	0.0						
1	20.2	87.0	87.0	0.096	10.10	0.969	38.800	2.12
2	31.6	139.0	52.0	0.057	25.90	1.485		
3	34.7	368.0	229.0	0.252	33.15	8.370		
4	29.8	427.0	59.0	0.065	32.25	2.098		
5	24.9	679.0	252.0	0.278	27.35	7.599		
6	16.5	736.0	57.0	0.063	20.70	1.301		
7	0	907	171.0	0.189	8.25	1.555		
		width:	907.0	Avg. depth:	23.376			

where,

y_p = measured depth at each break point (cm),

x_p = measured distance from origin at each break point (cm),

d(x) = distance between break points (cm),

k = fraction of the total length between break points,

$\bar{y}$ = average depth between successive break points (cm),

$k\bar{y}$ = weighted depth between successive break points (cm),

W/D = the width:depth ratio for the cross-section, and

A_c = cross-sectional area (m^2).

cross-section. First, the length between break points was divided by the total width to derive a weight for each length:

$$k = \frac{x_p - x_{p-1}}{w_n} \qquad (11)$$

where,

k = weight of length between break points, and
x_p = measured distance from origin to break point (cm).

An average channel depth was determined for each interval:

$$\bar{y} = \frac{y_p + y_{p-1}}{2} \qquad (12)$$

where,

$\bar{y}$ = average depth between break points (cm), and
y_p = measured value of depth at break point (cm).

Combining and summing equations (11) and (12) yields a weighted average for depth over the given cross-section:

$$\bar{d}_n = \sum_{1}^{a} k\bar{y} \qquad (13)$$

where,

$\bar{d}_n$ = average depth for the cross-section (cm), and
a = the number of break points for the cross-section.

The results of this spreadsheet operation are presented in table 4. Having derived the mean channel depth for each of the cross-sections surveyed at a sample point, the average channel depth of the channel link was computed:

$$\bar{D} = \frac{\bar{d}_1 + \bar{d}_2 + \cdots + \bar{d}_n}{n} \qquad (14)$$

where,

$\bar{D}$ = average depth of channel link (cm),
d_n = channel cross-section depth (cm),
n = number of cross-sections measured along the channel link.

The average width of the channel link was computed in a similar fashion.

GIS Analysis

STREAM ORDER

One of the primary variables needed for statistical analysis of geomorphic relationships is stream order. Because channels were digitized as polygonal features, in some cases with islands within the channel bounds, it was not possible to order the streams in their original state. It was necessary instead to turn these stream channels into vectors, which required thinning them. To do so, the hydrology map was transferred into GRASS to take advantage of that system's raster functions. It was then rasterized at a one-meter resolution. The GRASS module r.thin, which draws a parallel bisector through polygons, was executed on the stream map. Because the map was too large for the program to handle, it was sliced into three sections, and the routine executed on each slice. It was found that the r.thin routine had to be run repeatedly on each section in order to achieve an accurate vectorization. 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.

GRASS does not currently support vector-based processing, so the map was exported back into ARC, which does support vector and routing functions. An ordering routine was created by the author that takes advantage of the data structure that ARC imposes on the vector maps. It was later found that a similar approach had been undertaken by Lanfear (1990). Before attempting the ordering process, it was first necessary to orient all the streams in the downward direction. Using a routing function, it was possible to update a process that correctly oriented the streams with respect to the outlet of the Walnut Gulch watershed (Appendix a). Originally distributed with the 7.0 release of ARC (ESRI, 1994), the direction routine had to be slightly modified to work on the stream channel coverage. Once the streams were all "pointing" in the downstream direction, the ordering program was imposed on them.

This ordering routine (Appendix b) utilizes the "from" and "to" node topology in ARC. Each vector within the stream coverage has a node at each end, which may or may not be connected to another arc. These individual arcs may be assigned attributes, such as their order value. The orientation program discussed above effectively altered the channels so that the "from" node was always upstream of an associated "to" node. A first order stream, defined as that into which no other channels flow, will always have an open-ended "from" node, signifying the start of the channel network. By assigning all vectors which have 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 streams.

Filtering repeatedly through the channels and their associated nodes, the routine searches for arcs that are not ordered. Since the ordering process is a progressive one, only channels downstream and connected to previously-ordered channels may subsequently be ordered. All other channels, those which have an upstream channel that is unordered, are passed over. If a channel is not ordered and all channels flowing into it are, then it may be assigned an order value. Nodes with only one arc above and below are “pseudo-nodes”; where such nodes exist, the channel below the arc is ordered the same as the arc above. Where two or more arcs flow together into a single node, the order values of all incoming arcs are checked, whereupon a logic query was imposed. Since a channel only increases in order relative to its incoming channels if they are of the same order, this condition was inspected; if both incoming channels were of the same order, the downstream channel was assigned an order value one higher. If a difference in order existed between the converging channels, then the downstream channel was assigned the higher of the two order values. The routine stops when there are no channels that have not been ordered.

WATERSHED ANALYSIS

Certain variables describing the area contributing runoff to each sample point were desired for statistical analysis. These variables included: contributing area;

perimeter distance; cumulative channel length; maximum flow length; maximum, mean, and minimum elevation. To facilitate the acquisition of data by GIS analysis, ARC Macro Language (AML) programs were developed. These AMLs are presented in Appendices c-f. Using a ten-meter DEM created from spot elevation data, the watersheds were created in the ARC submodule GRID using a watershed analysis program created by this researcher (Appendix c). In order to accurately locate the outlet of the watershed at the midpoint of each channel link, this watershed delineation routine required user input. The routine is initiated by the user specifying the watershed outlet on the surface model via a point-and-click interface. Once the outlet was entered into the model, an algorithm searched for all the areas contributing runoff to that point. Upon completion of that algorithm, the results were shown to the user, who verified the results and initiated the next sequence.

If the watershed was deemed acceptable, statistical and geometric analyses were performed and the results output to a text file. To determine its maximum, minimum, and mean elevation, the watershed was multiplied by the DEM to create a surface model contained within the boundary of the watershed. Flow direction and flow length maps were created for each of these smaller surface models which determined the maximum length of flow within each watershed (Appendix d). The elevation of the centroid locations was also extracted from these subwatersheds using a similar routine (Appendix e). Finally, cumulative channel lengths were computed by integrating the smaller watershed maps with the stream channel map (Appendix f). In this fashion data relevant to the statistical analysis was extracted from the GIS and converted into a flat file format for import into spreadsheet and statistical software packages.

Statistical Variables

To provide a basis for a full investigation into statistical relationships between watershed and hydrologic variables, an array of variables was constructed from data collected during this project. Dependent variables of primary interest were average channel width, depth, and cross-sectional area at bankfull stage for the stream reaches subjected to measurement. These dependent variables related to channel hydrologic and hydraulic properties, while the independent variables describe the contributing area above each survey location. Independent variables characterized basin attributes (area, perimeter, gradient and shape properties), as well as stream flow (maximum flow length, cumulative channel length, channel order), and soil properties (clay content). Since topographic variables affect hydrologic processes downstream, in order to adequately model channel morphology, it is important to gain an understanding of these basin characteristics.

BASIN SIZE AND RELIEF

Because it influences virtually all other watershed parameters, Anderson (1957) referred to the size of a watershed as "the devil's own variable." For instance, due to the change in surface area on which precipitation may fall, basin size directly influences the amount of runoff occurring at a basin outlet. In his seminal work, Horton (1945) outlined the primary relationships between basin size and channel area, as well as the surrogate relationships existing between channel area and order, and order and basin size. Such relationships have become an established and well-understood fixture in the literature (Dunne and Leopold, 1978). However, some discrepancies exist in the relationships for basin area and discharge between climatic regions. In areas with high transmission losses and low amounts of precipitation, such as in Walnut Gulch, discharge does not increase linearly with basin size. Even in such cases, discharge changes with basin size, and statistical relationships describing this relationship have been derived (Osterkamp and Hedman, 1977; Dunkerly, 1992).

Relief within a basin affects channel hydraulics and discharge, thereby influencing sediment yield and channel geometry. Relief is a measurement of the potential energy within a stream system that directly influences flow velocity and the erosivity of runoff (Leopold et al., 1964). Schumm (1956) derived a simple index to drainage basin relief dubbed the relief ratio:

$$R_r = \frac{h}{L} \qquad (15)$$

where,

R_r = the relief ratio,
h = maximum difference in elevation within the basin (m), and
L = maximum length of the basin (m).

It was later demonstrated by Hadley and Schumm (1961) that sediment yield is related in an exponential fashion to this relief ratio. Sediment yield and runoff erosivity have been directly linked to channel shape, specifically cross-sectional area (Gordon et al., 1992).

BASIN SHAPE

Shape descriptors, such as basin length, width, and perimeter, also influence sediment and water yield by altering the time of concentration during a storm event (Leopold et al., 1964). The perimeter of a watershed is a function of both its size and shape, and so is a useful index of basin form. The area:perimeter ratio was derived for each point in this study:

$$A_p = \frac{A_w}{p} \qquad (16)$$

where,

A_p = the area:perimeter ratio (m),
A_w = area of the basin (m^2)
p = watershed perimeter (m).

An elongated watershed will likely demonstrate a wide range in flowlengths from the watershed divide. Conversely, flow lengths will be more uniform on a more circular watershed. A more rounded watershed, therefore, will typically have higher flood peaks, while the elongated watershed will have a longer flood stage and lower peaks. These runoff patterns influence the size and shape of channels below the watershed, specifically by altering the level of bankfull stage (Gregory and Walling, 1973). Various methods have been proposed for expressing basin shape, the basin circularity ratio (Miller, 1953), the basin elongation ratio (Schumm, 1956), and the lemniscate ratio (Chorley et al., 1957). In this paper, the compactness ratio devised by Horton (1932) was used to describe basin shape:

$$R_f = \frac{A_w}{L^2} \qquad (17)$$

where,

R_f = basin shape,
A_w = area of basin (m^2), and
L = length of basin (m).

CUMULATIVE CHANNEL LENGTH

Drainage basins may be characterized by the length of their interior drainage channels. Drainage density has been used to describe the proportion of channel length to watershed size, but this ratio was not related well to watershed and channel parameters (Schumm, 1956). The total drainage length within a basin was used instead:

$$R_l = \sum_{1}^{n} l_c \qquad (18)$$

where,

R_l = cumulative channel length (m), and
l_c = individual channel lengths (m).

A large value of cumulative channel length indicates a well-drained watershed, and relates directly to channel runoff (Gordon et al., 1992).

SOILS

One factor not taken into account during this investigation was the channel sediment, which can influence both sediment yield and runoff. Soil characteristics of the contributing watersheds were used as a surrogate for channel sediment. Several indices for soil characterization were investigated, each of which attempted to lump soil parameters together to provide sub-categorization of soils. Besides the grouping outlined earlier in this paper, a categorization based on soil clay content was also derived, according to the following equation:

$$S_c = \frac{A_{s1} C_{s1}}{A_w} + \frac{A_{s2} C_{s2}}{A_w} + \cdots + \frac{A_{sn} C_{sn}}{A_w} \qquad (19)$$

where,

S_c = soil clay content,
A_{Sn} = area of soil type n (m^2),
C_{Sn} = clay content of soil type n, and
A_w = drainage basin area (m^2).

Drainage basins were subdivided into two classes based on their soil clay content: those under 20% clay were grouped into one category, while those with an average clay content greater than 20% were grouped into another. The 20% threshold was chosen since that amount of clay represents an important difference in textural classification according to the USDA textural triangle (Jury et al., 1991).

Statistical Analysis

Regression analysis was used in order to define a deterministic model between geomorphic variables. Regression analysis serves to develop equations that estimate an average value of a random variable based on one or more independent variables (Milton, 1993). Both single and multiple linear regression models were developed to test the significance of relationships. There are several underlying assumptions on which this type of analysis is based: that the data is random; that the data is normally distributed; and that the independent variables are not correlated with one another.

Since data collected in the field was subjected to random placement, the demand that the data be random was satisfied by the statistical design. The Kolmogorov-Smirnov (K-S) test was used to test for normality. A goodness-of-fit test, the K-S test illustrates how closely data is aligned to a theoretical distribution (Daniel, 1991). Variables derived as the product of other variables were partitioned from their parent variables during multiple regression to remove correlative effects. Graphical outputs were used to derive a first-order approximation of the relative importance and relationship of variables to one another. By inspection, it was possible to establish important treatment effects and primary relationships. Box plots, quantile plots, and category plots were used in this process.

A one-way classification, completely random with fixed effects analysis of variance (ANOVA) was performed on different data elements to determine if significant differences existed between treatments. Treatments included: stream order; soil type; lumped soil type; and soil clay percentage. Experimental units subjected to the ANOVA were: width of channel; average depth of channel; width:depth ratio; and cross-sectional area. Significance was found between all treatments for all experimental units, implying the presence of an effect for all treatment variables. The ANOVA requires that three model assumptions are satisfied: that the samples are independent; that the sample populations are normal; and that each of the sample populations has the same variance (Devore, 1987). The questions of independence and normality was addressed in the previous section of this paper, while the variance between sample populations was analyzed using descriptive statistics. In order to determine if channel characteristics varied as the function of stream order, soil clay content, or an interaction between soil type and stream order a multiple analysis of variance was performed.

RESULTS AND DISCUSSION

Influence of Soil Texture

Sample points were categorized based on the average clay content of the areas contributing to runoff (equation 19). It was hypothesized that average clay content would have an impact on channel geometry because of its influence on hillslope and channel erosion processes. Other researchers (Leopold and Maddock, 1953; Schumm, 1960; Hedman and Osterkamp, 1982) have investigated the role of bed material located within the reach under investigation. Since channel bed materials were not sampled during this project that avenue of research was unavailable. One of the purposes of this investigation was to accurately assess and model channel variables using a high-quality GIS and cross-section data with minimal field sampling. It was hoped that an alternative method to on-site soil sampling could be developed.

Provided a high level of precision could be assigned to the soil survey, it might be possible to quantify soil characteristics for each of the sample points using GIS analysis. Unfortunately, the soil survey of Walnut Gulch was mapped at the association level and is at a level of precision too low for the confident assessment of site-specific conditions. However, when averaging over a watershed, problems associated with point assessment are eliminated.

SOIL ANALYSIS

It is logical that in areas with a higher percentage of binding material, silt and clay, that channel shapes would be different than in areas with loosely consolidated material. Indeed, this general trend has been investigated and supported by various researchers (Schumm, 1960; Gordon et al., 1992). In areas where there is high silt and clay in the channel bed and bank material, channels tend to be narrower and deeper than those areas where soils are less erodible. On Walnut Gulch, both width and depth are shown to have lower average values in areas with higher clay content. The plots of figure 11 show an inverse relationship between the value of all channel shape parameters and percent clay content. Recall that soil category one contains sites whose average clay content from the area contributing runoff is less than 20%, while category two has sites where the average clay content is greater than 20%.

Since most of the larger, high-order channels contain a deep bed material that is typically well drained (Soil types 1 and 24), it is plausible that the soil texture would be directly correlated with stream order, and therefore should be ignored as an independent variable. Following this logic, one would expect the smaller channels to contain a higher clay percentage than the corresponding larger channels that contain primarily alluvial fill. However, an analysis of this correlation using a multiple ANOVA with soil group and stream order as variables showed that such an interdependence does not exist on Walnut Gulch for channel width, depth or cross-sectional area. Stream order increases rapidly on Walnut Gulch, a tendency which would override the preceding logic, since many high-

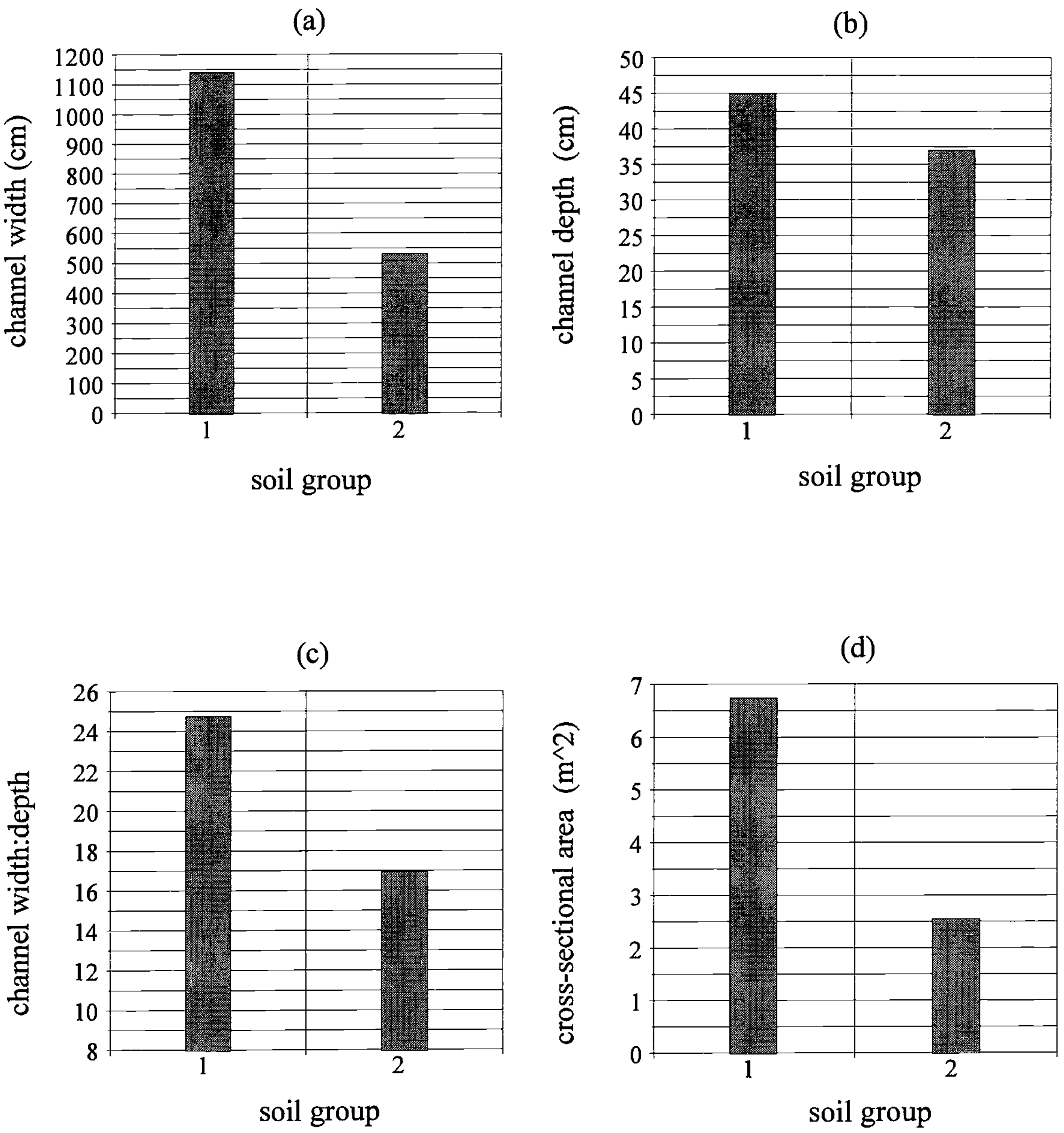


Figure 11: Category plots showing means of channel variables sorted by soil group

order channels are also located on clay-rich uplands rather than being strictly relegated to the alluvial lowlands.

Notably, the width:depth ratio decreases with increasing clay, a finding that is in concurrence with earlier research. It was not predicted that channel area would necessarily decrease with increasing clay content, but this relationship may be a function of the distribution of soil on Walnut Gulch. Walnut Gulch has two relatively distinct soil and vegetative zones which roughly bisect the watershed. On the eastern side of the watershed reside more clay-rich soils than on the western side. Grasses predominate in the clay-rich soils, while intermittent shrubs and bushes typify the western vegetation. Since water flows in a westerly direction through Walnut Gulch, channel size increases in that direction. Therefore, a greater proportion of small watersheds exist on clay-rich grassy areas. With the concentration of large channels occupying the clay-poor regions on the western side of the watershed, it is difficult to distinguish between the effects of soil and watershed area.

SIGNIFICANCE TESTING

Several treatment effects were investigated for their influence on channel shape. Of particular interest were the treatment categories of stream order and soil texture. Stream order has been repeatedly shown to influence many channel properties, including channel area and the width:depth ratio (Horton, 1945; Schumm; 1956; Leopold et al., 1964; Gregory and Walling, 1973; Gordon et al., 1992). As mentioned earlier in this paper, the sample design was stratified on the basis of soil characteristics. However, because the soil map was changed significantly after the sampling program was completed, not all the soil units were adequately sampled. Because of the inadequate sampling and lack of channel sampling, further investigation into the soil parameters of the watersheds above each sample point was done.

Descriptive Statistics

A large range in channel width exists for both soil categories one and two, although the variance is most profound in category one. Table 5 details the descriptive statistics for channel variables as a function of soil category. The range in measured values of depth, the width:depth ratio, and channel area are all substantially lower relative to channel width, although all exhibit a large range. In only one instance does the coefficient of variation drop below 1.0, and that is for channel area in soil category two (coefficient of variation = 0.34). Apparently there is a controlling factor on channel area in the areas of soil category 2. Perhaps the channels in this soil class have adjusted to runoff better than those in the other soil class, which are generally distributed on smaller watersheds in the upper reaches of the watershed.

Table 5: Descriptive statistics of channel variables, stratified by soil group

(a): soil group 1

	Width (cm)	Depth (cm)	Width:depth	Area (m^2)
N of cases	91	91	91	91
Minimum	154.67	13.48	2.13	0.22
Maximum	6141.5	142.19	97.55	47.15
Mean	1140.63	44.90	24.73	6.74
Variance	1705428	628.41	495.53	104.53
St'd Dev.	1305.92	25.07	22.26	10.22
C.V.	136.9	2.63	2.33	1.07
Median	595.67	39.45	15.74	2.66

(b): soil group 2

	Width (cm)	Depth (cm)	Width:depth	Area (m^2)
N of cases	130	130	130	130
Minimum	94.5	8.01	3.10	0.11
Maximum	2479.33	125.70	98.72	29.75
Mean	517.74	36.71	16.81	2.53
Variance	241112.7	642.15	216.67	15.21
St'd Dev.	491.03	25.34	14.72	3.90
C.V.	43.07	2.22	1.29	0.34
Median	330.83	29.10	12.26	0.89

Analysis of Variance

Soils were categorized into two groups for the purposes of this investigation. Soil clay content was used as a surrogate for soil characterization, with soil categories derived as shown in equation 10. ANOVAs were executed on the dependent variables under investigation (tables 6-9). The results of the ANOVA testing show that soil grouping based on percent clay content had a significant impact on population means.

Because the variances of the populations under investigation were dissimilar, a series of two-sample t-tests assuming unequal variances were executed on pairs of sample populations for the treatment of soil clay content. Significant differences were found between all pairs of population means.

Multiple ANOVA Test

Since it has been shown that both stream order and soil clay content influence channel characteristics (Abrahams, 1984), the relative importance these variables may be illustrated using a two-way Analysis of Variance (MANOVA) (Devore, 1987). In this project, the analysis tested if channel cross-sectional area is significantly different between soils groups within the different stream orders.

As shown in table 10, the MANOVA revealed the relative dominance of stream order in determining channel shape. With an insignificant P value, channel order can be regarded as having a main effect on channel shape, represented in this case as cross-sectional area, while soil clay content has no effect (P value = 0.51). The test for an

Table 6: ANOVA for measurements of width, treatment of soil group

source	sum-of-squares	degrees of freedom	mean-square	f-ratio	P
soil	.196 e+08	1	.196 e+08	23.25	0.0
error	.185 e+09	220	.843 e+06		

Table 7: ANOVA for measurements of depth, treatment of soil group

source	sum-of-squares	degrees of freedom	mean-square	f-ratio	P
soil	3512.98	1	3512.98	5.54	0.02
error	139506.3	220	634.12		

Table 8: ANOVA for measurements of width:depth ratio, treatment of soil group

source	sum-of-squares	degrees of freedom	mean-square	f-ratio	P
soil	3211.14	1	3211.14	9.70	0.02
error	72864.22	220	331.20		

Table 9: ANOVA for measurements of channel area, treatment of soil group

source	sum-of-squares	degrees of freedom	mean-square	f-ratio	P
soil	926.72	1	926.72	17.88	0.0
error	11404.46	220	51.84		

Table 10 : MANOVA for measurements of channel area, treatments of soil group and stream order

source	sum-of-squares	degrees of freedom	mean-square	f-ratio	P
stream order	3713.5	5	742.70	40.229	0.0
soil group	7.98	1	7.98	0.432	0.51
order*group	24.25	5	4.85	0.263	0.99
error	3876.98	210	18.46		

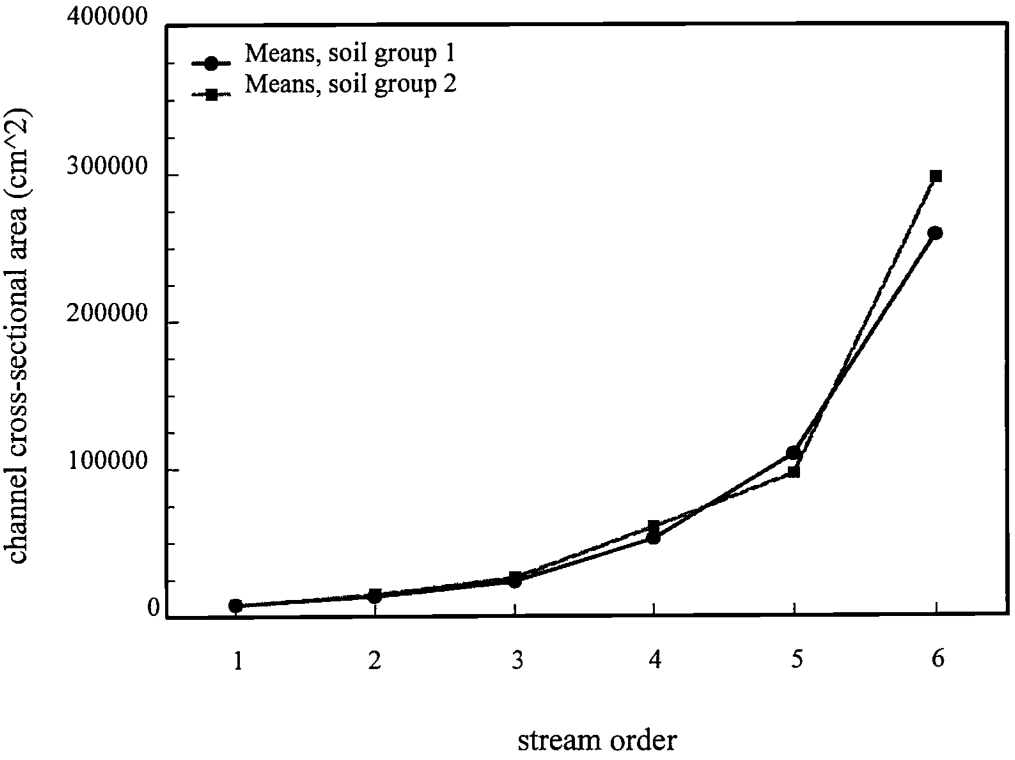


Figure 12 : Mean responses of channel cross-sectional area as a function of stream order

interactive effect between these two variables failed, as the P value for this test is 0.93 (table 10). Channel cross-sectional area can therefore be related to stream order independent of soil clay content. Figure 12 illustrates the response of channel cross-sectional area to stream order for the two soil groups. In figure 12, the two data groups respond in a virtually identical fashion to increasing stream order.

Since stream order was shown by the MANOVA to have the main effect on channel shape and that the channel cross-sectional areas were equal between soil groups within each stream order, the data from the two soil groups was pooled. For the purposes of this report, further relationships between channel shape variables and watershed parameters were developed using the pooled data.

Influence of Stream Order

In 1945, Horton introduced several “laws” of basin morphology related to stream order. Those laws refers to the basic relationships governing how watershed variables related to increasing stream order. Drainage area and cumulative stream length were shown to be directly proportional to increasing order (equation 2), while the number of streams per order was inversely proportional (equation 1). These general relationships were found to be true on Walnut Gulch, with some notable exceptions.

CHANNEL VARIABLES

Number of Channels

Horton (1945) and others (Dunne and Leopold, 1978) theorized that the bifurcation ratio would remain the same between all steps in increasing stream order, and that the relationship of number of streams to increasing order would approximate a geometric series. This was not found to be the case for Walnut Gulch, where the ratio varies from 2.71 to 4.72 for first to fifth order channels (table 11). The stream order map created with the ordering program designed for this project from which this data was collected is presented in figure 13.

The bifurcation ratio oscillates around a mean value of 3.7 for the first four steps between orders, which corresponds well with Horton's (1945) findings, which revealed a bifurcation ratio of 3.2 for many basins in upstate New York. There is a significant increase between the fifth and sixth order channels. This increase is reflected in figure 14 (a), which illustrates the approximately geometric series between the number of channels and their respective orders. As predicted, there is a roughly semi-log relationship through the first several orders, with a break in slope occurring at the sixth order. In a basin the size of Walnut Gulch, where a sixth order channel is created high up on the watershed, it is expected that there would be enough higher order channels to maintain the geometric series, but that is clearly not the case. This is a reflection in the geometric arrangement of channels in the watershed, where several fifth order channels in the lower reaches of the

Table 11: Distribution of channel length and number of streams by stream order

Stream order	Number of streams	Cumulative length (m)	Bifurcation ratio	Average stream length (m)
1	2627	486,204		185.08
2	588	246,833	4.47	419.78
3	217	148,823	2.71	685.82
4	46	74,712	4.72	1624.17
5	16	46,593	2.88	2912.06
6	1	24,802	16	24802.0

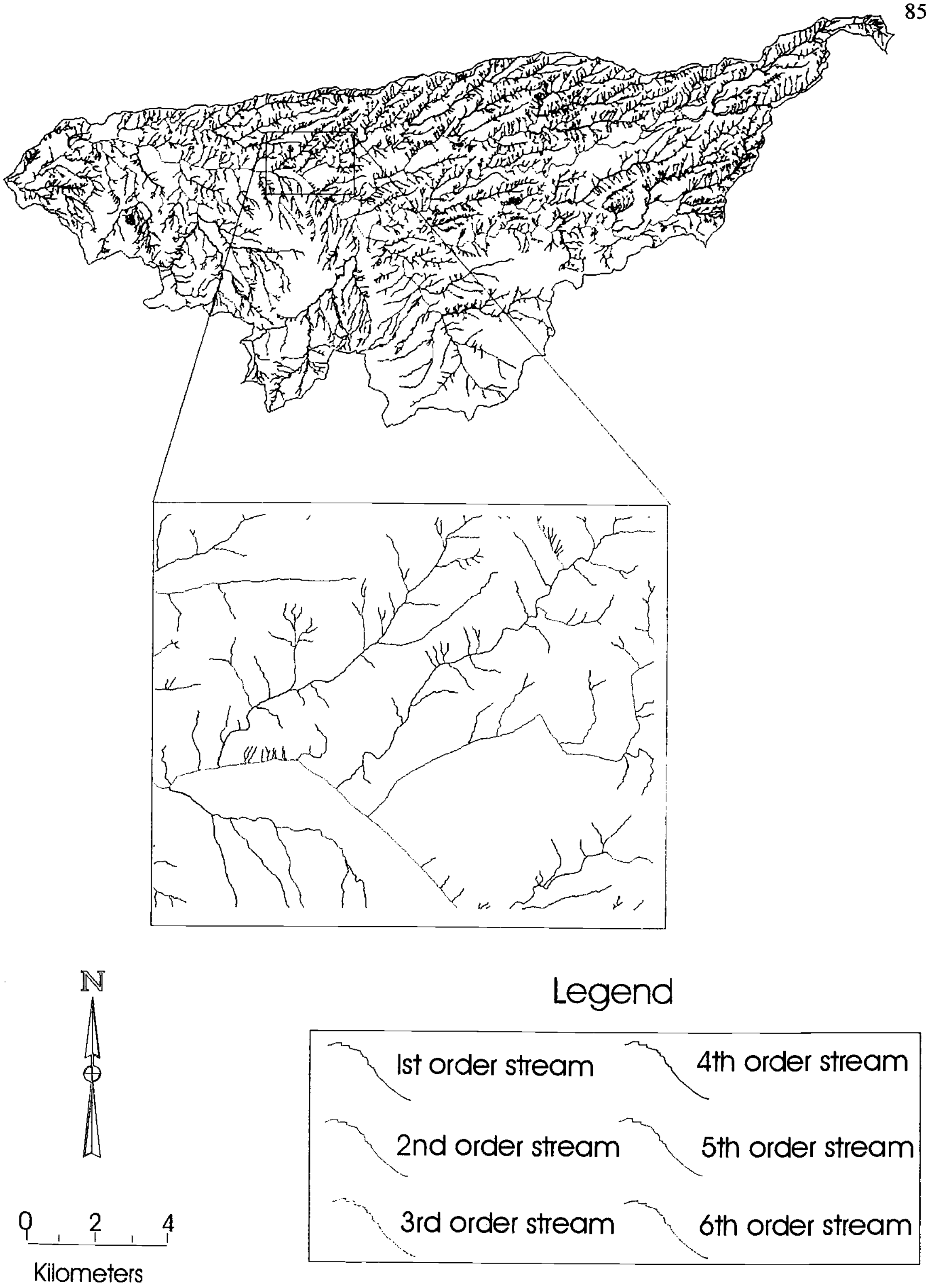


Figure 13: Output of channel ordering routine

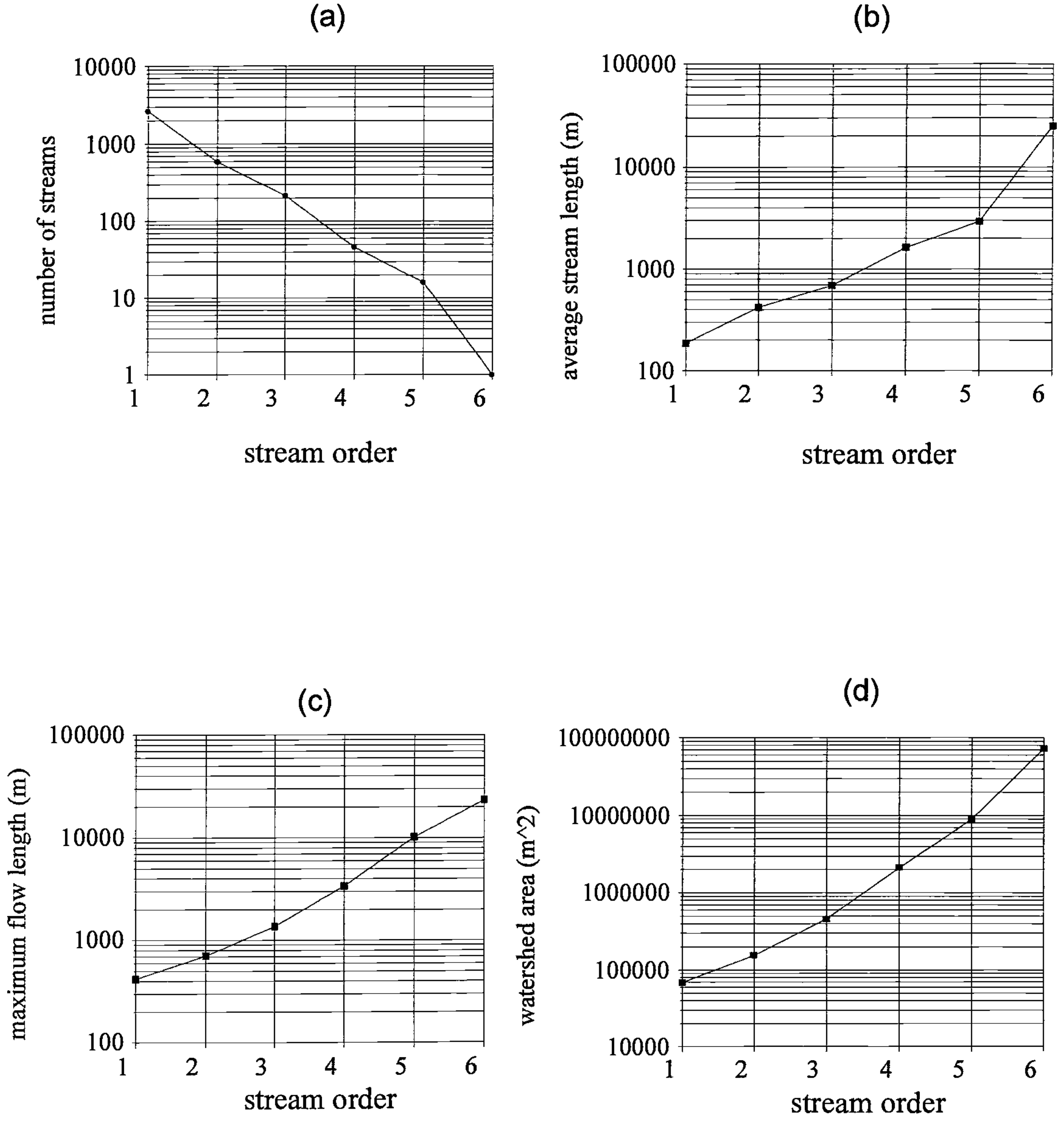


Figure14: Semi-log plots of channel properties per stream order

watershed flow into a single sixth order channel but never into each other. Results one gains from any ordering process are partly a function of methodology and scale. Future research into the role of scale on ordering and its impact on these relationships would further define the fundamental structure of channels within Walnut Gulch.

Channel Length Properties

Average channel length per stream order also approximates a semi-log relationship, with a break in the trend of the data occurring between orders five and six (figure 14, b). Once again, this break is due to the singular sixth order channel. Since the channel becomes a sixth order stream so rapidly, it has a very long flow path to the outlet of Walnut Gulch. With a sample population of one for sixth order streams, the data becomes skewed in the direction of long stream lengths for high order channels.

The maximum flow length contributing to each of the sample points showed a semi-log relationship to stream order (figure 14, c). Watershed area has a strong relationship to stream order (figure 14, d), and is presumable the driving force behind the correlation of flow length to order. As basin size increases, the maximum flow length within the basin will also increase. Therefore, maximum flow length will be correlated to stream order in a similar fashion to watershed area.

Channel Shape

Trends and relationships in the data were examined using graphical techniques. Category plots of channel parameters on the basis of their order revealed underlying structures in the data. Category plots show the average value of the dependent variable for each group category. For instance, in figure 15 average values for channel width, depth, area, and the width:depth ratio are plotted as a function of stream order. From these category plots certain inferences can be made about the channel geometry data.

It can be inferred from these category plots that stream order will provide a significant treatment effect in the statistical analysis. In all instances save one, the mean value of the dependent variable increased with increasing stream order. The single instance where this did not occur was for mean channel depth between stream orders four and five (figure 15, b). A general semi-log increase in channel size and the correlated variables of width, depth, and the width:depth ratio exist in relation to increasing stream order (figure 16). Depth has been cited as the most difficult variable to quantify with a high degree of accuracy (Osterkamp et al., 1983), and this perturbation in the trend may be due to the high variance associated with these measured values. Microtopography at sample locations will affect depth to a greater degree than width. This is because channel beds have a greater variation in their surface due to deposition and scour occurring during flow events. Moving small distances along a channel reach can profoundly affect the average depth, especially in higher order channels where channels islands and bars are prevalent.

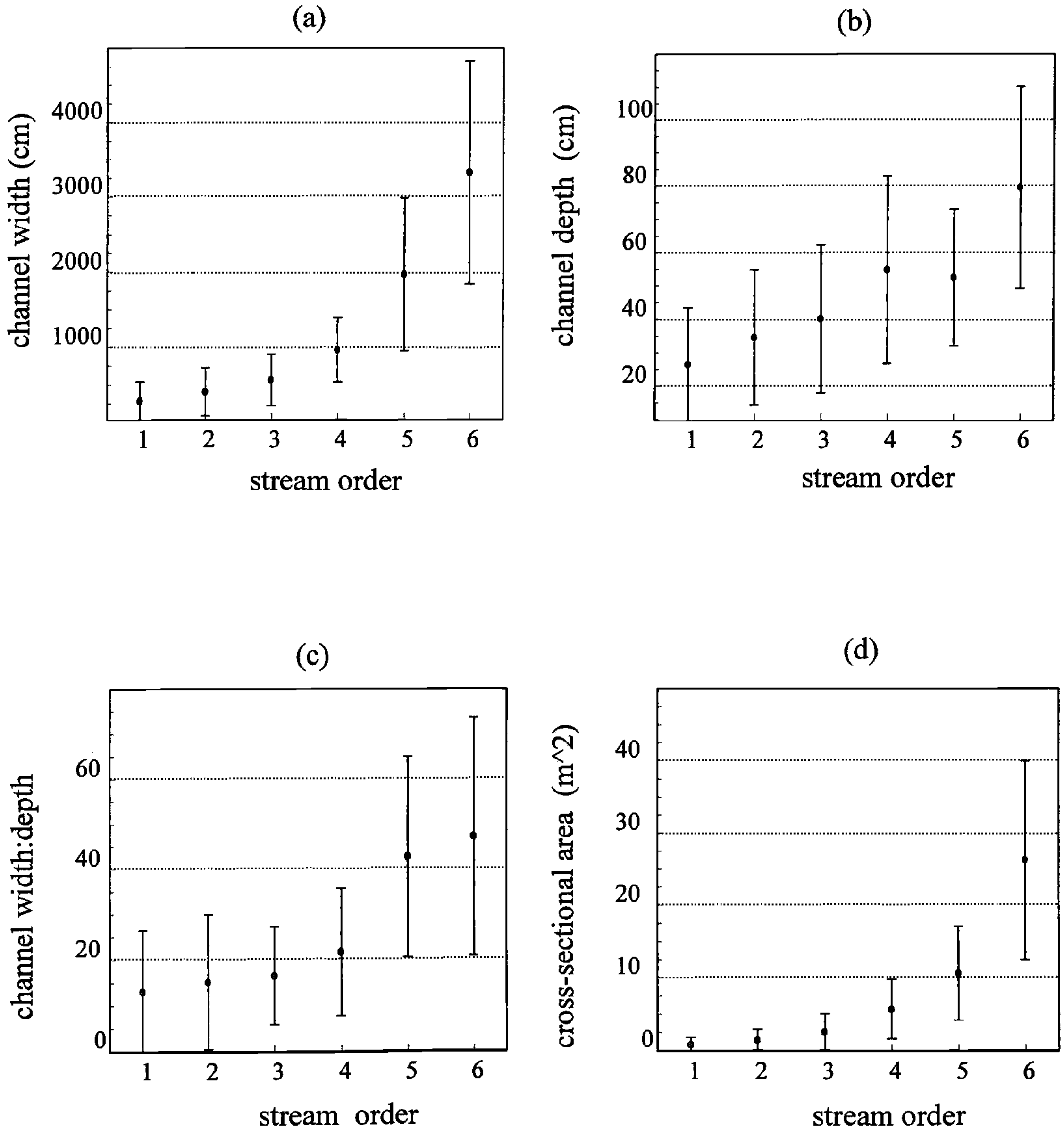


Figure 15: Category plots showing mean and standard deviation of channel variables sorted by stream order

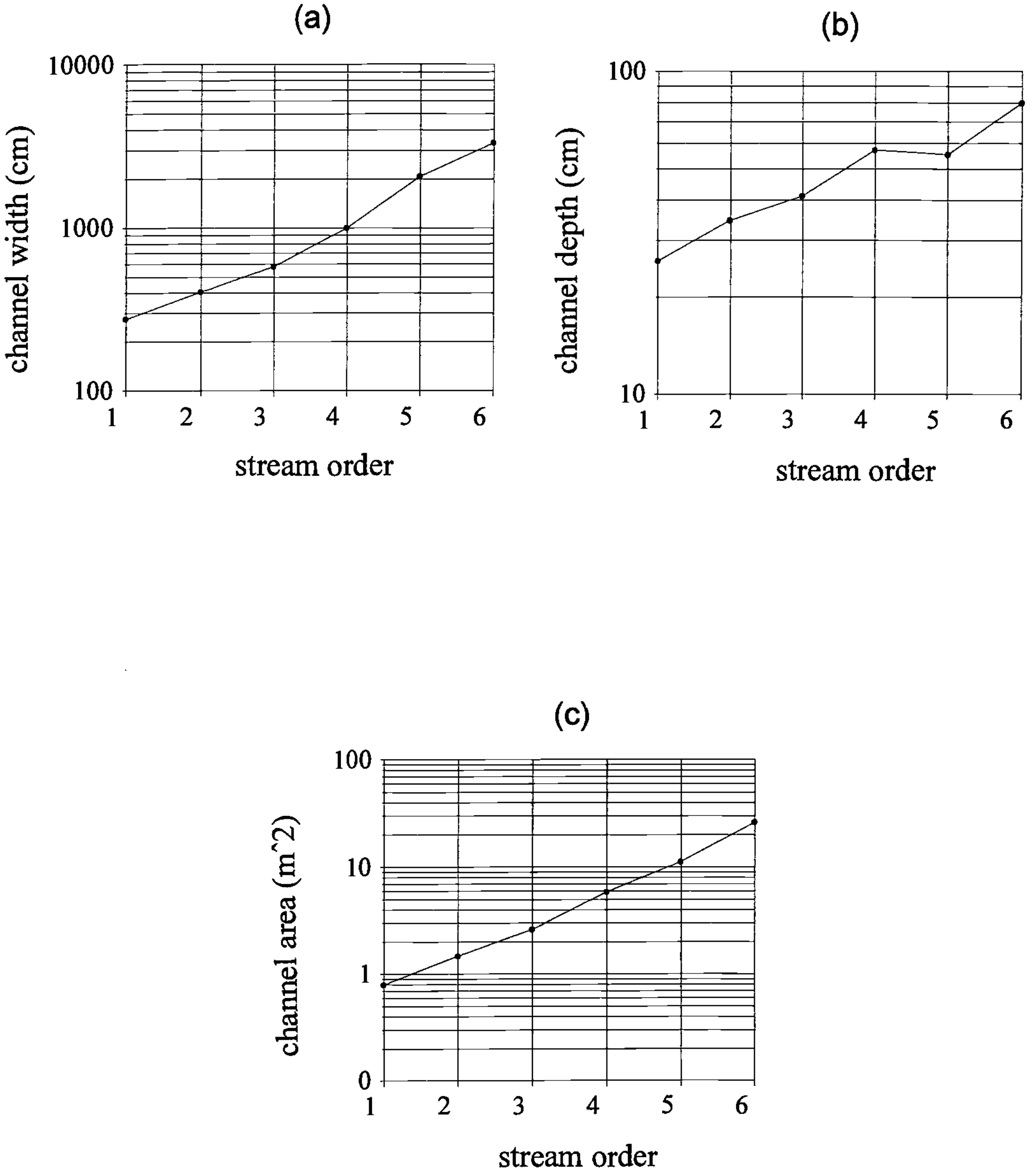


Figure 16: Semi-log plots of channel variables per stream order

THRESHOLD EFFECT

Although the variables of channel width, depth, and area show a general semi-log relationship to stream order (figure 16), a review of the categorical plots of figure 15 reveals a break in the trend for most variables between the lower and upper stream orders. For instance, the average value of width shows a general geometric increase with stream order from the first through fourth order channels, but changes significantly for the fifth order channels (figure 15, a). A similar break in slope occurs for the width:depth ratio (figure 15, c), and between the fifth and sixth order channels for channel area (figure 15, d). Channel depth shows the opposite change in trend, with a decrease in average value occurring between the fourth and fifth order channels (figure 15, b). This change in slope may be indicative of a threshold effect altering the channel shape properties. When two channels flow together they contribute stream power to the downstream channel. Stream power, the ability of a stream to do work, is dependent on flow volume and is related directly to erosivity and sediment yield (Lane et al., 1994). The increase in power is compounded when channels of a similar order flow together, since they will generally have similar flow characteristics and both contribute significantly to increasing stream power. This increase in stream power apparently affects the channel width most significantly between stream orders four and five, which may represent a threshold of critical power for bank erosion. Where the stream power increases to a certain level, the resistance to lateral erosion is overcome, resulting in the widening of the channels.

Countering the upward shift in average width between orders four and five, average channel depth actually decreases between those two orders. While bank erosion is occurring in response to changing hydraulic parameters, bed material is not removed at the same rate, and is actually deposited through the channels. A characteristic of higher-order channels is the increased presence of channel islands and bars. Islands and bars rarely occur in smaller channels, but are frequent in fifth and sixth order channels. The presence of these in-channel features may reduce the average channel depth, while the width is increased by the higher erosive power. With the increase in channel width offset by the concurrent decrease in average depth, the average channel area maintains a remarkably strong geometric increase relative to the lower-order channels (figure 16).

A notable increase in the average value of cross-sectional area occurs between orders five and six. Apparently, the overall increase in stream power overcomes the resistance to incisement that is characteristic of the fifth order channels because the average depth of sixth order streams is much greater than that of the fifth order streams. Average channel width also increases, leading to a rather large increase in average width between orders five and six. Additional investigation into the relationship between flow volume and stream order is recommended.

SIGNIFICANCE TESTING

Descriptive Statistics

The results of this study illustrate the natural variability in channel morphology. Table 12 details the standard deviation, variance, and coefficient of variation for channel variables of different stream orders. Note the high coefficient of variation that exists for these variables. In some cases the coefficient exceeds one. In general, width displays a greater range than depth, although the reverse is true for third-order channels. Stratifying the data by order significantly reduced the variance for all the channel shape parameters, although width was most affected. This reduction in variance is a product of the relationship between channel size and stream order; by focusing on a subset of the data, channels more alike in shape are grouped together, lessening the spread in the data.

Channel area, the product of width and average depth, shares statistical properties and similarities with its parent variables. Displaying a wide spread in the data, channel area has a high variance, and a coefficient of variation of 1.76 (table 12, a). Stratification of the data on the basis of stream order shrinks the spread of the data, and the coefficient of variation lessens with each increase in stream order. This trend is partly a reflection of the actual range of channel areas on Walnut Gulch, but it is also due to the relatively small sample sizes that exist for the higher orders. With small sample populations, the inherent variation of measured variables may not be adequately represented (Milton, 1993).

Table 12: Descriptive statistics for channel variables, stratified by order

(a): all channels

	Width (cm)	Depth (cm)	Width:depth	Area (m^2)
N of cases	222	222	222	222
Minimum	94.500	8.008	2.135	0.115
Maximum	6141.500	142.195	98.716	47.155
Mean	777.633	40.061	20.014	4.244
Variance	927601.157	647.146	344.232	55.797
St'd Dev.	963.121	25.439	18.554	7.470
C.V.	1.239	0.635	0.927	1.760
Median	378.167	33.318	13.776	1.306

(b): first-order channels

	Width (cm)	Depth (cm)	Width:depth	Area (m^2)
N of cases	58	58	58	58
Minimum	94.500	8.008	3.095	0.115
Maximum	1513.500	92.917	98.716	4.713
Mean	279.652	26.324	13.096	0.802
Variance	64096.134	285.144	176.382	0.931
St'd Dev.	253.172	13.281	0.965	253.172
C.V.	0.905	0.641	1.014	1.203
Median	221.083	20.489	10.204	0.465

(c): second-order channels

	Width (cm)	Depth (cm)	Width:depth	Area (m^2)
N of cases	65	65	65	65
Minimum	107.333	10.619	2.135	0.115
Maximum	1615.333	114.387	91.174	7.036
Mean	404.318	34.566	15.200	1.465
Variance	101958.813	411.489	218.860	1.935
St'd Dev.	319.310	20.285	14.794	1.391
C.V.	0.790	0.587	0.973	0.949
Median	301.000	29.892	10.926	0.959

Table 12, *cont'd*: Descriptive statistics of channel variables, stratified by order

(d): third-order channels

	Width (cm)	Depth (cm)	Width:depth	Area (m^2)
N of cases	40	40	40	40
Minimum	133.000	11.498	4.864	0.203
Maximum	1582.000	107.919	49.100	11.476
Mean	563.033	40.101	16.530	2.543
Variance	118727.241	491.475	115.225	6.112
St'd Dev.	344.568	22.169	10.734	2.472
C.V.	0.612	0.553	0.649	0.972
Median	475.500	32.528	13.350	1.753

(e): fourth-order channels

	Width (cm)	Depth (cm)	Width:depth	Area (m^2)
N of cases	26	26	26	26
Minimum	294.333	17.585	6.282	0.518
Maximum	2440.000	119.680	70.947	16.718
Mean	960.385	54.936	21.708	5.633
Variance	184674.022	799.024	195.787	16.638
St'd Dev.	429.737	28.267	13.992	4.079
C.V.	0.447	0.515	0.645	0.724
Median	991.333	49.885	17.558	3.799

(f): fifth-order channels

	Width (cm)	Depth (cm)	Width:depth	Area (m^2)
N of cases	20	20	20	20
Minimum	829.000	25.894	11.654	2.992
Maximum	5127.000	106.818	86.807	30.285
Mean	1967.642	52.575	42.760	10.582
Variance	1032457.463	421.190	493.517	41.936
St'd Dev.	1016.099	20.523	22.215	6.476
C.V.	0.516	0.390	0.520	0.612
Median	1768.333	49.493	36.912	8.976

Table 12, *cont'd*: Descriptive statistics of channel variables, stratified by order

(g): sixth-order channels

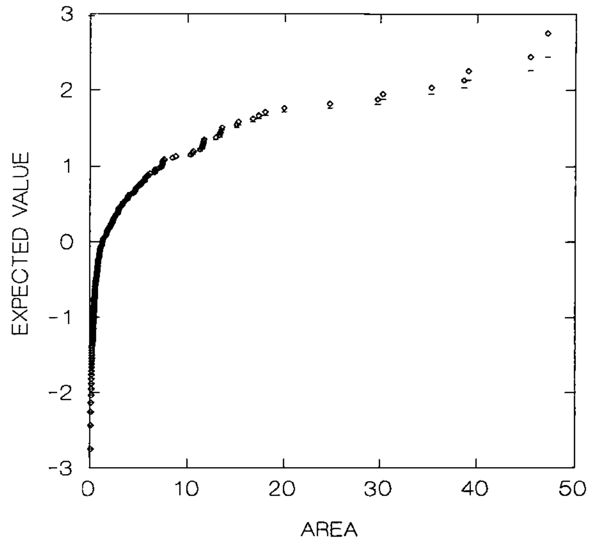
	Width (cm)	Depth (cm)	Width:depth	Area (m^2)
N of cases	13	13	13	13
Minimum	1441.667	48.197	18.700	8.796
Maximum	6141.500	142.195	97.553	47.155
Mean	3329.987	79.694	47.293	26.206
Variance	2232817.275	922.684	698.773	189.535
St'd Dev.	1494.261	30.376	26.434	13.767
C.V.	0.449	0.381	0.559	0.525
Median	3197.333	69.175	36.127	24.760

Testing for Normality

Many statistical analyses are predicated on the sample distribution being normal. Therefore, the dependent variables in question were tested for normality using the Kolmogorov-Smirnov (K-S) test. Graphical examination of the variables' distributions supported the results of the K-S tests, which indicated that the variables of width, depth, width:depth ratio, and channel area were log-normally, distributed. Figure 17, a normal probability plot, shows the sample distribution of channel cross-sectional area before and after log transformation Probability plots are a tool for investigating the distribution form of data by plotting the points against a theoretical distribution (Devore, 1987). If the data is from a normal distribution, the plotted values will form a relatively straight line diagonally across the graphical display. Note that the raw data in figure 17 is not distributed in such a fashion. After log transformation, the data more closely approximates straight lines on the graphs. Similar results were found for the channel properties of width, depth, and the width:depth ratio.

Analysis of Variance

It was found using GIS analysis that channels in Walnut Gulch accumulated to the point where the highest-ranked was of the sixth order. Upon investigation of the category plots, it was hypothesized that stream order would play a dominant role in the derivation of channel shape parameters, and could therefore be used as a treatment. In order to impose stream order as a treatment, it was first necessary to determine if a significant



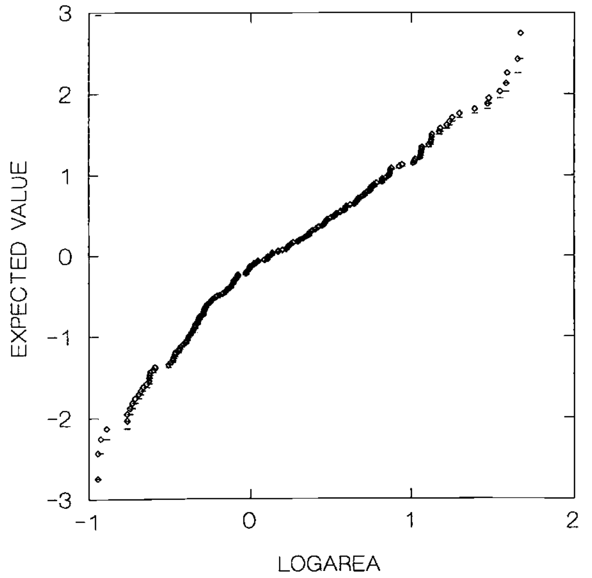


Figure 17: Normal probability plots of raw and transformed channel area data

difference existed between orders for the dependent variables under investigation. The sample design was set up such that independent random samples of sizes $n_1, n_2, \ldots, n_k$ were selected from each of the six orders. This allowed the use of an analysis of variance (ANOVA) to test for significant differences between population means. The hypothesis used in this ANOVA is:

$$H_o : \mu_1 = \mu_2 = \cdots = \mu_k$$

$$H_1 : \mu_i \neq \mu_j$$

where,

μ_i = the mean response for the ith population,
H_o = null hypothesis, that no difference exists between population means, and
H_1 = alternate hypothesis, that at least one mean differs from the others.

Results from the ANOVAs are presented in tables 13-16. A low "p" value indicates that the null hypothesis is invalid, validating the alternate hypothesis. As is illustrated in the ANOVA tables, the alternate hypothesis is correct for the dependent variables under investigation. Therefore, it was concluded that a significant level of difference existed between at least two of the sub-populations for each of the dependent variables

Tukey Test

Having found significant differences between the population means, it was necessary to establish whether significant differences existed between all sub-categories. For this, a Tukey t-test was used. A Tukey test executes multiple comparisons using an ANOVA to determine which of the means are different from one another. This procedure uses the studentized distribution and can be run on populations with similar or dissimilar

Table 13: ANOVA for measurements of width, treatment of stream order

source	sum-of-squares	degrees of freedom	mean-square	f-ratio	P
order	.139 e+09	5	.278 e+08	91.315	0.0
error	.658 e+08	216	.305 e+06		

Table 14: ANOVA for measurements of depth, treatment of stream order

source	sum-of-squares	degrees of freedom	mean-square	f-ratio	P
order	42212.9	5	8442.6	18.09	0.0
error	100806.4	216	466.7		

Table 15: ANOVA for measurements of width:depth ratio, treatment of stream order

source	sum-of-squares	degrees of freedom	mean-square	f-ratio	P
order	24864.0	5	4972.8	20.97	0.0
error	51211.3	216	237.1		

Table 16: ANOVA for measurements of channel area, treatment of stream order

source	sum-of-squares	degrees of freedom	mean-square	f-ratio	P
order	8428.7	5	1685.7	93.3	0.0
error	3902.4	216	18.1		

variances (Devore, 1987). Significant differences were found between all pairs of population means for each stream order. Probabilities that the means of any two populations were equal for any two stream orders did not exceed three percent.

Empirical Relations

A principal goal of this research was to establish a methodology for predicting channel shape from watershed characteristics. Building a deterministic model through regression analysis fulfilled this goal, with the expectation that research to quantify the stochastic properties of the data would further refine the results. For the purposes of this evaluation, the relationships describing the channel cross-sectional area were of primary interest. Channel 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 predict channel depth and fully articulate channel geometry throughout Walnut Gulch.

CHANNEL WIDTH AND DEPTH

Channel width proved to be more easily measured with precision than did channel depth. Although determining the proper height to which floodwaters would rise proved to be a difficult enterprise, 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, natural variability of the stream channels tends to be exhibited more in channel depth, leading to the conclusion by Hedman and Osterkamp (1982) that channel geometry relations should focus on channel width when attempting to relate channel form to discharge.

Statistical Properties

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. However, when regression analysis was performed on the data, an interesting property of the channel shape and its response to watershed parameters emerged. Without exception, channel width proved to have a higher coefficient of determination than depth. In fact, depth proved to be resistant to any deterministic model based on the variables used in this study. Table 17 shows regression results relating channel depth to several watershed parameters. There does appear to be a log-log relationship between channel depth and watershed area, albeit a relationship that cannot adequately be expressed mathematically (figure 18). There is a considerable amount of scatter within the diagram, resulting in a

Table 17: Results of linear regression analyses between channel depth and watershed parameters.

Dependent	Parameter	r^2	coefficient	constant	SE_{yx}
$\log D_c$	$\log A_w$	0.33	0.15	0.70	0.22
$\log D_c$	$\log L_m$	0.33	0.11	0.75	0.22
$\log D_c$	$\log h$	0.18	0.24	1.11	0.24
$\log D_c$	$\log h_o$	0.22	0.32	1.08	0.24
$\log D_c$	$\log S$	0.21	0.43	0.98	0.24
$\log D_c$	$\log A_p$	0.34	0.34	0.87	0.22
$\log D_c$	$\log S_b$	0.12	-0.41	1.26	0.25
$\log D_c$	$\log D_l$	0.32	0.16	1.02	0.22
$\log D_c$	$\log R_r$	0.20	-0.43	0.98	0.24
$\log D_c$	$\log A_w$	0.33	0.15	0.70	0.22

where,

D_c = depth of stream channel (cm),
A_w = contributing area (km^2),
L_m = maximum flow length (m),
h = maximum change in elevation (m),
h_o = mean - minimum elevation (m),
S = basin slope,
A_p = area:perimeter ratio (m),
S_b = basin shape,
D_l = cumulative channel length (m), and
R_r = relief ratio.

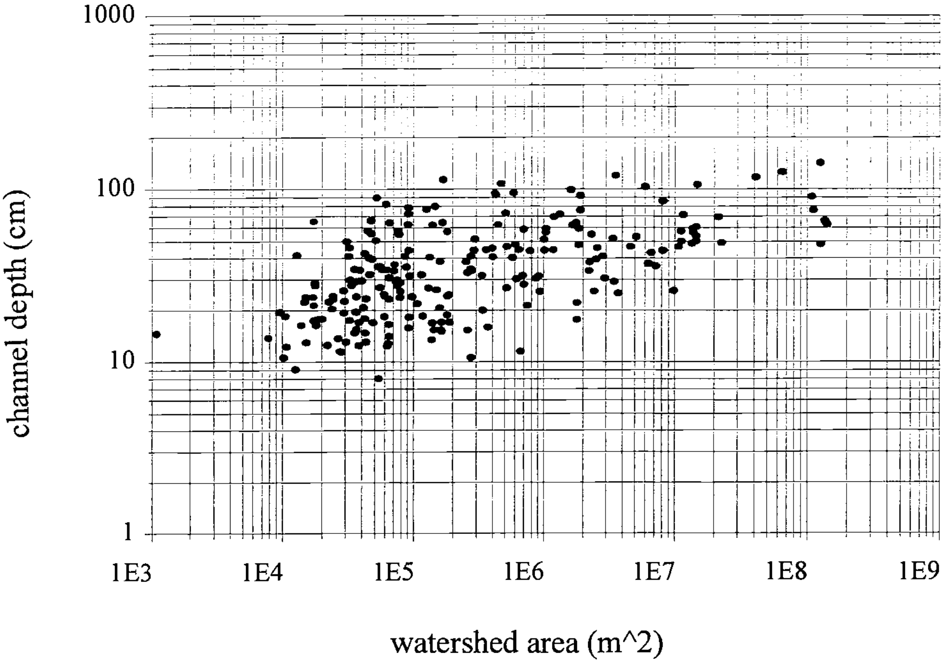


Figure 18: Channel depth as a function of watershed area

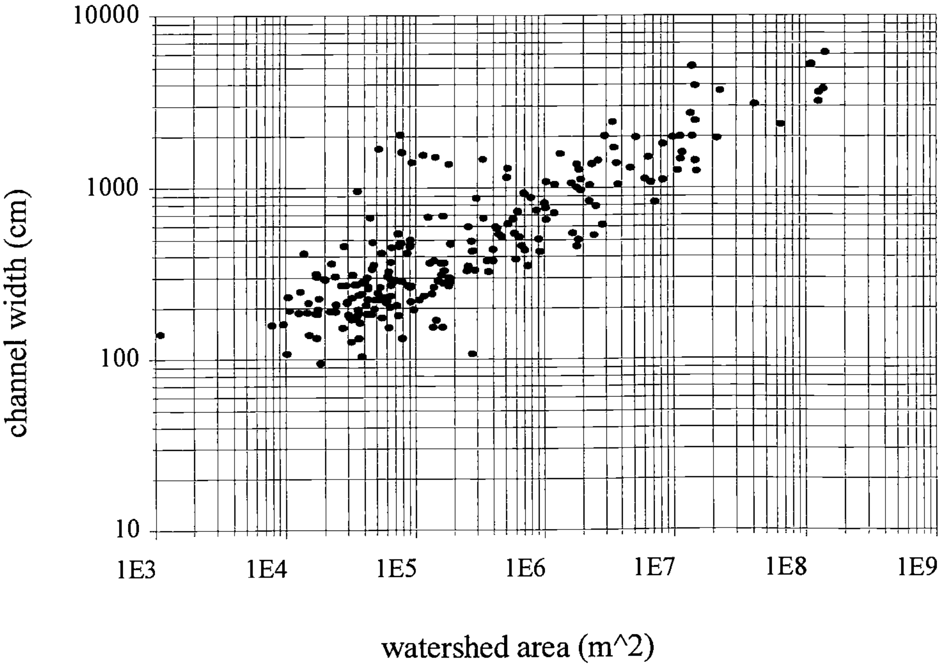


Figure 19: Channel width as a function of watershed area

rather low coefficient of determination for the regression equation governing this relationship (r^2=0.33).

Conversely, regression analysis between channel width and watershed factors proved to illustrate the strong relationship that exists between those factors governing runoff and erosivity and channel width (table 18). Watershed scale descriptors also related strongly to channel width. Watershed area proved to have a log-log relationship with width (figure 19; $r^2 = 0.72$). There is a greater amount of scatter around the 1:1 line for the smaller watersheds. This is partly a function of the sampling scheme used in this project: a greater number of small watersheds were sampled, which allowed for a greater amount of the natural variability to be accounted for in the data. The log of the area:perimeter ratio was directly related to the log of channel width, with a coefficient of determination of 0.71 (figure 20).

A strong relationship exists between width and the maximum flow length within the contributing watershed (figure 21; $r^2 = 0.78$). Maximum flow length represents the relative amount of runoff that can contribute to the erosive action at a particular point. A strong relationship also exist between width and the gradient variable of maximum elevation change (figure 22; $r^2 = 0.68$). The maximum elevation change within a watershed represents potential erosive power for water flowing through the watershed. The log of cumulative channel lengths exhibited a relationship to the log of channel width, and little or no relation to channel depth (figure 23). With a coefficient of determination of 0.64, the relationship to log of width is fairly robust.

Table 18: Results of linear regression analyses between channel width and watershed parameters.

Dependent	Parameter	r^2	coefficient	constant	SE_{yx}
$\log W_c$	$\log A_w$	0.72	0.34	0.86	0.211
W_c	L_m	0.78	0.14	339.27	452.88
W_c	h	0.68	5.44	188.58	544.19
W_c	h_o	0.69	22.29	-12.81	539.27
W_c	S	0.27	36.96	-53.51	822.68
$\log W_c$	$\log A_p$	0.71	0.76	1.24	0.22
$\log W_c$	$\log S_b$	0.34	-1.00	2.04	0.33
$\log W_c$	$\log D_l$	0.64	0.34	1.61	0.24
$\log W_c$	$\log R_r$	0.26	-0.74	1.74	0.34

where,

W_c = width of stream channel (cm),
A_w = contributing area (km ^{2}),
L_m = maximum flow length (m),
h = maximum change in elevation (m),
h_o = mean - minimum elevation (m),
S = basin slope,
A_p = area:perimeter ratio (m),
S_b = basin shape,
D_l = cumulative channel length (m), and
R_r = relief ratio.

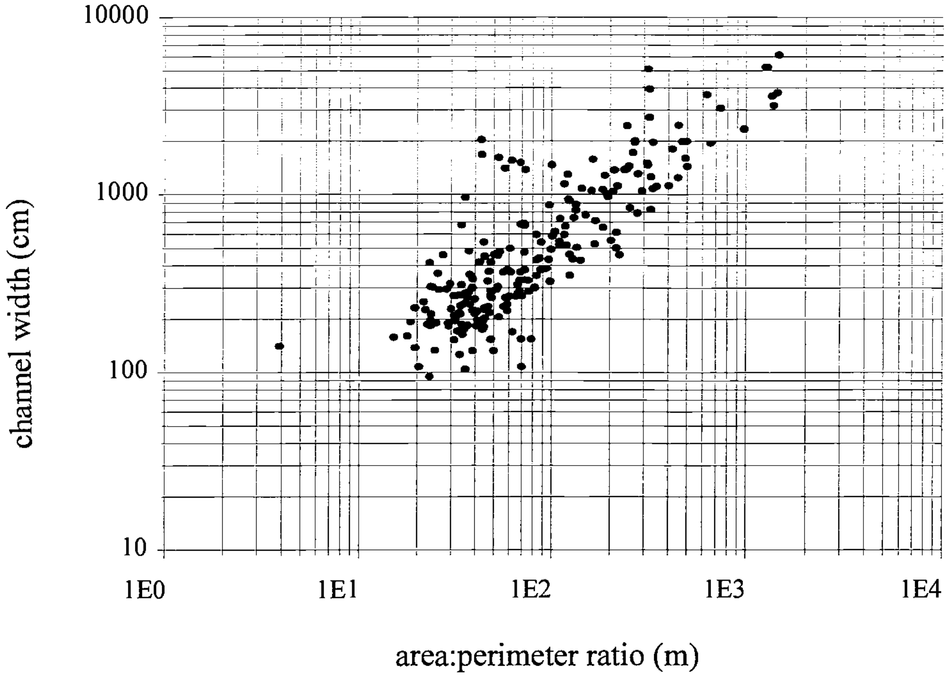


Figure 20: Channel width as a function of the area:perimeter ratio

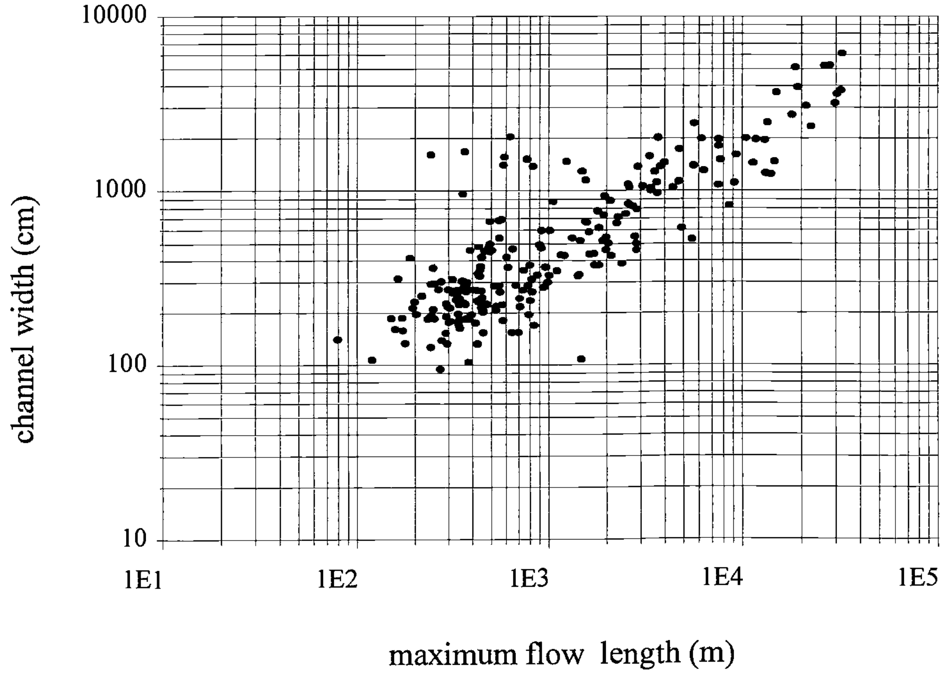


Figure 21: Channel width as a function of maximum flow length

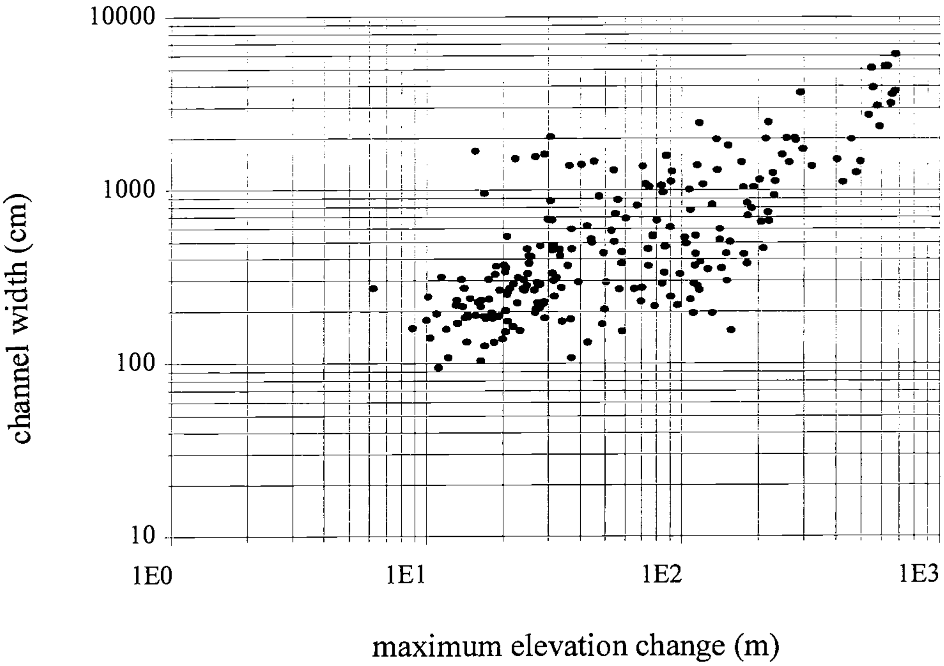


Figure 22: Channel width as a function of maximum elevation change

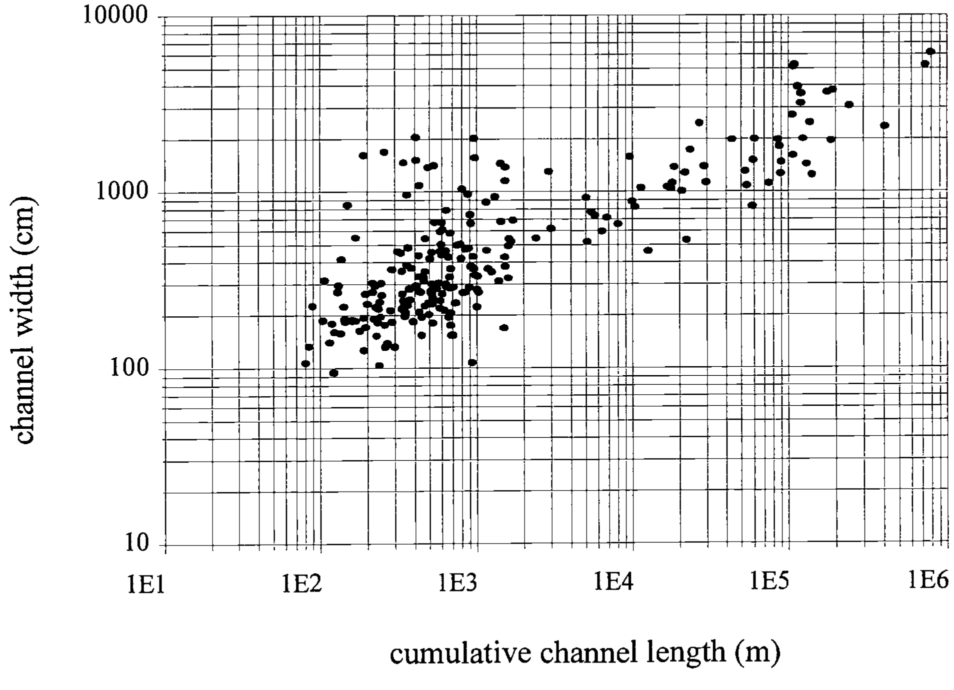


Figure 23: Channel width as a function of cumulative channel length

Explanation

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. Schumm (1960) illustrated the relationship between channel shape and sediment, revealing that in clay-rich soils channels tend to become more incised in response to increasing erosivity. The reverse is true for channels in clay-poor soils which generally respond by increasing their width.

On Walnut Gulch, where streams adjust to energy changes by widening, there is a larger spread in the measured values of channel width. Channel depth also has a large spread in its data, but to a lesser degree than width. As a result, channel width has a larger coefficient of variation than depth but relates more closely to watershed variables that influence runoff and channel energy.

WIDTH:DEPTH RATIO

Contrary to earlier findings, this study shows that the width:depth ratio does not remain approximately the same for all stream reaches within the watershed. Other researchers have hypothesized that within a relatively homogeneous area the width:depth ratio should be fixed for all channels (Schumm, 1960). Schumm (1960) developed a relationship to describe the width:depth ratio as a function of the percent of silt and clay within the channel bed and bank:

$$W/D = 255I^{-1.08} \tag{20}$$

where:

I = percent of particles within the channel bed and banks less than 0.074 mm in diameter.

Although this relationship was derived from data collected in the midwestern United States and Australia, it demonstrates a fundamental relationship between channel shape and soil. As the amount of small binding particles increases within the soil matrix, its resistance to erosive action increases in the channel banks, and greater incisement is the result. In sandy alluvium such as exists at Walnut Gulch, it is predicted from such a relationship that the channels would have a relatively high width:depth ratio.

Vegetative material also serves to limit the erosive work runoff can achieve on channel shape. Since vegetation exists mostly on the banks and overbank area, it primarily restricts the widening of a channel. Walnut Gulch, located in a semi-arid climate, has limited vegetative cover, which further influences the tendency towards wider channels.

Statistical Properties

The width:depth ratio is controlled primarily by measurements of flow energy such as flow length and elevation change within the subwatersheds. For example, the maximum flow length is weakly related to the width:depth ratio ($r^2 = 0.34$) With an r^2 of 0.37, the maximum change in elevation is also weakly correlated with the width:depth ratio ($r^2 = 0.37$; table 19; figure 24). The width:depth ratio displayed a log-log relationship to watershed area ($r^2 = 0.33$), although the correlation between the two variables was still weak (figure 25).

Explanation

Simply put, the width:depth ratio does not relate strongly to any particular watershed parameter. This could be due to the large variance in width and depth measurements. Channels at Walnut Gulch seem to be adjusting their shape to accommodate increasing flow in a manner not definable by the width:depth ratio. As a predictive tool for channel shape and the relationship of depth to width, this variable is unreliable. More focus should be placed on channel cross-sectional area in this regard.

Basin shape describes the relationship between the watershed area and the length of the basin (equation 17). A large value indicates a relatively round watershed, while a smaller value would describe an elongated watershed. Watershed shape may profoundly affect the timing and amount of runoff through a channel link, affecting the channel shape in the process. A round-shaped watershed will concentrate water more quickly during a rain event than an elongated watershed, resulting in typically higher peak flows (Brooks et al., 1991). Channel shape on semi-arid watersheds is determined primarily by

Table 19: Results of linear regression analyses between channel width:depth ratio and watershed parameters.

Dependent	Parameter	r^2	coefficient	constant	SE_{yx}
$\log WD_c$	$\log A_w$	0.33	0.19	0.18	0.26
WD_c	L_m	0.34	0.002	14.41	15.07
WD_c	h	0.37	0.08	11.63	14.73
WD_c	h_o	0.35	0.31	9.11	14.96
$\log WD_c$	S	0.10	0.01	1.00	0.31
$\log WD_c$	$\log A_p$	0.32	0.41	0.39	0.27
$\log WD_c$	$\log S_b$	0.18	-0.59	0.79	0.29
$\log WD_c$	$\log D_l$	0.28	0.18	0.60	0.27
$\log WD_c$	$\log R_r$	0.33	-1.26	1.25	0.317

where,

WD_c = width:depth ratio of stream channel,
A_w = contributing area (km^2),
L_m = maximum flow length (m),
h = maximum change in elevation (m),
h_o = mean - minimum elevation (m),
S = basin slope,
A_p = area:perimeter ratio (m),
S_b = basin shape,
D_l = cumulative channel length (m), and
R_r = relief ratio.

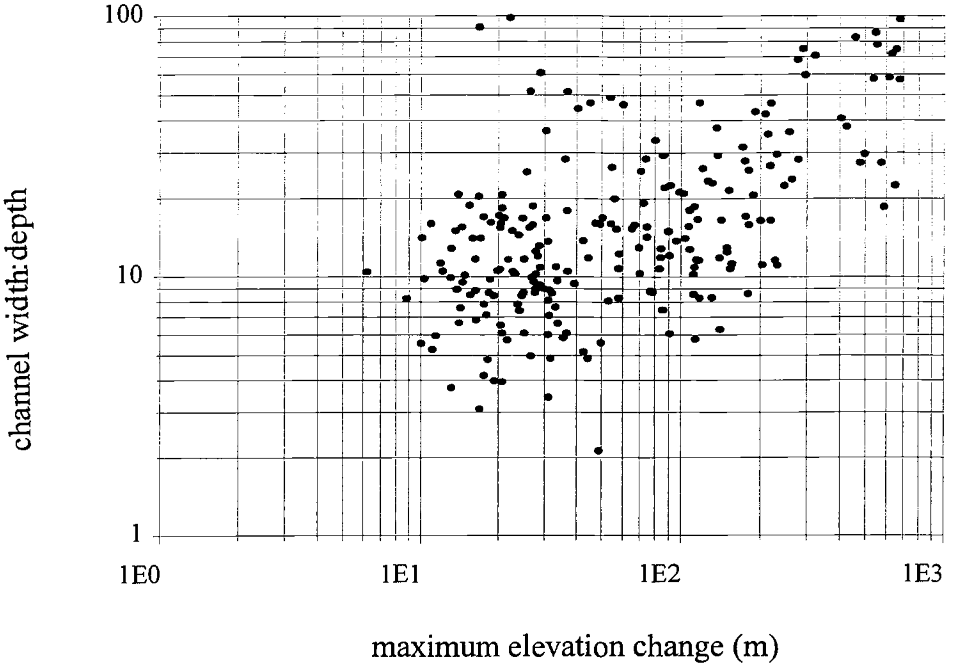


Figure 24: Channel width:depth ratio as a function of maximum elevation change

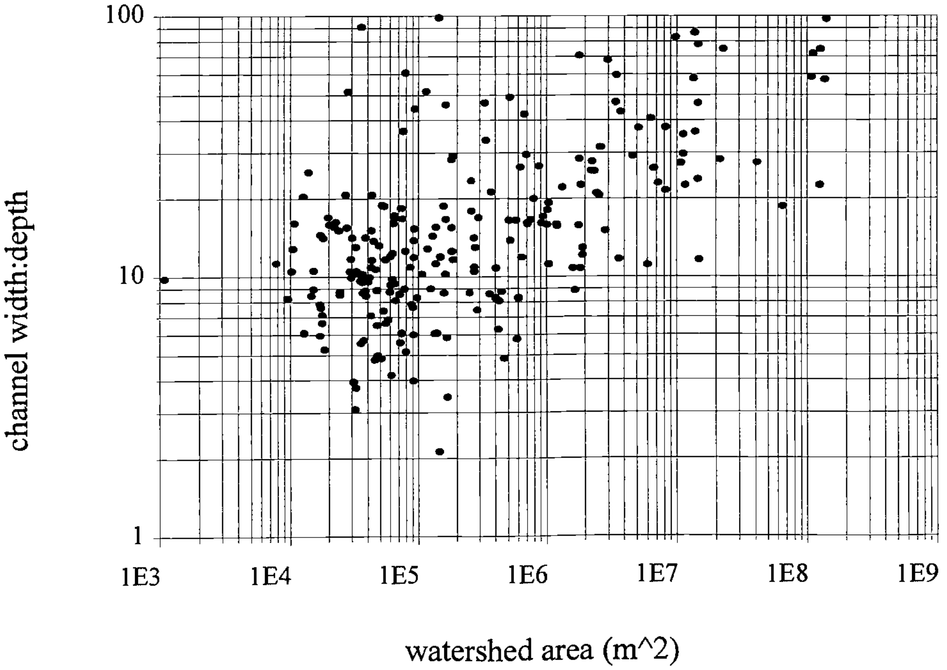


Figure 25: Channel width:depth ratio as a function of watershed area

short-term flood events, the volume of which is dependent partially on watershed shape. On Walnut Gulch, the round-shapes watersheds create wide, shallow channels, while the more elongated watersheds contribute to narrower, deeper channels.

CROSS-SECTIONAL AREA

Stream channels, responding to the runoff they receive from uplands, constantly adjust their shape to achieve equilibrium with the volume of flow flowing through them. Changes in channel morphology may result in either degradation or aggradation, but the overall effect is an alteration in the channel cross-sectional area. As such, the measurement of channel area is an effective method for illustrating the manner in which channels are responding to watershed parameters. ANOVA and t-testing revealed that distinct populations existed between each of the different stream orders.

Statistical Properties

A strong relationship exists between channel area and the maximum flow length within a watershed (figure 26; $r^2 = 0.79$). Table 20 shows the results of regression models involving channel area. Long flow lengths within a watershed generally relate to an increase in runoff. With higher flows, the channel will become enlarged, either through bed scour or bank erosion, to accommodate the larger flows. Following the same reasoning, it would also be expected that there would be a strong relationship

Table 20: Results of linear regression analyses between channel area and watershed parameters.

Dependent	Parameter	r^2	coefficient	constant	SE_{yx}
$\log A_c$	$\log A_w$	0.68	0.49	-2.44	0.34
A_c	L_m	0.79	0.001	1.83	3.46
A_c	h	0.64	0.04	-0.18	4.49
A_c	h_o	0.62	0.17	-1.59	4.59
$\log A_c$	$\log S$	0.30	1.17	-1.28	0.51
A_c	A_p	0.77	0.03	0.17	3.60
$\log A_c$	$\log S_b$	0.29	-1.41	-0.70	0.50
$\log A_c$	$\log D_l$	0.62	0.51	-1.38	0.40
$\log A_c$	$\log R_r$	0.29	-1.17	-1.28	0.51

where,

A_c = cross-sectional area of stream channel (cm^2),
A_w = contributing area (km^2),
L_m = maximum flow length (m),
h = maximum change in elevation (m),
h_o = mean - minimum elevation (m),
S = basin slope,
A_p = area:perimeter ratio (m),
S_b = basin shape,
D_l = cumulative channel length (m), and
R_r = relief ratio.

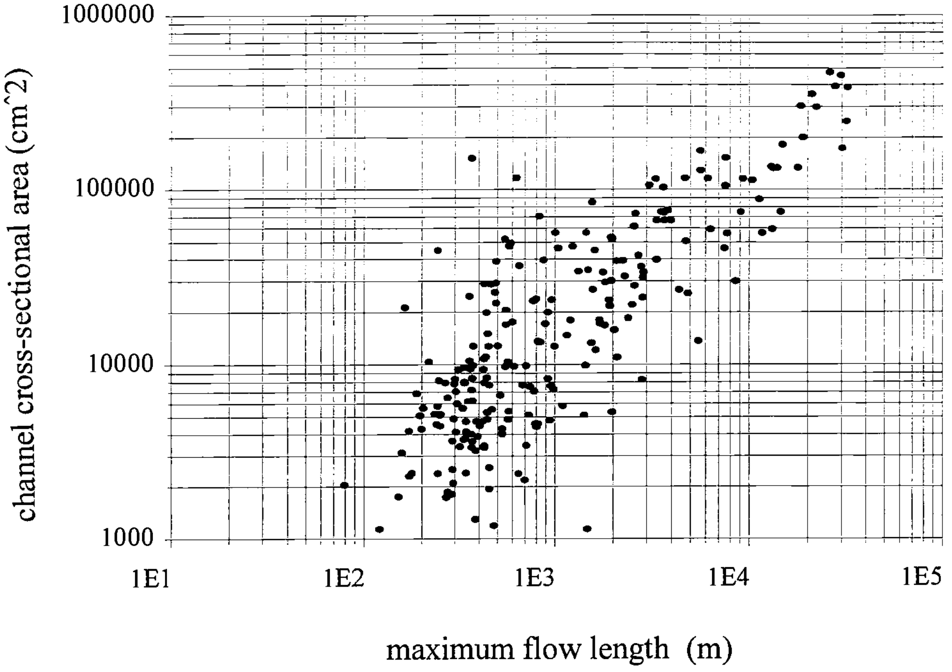


Figure 26: Channel cross-sectional area as a function of maximum flow length

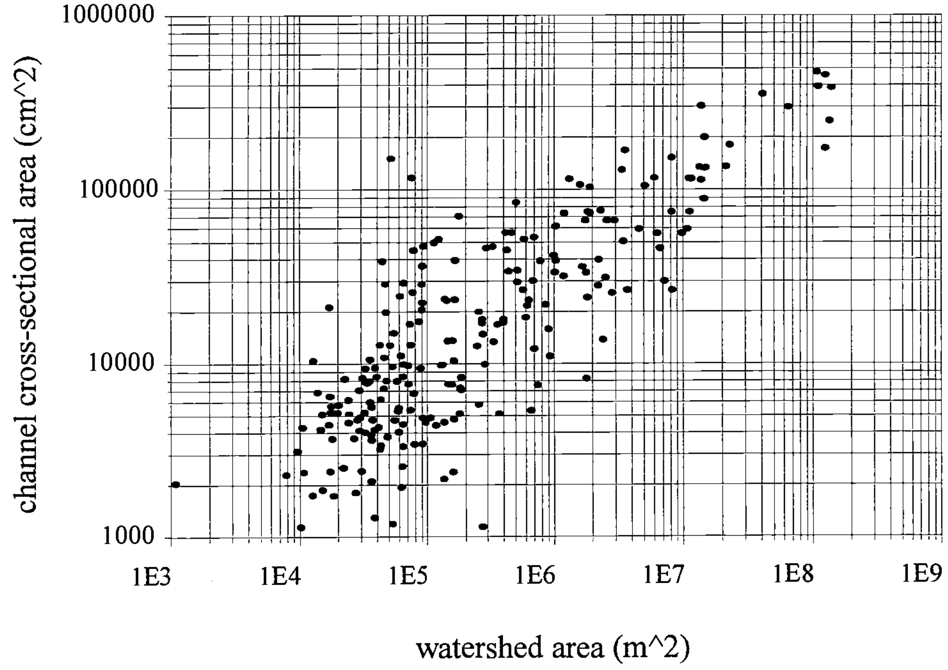


Figure 27: Channel cross-sectional area as a function of watershed area

between channel area and watershed area. Data collected in this research validate that assumption. A strong log-log relationship ($r^2 = 0.68$) exists between channel area and watershed area (figure 27).

Surprisingly, basin shape plays little role in the determination of channel area, although a relatively strong relationship ($r^2 = 0.77$) does exist between channel area and the area:perimeter ratio (figure 28). Measurements of energy, neither slope or the relief ratio correlated strongly with channel area. As shown in figure 29, the log of cumulative drainage density had a fair relationship to the log of cross-sectional area ($r^2 = 0.62$).

Multiple Regression Models

In order to more fully understand the factors contributing to channel morphology, multiple linear regression analysis was employed. An array of factors, including log-normalized data, was investigated in order to determine the relative importance of different variables. Stratification based on stream order was assumed, due to the discrete channel populations within each order group.

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. Depending on the subset of parameters investigated, it was possible to extract a

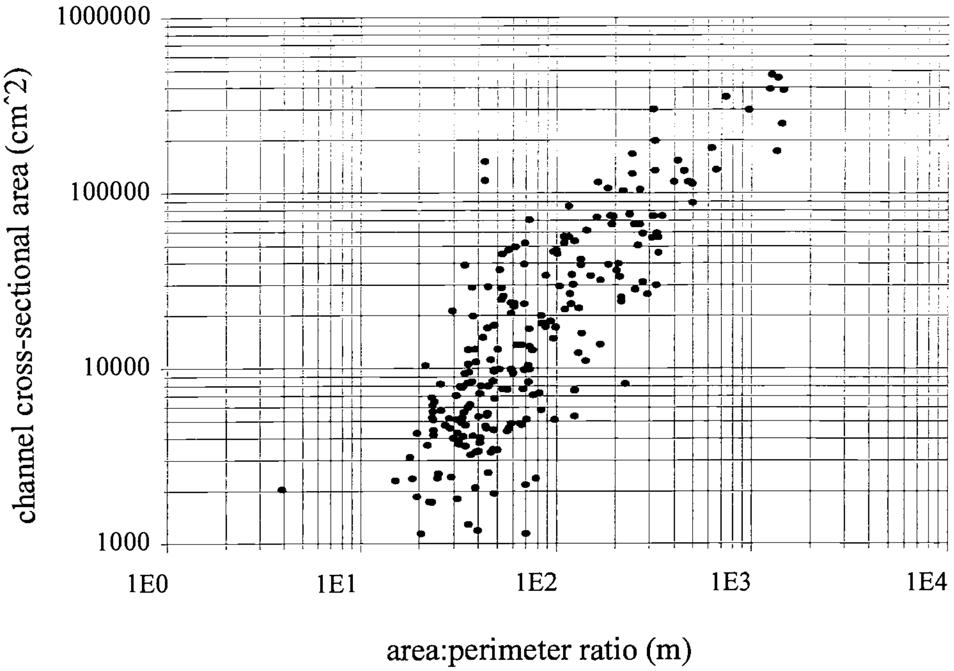


Figure 28: Channel cross-sectional area as a function of area:perimeter ratio

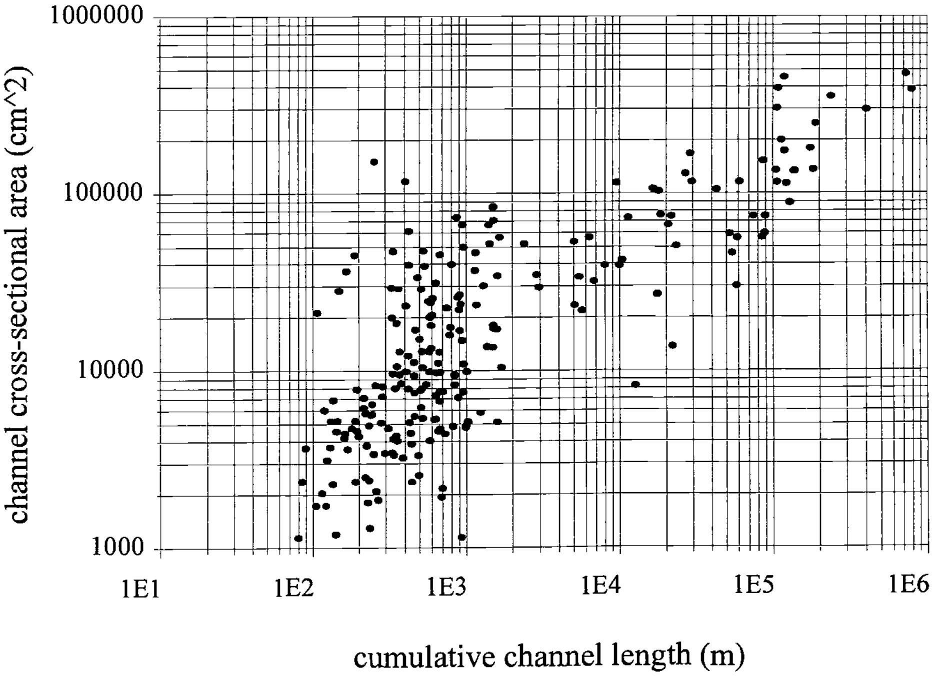


Figure 29: Channel cross-sectional area as a function of cumulative channel length

significant regression model with a number of different independent variables. To avoid collinearity, multiple pools of data were used during the regression 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.

In every case but one, when included in the data pool, watershed area was preferentially selected for inclusion in the mathematical model describing channel area. Table 21 details the results of eight principal regression models determined using stepwise backward multiple linear regression. Note that a constant was not used in the analysis, and the equations were driven through the origin. In only one case was a form of watershed area not selected for inclusion in the model; in that case the basin shape variable was included in the data pool. Figures 30-33 are graphical representations of the results of several of the multiple regression models.

Using multiple regression models necessarily increases the complexity of a deterministic model because of the addition of additional variables. This increases the burden on the researcher during the data gathering phase of a project. However, using tools such as were developed for this project, multiple watershed parameters can be extracted from a GIS with relative ease. It is expected that multiple regression models with significantly improve the model's ability to predict the dependent variable. When predicting channel cross-sectional area, multiple regression improved the relationship from an r^2 value of 0.79 to 0.85. Whether this improvement justifies the additional

Table 21: Results of multiple regression analysis to describe channel area

Case	Regression model	r^2	SE_{yx}
1	$0.686(S_o) + 0.065(A_w) + 0.909(L_m) - 0.006(h)$	0.849	3.36
2	$0.40(S_o) + 0.009(A_p) + 0.821(L_m) - 0.006(h)$	0.851	3.35
3	$0.72(S_o) + 0.095(A_w) + 0.001(L_m) - 0.007(h) - 0.001(D_l)$	0.851	3.34
4	$1.616(S_o) - 17.389(R_r) + 0.219(A_w)$	0.826	3.60
5	$0.496(S_o) + 0.024(A_p) - 10.062(R_r)$	0.833	3.52
6	$0.557(S_o) - 0.008(h) + 0.001(L_m)$	0.845	3.40
7	$0.616(S_o) + 0.001(L_m) + 0.001(S)$	0.849	3.42
8	$0.013(A_p) + 0.649(L_m)$	0.845	3.39

where,

S_o = stream order
A_w = contributing area (km^2),
L_m = maximum flow length (m),
h = maximum change in elevation (m),
A_p = area:perimeter ratio (m),
D_l = cumulative channel length (m),
R_r = relief ratio, and
S = basin slope.

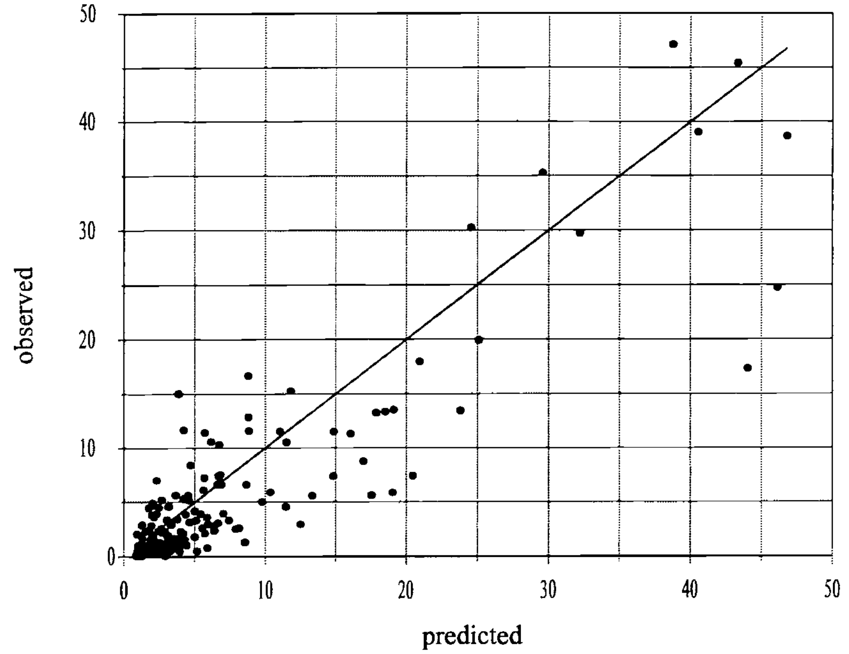


Figure 30: Results of multiple regression, case 1
cross-sectional area = 0.686(So) + 0.065(Aw) + 0.909(Lm) - 0.006(h)

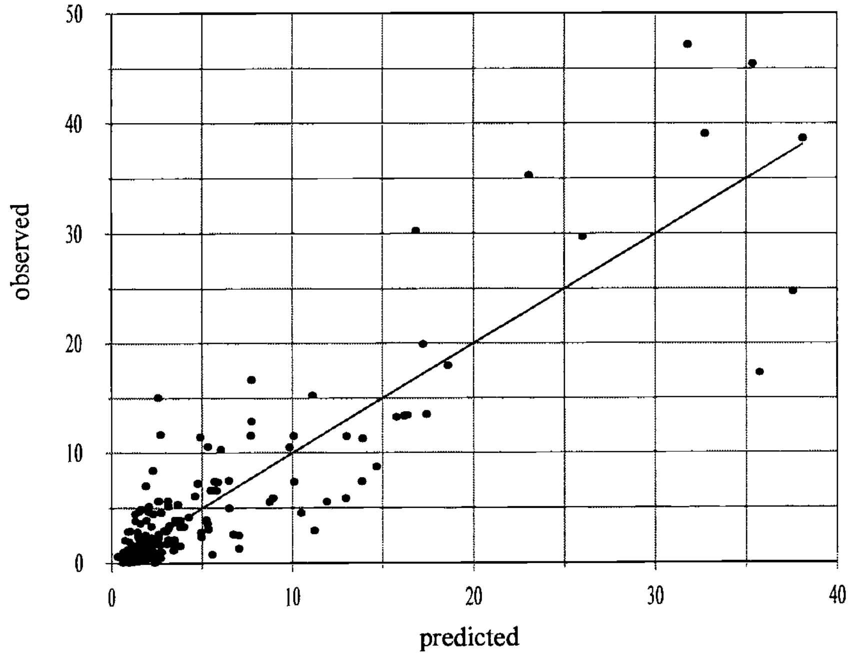


Figure 31: Results of multiple regression, case 2
cross-sectional area = 0.40(So) + 0.009(Ap) + 0.821(Lm) - 0.006(h)

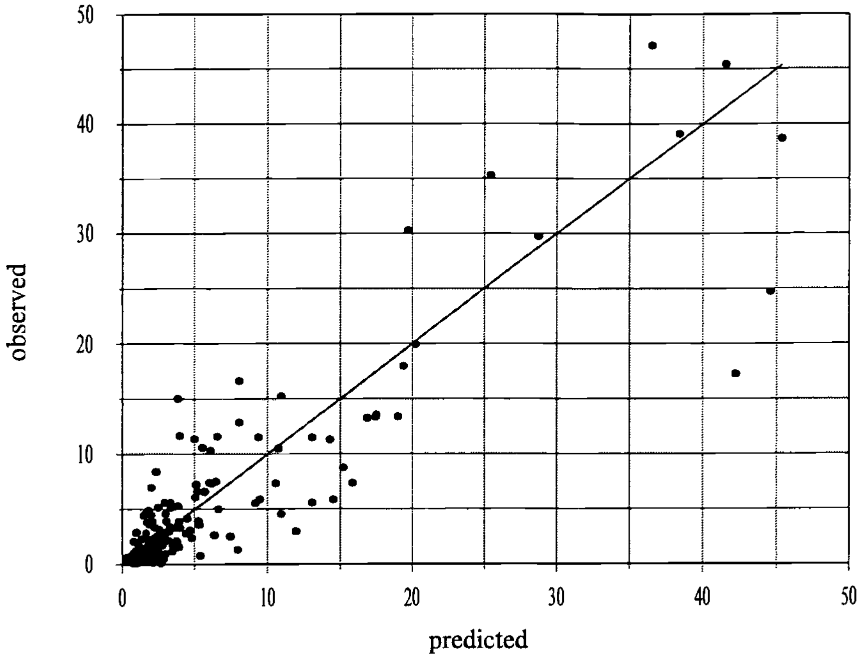


Figure 32: Results of multiple regression, case 2
cross-sectional area = 0.72(So) + 0.095(Aw) + 0.001(Lm) - 0.007(h) - 0.001(Dl)

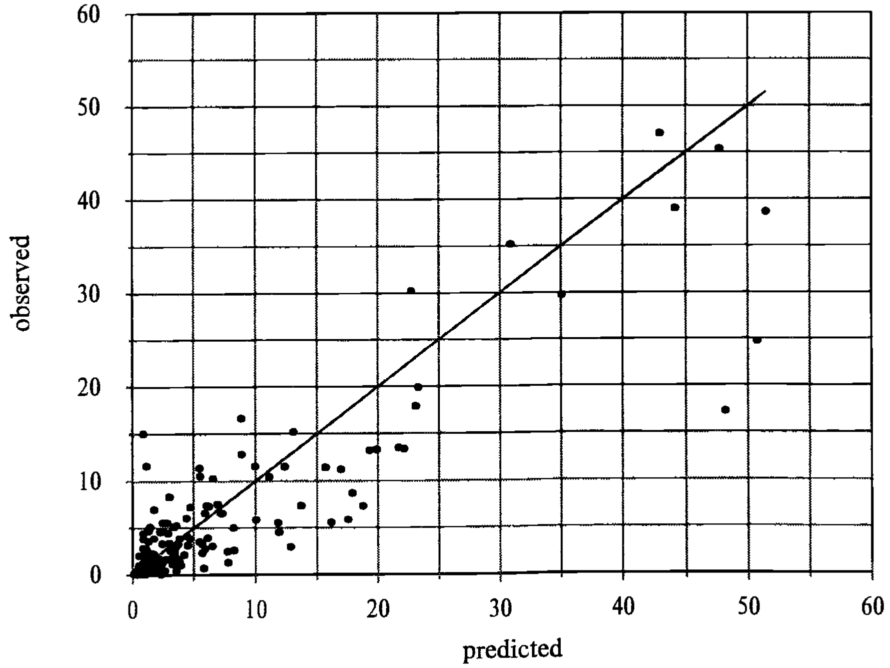


Figure 33: Results of multiple regression, case 8
cross-sectional area = 0.013(Ap) + 0.001(Lm)

research is an open question. To resolve this question, sensitivity analysis must be administered for the model on which the results of the regression will be applied.

Explanation

An unfortunate consequence of using multiple regression models is the implicit assumption of multicollinearity between independent variables. There is a distinction to be made between perfect collinearity and multicollinearity (Berry and Feldman, 1985). In the case of perfect collinearity, two of the independent variables are correlated perfectly to one another (correlation of determination of 1.00), and should never be used in the same regression analysis. However, multicollinearity is acceptable according to Berry and Feldman (1985), who pointed out that even a high degree of multicollinearity does not violate the assumptions of multiple regression. Problems do exist when variables are highly correlated, however, and results of equations containing highly correlated independent variables are less desirable than those without such variables.

Although perfect collinearity was avoided in the analysis, the watershed variables themselves are interrelated to some degree. The correlation matrix between independent variables is presented as table 22. Note that some of the relationships between watershed variables are quite strong, such as the relationship between the area:perimeter ratio and maximum flow length ($r^2 = 0.909$). These highly correlated variables make it difficult to separate out the relative importance of the individual parameters, since multiple variables may be explaining the same variability and response in the dependent variables.

Table 22: Correlation matrix of watershed variables

	A_w	L_m	h	A_p	S	D_l	S_b	R_r
A_w	1	0.785	0.584	0.876	0.147	0.746	0.044	0.049
L_m		1	0.849	0.909	0.310	0.627	0.154	0.114
h			1	0.745	0.105	0.463	0.156	0.020
A_p				1	0.284	0.693	0.106	0.102
S					1	0.143	0.212	0.572
D_l						1	0.051	0.054
S_b							1	0.130
R_r								1

where,

A_w = contributing area (m^2),
L_m = maximum flow length (m),
h = maximum change in elevation (m),
A_p = area:perimeter ratio (m),
S = basin slope,
D_l = cumulative channel length (m),
S_b = basin shape, and
R_r = relief ratio.

Since channel area is a function of both width and depth, it serves as a strong descriptor for channel adjustment to watershed variability. In most cases, channel area displays a stronger relation to watershed variables than channel width. This difference in relationship strength underscores the role that channel depth plays in channel adjustment. The fact that these differences are small (table 22) reveals the greater dependence of cross-sectional area on channel width than on depth.

Transmission losses on Walnut Gulch are quite high (Wallace and Lane, 1978), and reduce the amount of runoff accumulating throughout the watershed. It could be inferred from this fact that the relationship between channel area and watershed area would flatten out with increasing watershed size as transmission losses reduced the increase in stream power. This is not the case, however, as channel area maintains a geometric increase with watershed size. This apparent conflict can be explained by taking into account the role of large events. Although rare, large events may be principally responsible for the development of channel shape, while smaller events mostly re-distribute channel material. Accepting the premise that large events are mainly responsible for erosion and channel formation, it would be expected that the importance of transmission losses would be minimized and channel area would show a consistent increase across watershed sizes.

The strongest relationship, case two of table 21, includes watershed variables that describe both the shape (area:perimeter ratio) and the energy (maximum flow length and elevation change) associated with a contributing area. What is perhaps surprising about the results of the regression models presented in table 22 is that all illustrate a very strong relationship between channel cross-sectional area and watershed variables. Stepwise multiple regression selectively includes only those variables that improve the mathematical model, but in all the cases where principal watershed variables were input to the model, a coefficient of determination greater than 0.82 was found. In most cases, the coefficient of determination was approximately 0.85. The fact that many different arrangements of variables still construct such a strong model illustrates the essential interconnectivity of the variables themselves.

Implications for Sediment Yield from Channel Erosion

Of serious concern to land use managers are the problems associated with accelerated erosion. As shown by Hastings and Turner (1965) rangelands in the arid Southwest have undergone profound incisement and been subjected to relatively high rates of erosion since the latter part of the 19th century. The same processes have occurred on Walnut Gulch, resulting in the present-day appearance of the watershed, which is dominated primarily by incised channels. Given that minor channels within the watershed boundaries were originally swales, while today most are highly incised, it is apparent that a great deal of erosion and sediment transport has resulted in the removal of large quantities of sediment. The total volume of channel material excavated since the onset of incisement was derived for each channel order according to the following formula:

$$V_o = l_o \cdot \overline{A}_o, \qquad (21)$$

where,

V_o = excavated channel volume for a given order (m^3),
l_o = total channel length for that order (m), and
$\overline{A}_o$ = average cross-section width for that order (m^2).

As shown in table 23, the channel volume excavated for each order approximates a constant value of $400{,}000 m^3$ through the first four orders, with more profound deviations for the fifth and sixth order channels (table 23). As was presented earlier in this paper, the log-linear relationships between channel morphology and various watershed variables break down between the fourth and fifth order channels. Excavated volume is a function of channel area; therefore, the deviation of the fifth order channels from a constant value might be directly related to the same environmental factors that are disrupting the relationships between channel morphology and watershed variables. The high value for the sixth order channel may be explained by the relative lack of sampling of such channels, a conclusion which would consistent with earlier findings relating channel order to point samples of channel width, depth, and cross-sectional area, each of which showed a strong outlying value for sixth order channels.

Table 23: Channel volume excavated for each stream order

Stream order	Number of streams	Average stream length (m)	Average cross-section area (m^2)	Excavated volume (m^3)
1	2627	185.08	0.802	389,937
2	588	419.78	1.465	361,607
3	217	685.82	2.543	378,456
4	46	1624.17	5.633	420,852
5	16	2912.06	10.582	493,047
6	1	24802.0	26.206	649,961

Many of the channels designated as first order did not exist until relatively recently, which would indicate a constant re-ordering of channels on the watershed as erosion events create new channels and alter the morphology of existing channels. This constant restructuring of channel morphology would be reflected in the total volume of material removed from the channels. The similarity in estimates of volume removed from each order implies a relationship between the stream orders, perhaps indicating that excavated volume is a function of the material removed from lower-order channels (table 23). Alternatively, it may be deduced that stream channels are responding in a similar manner to environmental stimuli and excavating channel material at a relatively constant rate through time, resulting in the relatively similar values for excavated material per order.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

GIS Development and Applications

A primary goal of this project was to create a high-resolution, highly accurate representation of Walnut Gulch within a GIS environment (objective 1). Without question, the development of a GIS with a precision and resolution similar to the Walnut Gulch database is costly and perhaps impractical for a larger area or one on which intensive research will not be performed. However, on an area such as Walnut Gulch, where watershed processes are investigated on different scales and an abundant amount of research is performed, a GIS such as is described in this report can become a valuable asset. Small changes in spatial data can be accurately measured and stored within such a database, affording the development and refinement of large-scale models sensitive to minor perturbations in their parameters.

No other GIS has been found that represents an area's channel network with the detail and precision than that which was created during this project. This detailed representation of channel network is particularly significant since it was created for an experimental watershed that is highly gaged and serves as an important location for the collection of data used to develop and parameterize runoff and erosion models. With an accurate representation of all channels on Walnut Gulch, verification and parameterization of such models may be enhanced by linking field-based models with this GIS.

Additionally, the other theme layers used to describe the topography, soils, and vegetation of Walnut Gulch are of a high resolution and cover the watershed with great detail. Some validation and error checking remains to verify the positional accuracy of soil map units, but the maps were created at a large scale, and the potential errors are still quite small in comparison to those associated with GIS databases created with conventional means. Overall, the GIS representation of Walnut Gulch is of a scale and accuracy not commonly found.

Objective 2 of this study was to develop new techniques for data acquisition and to enhance existing techniques. GIS analysis affords the researcher an enormous improvement in the time necessary to complete analysis of spatially distributed data. The protocol and programs developed during this research enabled the fast and accurate analysis of over two hundred watersheds. These analyses each represented an enormous amount of computational work, far beyond the ability of a person to do by hand given the amount of time to complete this project. Stream ordering by conventional means is a relatively slow process and subject to human error. Having found existing GIS ordering routines to be unacceptable, a new approach to this problem was developed, culminating in an algorithm that was created for this project. This channel ordering algorithm, presented as Appendix b, will allow future analysis of channel ordering to be both rapid and accurate.

Geomorphology Study

A more thorough understanding of the hydrologic principles and geomorphologic interrelationships of Walnut Gulch was objective 3 of this project. It has been said that there are perhaps only three truly independent variables; climate, geology, and time and that all else can be derived from the interaction between them (Osterkamp, 1995). However, for the purposes of geomorphologic investigation, it is necessary to utilize variables that are more easily obtained and quantified. To that end, a survey of channel cross-sections was undertaken across Walnut Gulch.

In order to fully describe channel form on Walnut Gulch, a random sampling of 222 channels across all soil types served as the basis for statistical analysis. Channels were surveyed according to the best estimate of bankfull depth, and channel shape was defined by breaks in slope across the cross-section. At each sample point three to five surveys were performed, the results of which were averaged to reduce the impact of microtopography on channel form. Average channel width, depth, cross-sectional area, and the width:depth ratio were derived for the reaches under consideration.

Integration of GIS and Field Research

Objective 4 concerned the integration of field research and GIS applications. Data describing channel shape was measured in the field, while parameters describing the area contributing runoff to each of the sample points were extracted from the GIS. These variables were integrated using statistical analyses to derive relationships among them.

It was shown in this paper that channel cross-sectional area is a function of several basic watershed variables that govern the hydrologic response and therefore the shape of channels within Walnut Gulch. Channel order governs the size and shape of channels and was used as a stratification layer. The size of an area contributing to runoff and the length of flow to a point are the primary factors determining channel shape. However, strong deterministic relationships were also drawn between channel shape variables and a host of other watershed parameters.

Recommendations

Furthering this research by investigating runoff properties at the measured channel reaches would establish a method for modeling runoff on all channels throughout Walnut Gulch. Runoff and channel flow has been intensively studied at Walnut Gulch for decades, and a large amount of data has been collected on a variety of channel sizes. Channel shape variables used in the channel geometry technique were sampled intensively throughout the watershed for this project. These channel variables could be combined with runoff data to develop deterministic relationships between channel shape and runoff (equations 3 and 4).

In order to make better use of relationships derived from this study, it would be useful to parameterize the channel network map of the GIS such that channel shape is calculated for all stream sections throughout the watershed. Since channel width may be extracted from the present channel network map, this would entail correlating channel width with cross-sectional area in order to derive average depth. Such a procedure would provide a better estimation of channel volume and capacity across the watershed, and would lend itself towards the examination of infiltration and channel losses throughout the watershed.

As is shown on figure 8, the stream channels display a runoff pattern independent of scale. Fractal mathematics could be used to investigate what is governing drainage patterns. The GIS layer describing the channels as vectors would lend itself nicely to a study of fractal geometry.

Results of this project could be compared to those derived using USGS 30m DEM data. USGS surface models are widely available, and are often used in hydrologic modeling. Their applicability across watershed scales could be analyzed by comparing the results of this study with the product of USGS surface models.

It was found during the examination of surface slope that the slope break categories indicated by the soil classification do not match with those derived from the

DEM. An investigation into this apparent conflict would have the short-term effect of improving the GIS database, but also has implications for the integration of soil surveys and GIS throughout the United States.

Strahler analyses at different scales have been completed on Walnut Gulch (Lane, 1994). The research was conducted using 1:24000 and 1:12000 scale maps using traditional ordering and mapping techniques. Results from Strahler analysis in this study, executed on a 1:5000 scale could be compared to the older work to assess the impact of scale and ordering technique on geomorphic analysis.

APPENDIX A
STREAMFLIP.AML

APPENDIX A

STREAMFLIP.AML

```
/* Usage: Streamflip <cover> <subclass>

&args cover subclass
&stat 9999

DISPLAY 9999 3
ARCEDIT
        EC %cover%
        EDITFEATURE arc
        DRAWENVIRONMENT ARC ARROWS SECTION.%subclass%
        DRAWSELECT ALL
        DRAW
        SELECT ALL

/* Interactively specify where to start the route.

&type 'Specify a mouth or outlet of the network'

        MAKEROUTE %subclass% *
        EDITFEATURE SECTION.%subclass%
        SELECT ALL
        RESELECT F-POS LT T-POS
        SELECTPUT ARC
        EDITFEATURE ARC
                FLIP

&return
```

APPENDIX B
ORDER.AML

APPENDIX B

ORDER.AML

```
/* This is the file order.aml. It is designed to calculate the ordering
/* sequence for a connected stream system.

ec test2

&label beginning

        &sv .num1 = 0
        &sv howmany = 0

/* Select all the labels and figure out how many times you must go through
/* the loop to select all the records.

ef node

        &sv .num2 [show maximum node#]

&label here

/* Set up a counter which will bail you out of the program when it reaches
/* beyond the number of records in the attribute field.

ef arc
&sv .num1 = %.num1% + 1
        &if %.num1% > %.num2% &then &goto test


/* If the arc attached to the node already has been ordered, skip
/* down to the bottom. This avoids calculating the order and all the
/* logic statements

  sel fnode# = %.num1%
  &sv .num30 = [show number select]
                &if %.num30% = 0 &then &goto skip
        &sv .num31 = [show select 1]
                &sv .num32 = [show arc %.num31% item order]
                        &if %.num32% > 0 &then &goto here
```

```
/*  Select a to-node equal to the counter.  If none are selected, then run
/*  ord1.aml.  If one is selected, it is a pseudonode, and ord2.aml will
/*  be run.  If two or more are selected, a slew of possible iterations
/*  occurs.  Ord3.aml, ord4.aml, and ord5.aml are designed to handle those
/*  occurences

&label skip

sel tnode# = %.num1%
        &sv .num3 = [show number select]

                &if %.num3% = 0 &then &run ord1.aml
                &if %.num3% = 1 &then &run ord2.aml

                &if %.num3% = 2 &then &run ord3.aml

                &if %.num3% = 3 &then &r ord4.aml

&goto here

&label test


/*  Set up a counter to tell how many times you had to go through this routine
/*  to get to the end.

        &sv howmany = %howmany% + 1


/*  Check to see if there are any records without orders attached to them.
/*  If there are none, then the program is done and it stops.  If there are
/*  still some unordered streams, go back to the beginning and start over.

sel order = 0
        &sv .junk [show number select]
                &if %.junk% = 0 &then &stop
                &if %.junk% ne 0 &then &goto beginning

&label ender

&stop
```

Ord1.aml

```
sel fnode# = %.num1%
        calc order = 1
&return
```

Ord2.aml

```
/*  This is the aml ord2.aml.  It is for the ssignation of stream order to
/*  pseudonodes.

sel tnode# = %.num1%

        &sv .num4 [show select 1]
        &sv .num5 = [show arc %.num4% item order]

/*  If the contributing stream has no order attached, return to the program
        &if %.num5% = 0 &then &return

/*  Calc the order of the downstream section equal to the value of
/*  the upstream section.

sel fnode# = %.num1%
        calc order = %.num5%
&return
```

Ord3.aml

```
/*  This is the file ord.3 - it will be used for calculting the order of
/*  streams below a confluence of two other streams.

/*  First set up the global variables equal to the order of incoming streams

        &sv .num6 [show select 1]
        &sv .num8 [show arc %.num6% item order]
        &sv .num7 [show select 2]
        &sv .num9 [show arc %.num7% item order]
```

```
/*  If either of the streams is unlabeled, return to the main program

                    &if %.num8% = 0 &then &return

                    &if %.num9% = 0 &then &return

/*  If one of the streams has a higher order, use that value

        &if %.num8% > %.num9% &then &sv .num10 = %.num8%
        &if %.num9% > %.num8% &then &sv .num10 = %.num9%


/*  If they have the same value, use that value + 1

        &if %.num8% = %.num9% &then &sv .num10 = %.num8% + 1

/*  Select the appropriate vector and calc its order equal to .num1

sel fnode# = %.num1%
        calc order = %.num10%
&return
```

Ord4.aml

```
/*  This is the program ord4.aml - it is designed to handle the occurence
/*  of three streams confluencing at the same place.

/*  Set up some global variable equal to the order values of the three incoming
/*  streams.

        &sv .num11 [show select 1]
        &sv .num12 [show arc %.num11% item order]
        &sv .num13 [show select 2]
        &sv .num14 [show arc %.num13% item order]
        &sv .num15 [show select 3]
        &sv .num16 [show arc %.num15% item order]
```

```
/*  Return to the main program if any of the incoming streams are unlabeled

                &if %.num12% = 0 &then &return

                &if %.num14% = 0 &then &return

                &if %.num16% = 0 &then &return

/* if all the values for incoming streams are labeled, then go ahead and
/* figure out if they are all different, and if so set the variable .num17
/* equal to the greatest of the three

&if %.num12% > %.num14% and %.num12% > %.num16% &then &sv .num17 = %.num12%

&if %.num14% > %.num12% and %.num14% > %.num16% &then &sv .num17 = %.num14%

&if %.num16% > %.num14% and %.num16% > %.num12% &then &sv .num17 = %.num16%


/*  Deteremine if all incoming streams have the same order - if they do, then
/*  calc .num17 = order + 1

&if %.num12% = %.num14% and %.num12% = %.num16% &then &sv .num17 = %.num12% +
1


/*  Determine if two of the streams are the same, but the third is higher order
/*  than they - if so, then calc .num17 = order of the largest.

&if %.num12% > %.num14% and %.num14% = %.num16% &then &sv .num17 = %.num12%

&if %.num14% > %.num12% and %.num12% = %.num16% &then &sv .num17 = %.num14%

&if %.num16% > %.num12% and %.num12% = %.num14% &then &sv .num17 = %.num16%


/*  Determine if two are the same but the third is smaller - if so, then calc
/*  .num17 = order of the two + 1

&if %.num12% < %.num14% and %.num14% = %.num16% &then &sv .num17 =
 %.num14% + 1

&if %.num14% < %.num12% and %.num12% = %.num16% &then &sv .num17 =
%.num12% + 1
```

```
&if %.num16% < %.num12% and %.num12% = %.num14% &then &sv .num17 =
 %.num12% + 1


/*  Now select the fnode needed and calc its order = .num17

sel fnode# = %.num1%
          calc order = %.num17%
&return
```

APPENDIX C
WATERSHED.AML

APPENDIX C

WATERSHED.AML

```
/*  This is an aml for creating watersheds for contributing areas to
/*  points inputted by the user.  A DEM is required  (in this case it
/*  is called fill10), as is a flowdirection map, and a stream map is
/*  useful for helping discern the bottomland areas.
/*  First show the elevation and point map and zoom in
        mapex nofill10

markerset municipal
markersym 201
markersize .05
        points done_samp

textset plotter
textsym 97
textsize .3
        text 'Zoom in on the desired area'
                mapex *
                clear

linecolor 1
        arcs wagu

/*  Then show the stream network
linesym 4
        arcs strmcopy2

/*  Then show the points of interest
markersize .15
        points done_samp

/*  Zoom in again
         text 'Zoom in again'
                mapex *
                clear

gridshades nofill10
```

```
linecolor 1
        arcs wagu
linecolor 4
        arcs strmcopy2
markersize .2
        points done_samp

/*  Query what the point's target value is, which will serve as the basis
/*  for the maps name

text 'Check to see the value of the target cell'
        cellvalue samp_grid *

/*  Inquire what the resultant map should be called
&sv .mapname = [response 'Enter the mapname (in CAPS)']

/*  Run the watershed routine that calls for input from the user
%.mapname% = watershed (noflow10, selectpoint (nofill10, *))

/*  Show the resultant map to the user
        gridshades %.mapname%
        points done_samp

linecolor 1
        arcs wagu

/* Ask if the map looks ok.  Rub the subroutines dependent on the answer
&sv okay = [response ' Does this look OK? y/n']
        &if %okay% = n &then &r subws1.aml
        &if %okay% = y &then &run zonal.aml

                &r subws2.aml
```

Subws1.aml

```
kill %.mapname% all
&r subws2.aml
```

Subws2.aml

```
clear

/*  Check to see if the user wants to go on to the next watershed
&sv again = [response 'Do you want to run this again? y/n']
        &if %again% = y &then &r wshed.aml
        &if %again% <> y &then quit
```

Zonal.aml

```
/*  This is a subroutine that runs statistical & geometric analysis on watersheds created in the
/*  watershed.aml program.

/*  First use the GRID function zonalstats & zonalgeometry to acquire the needed data

%.mapname%.stat = zonalstats (%.mapname%, nofill10, all)
%.mapname%.geo = zonalgeometry (%.mapname%, all)


/*  Now pipe the names of the files into text files & then pull the data out of
/*  the INFO files & into the same text files

&sys echo %.mapname% >> watershed.geo
&sys echo %.mapname% >> watershed.stats

&data ARC INFO
ARC
        SELECT %.mapname%.STAT
                OUTPUT ../watershed.stats
                        DISPLAY MEAN,MIN,MAX,STD PRINT
                OUTPUT arcsnp
        SELECT %.mapname%.GEO
                OUTPUT ../watershed.geo
                        DISPLAY
AREA,PERIMETER,THICKNESS,XCENTROID,YCENTROID,
MAJORAXIS,MINORAXIS,ORIENTATION PRINT
                OUTPUT arcsnp
        Q STOP

&end
```

APPENDIX D
MAX_ELEV.AML

APPENDIX D

MAX_ELEV.AML

```
/*  This is an aml that runs through all the subwatersheds that have been
/*  created for the sample points I used for my thesis on Walnut Gulch
/*  Experimental Watershed.  This program is designed to go through
/*  the subwatersheds and create an output grid that contains cellvalues
/*  of the distances from all points on the subwatershed to their
/*  respective outlets.   It then finds the point of maximum elevation
/*  and exports that value to a text file. Updated 5-12-95 by Scott Miller

/*  First, set it up so that the routine won't crash if it runs into a
/*  filename that doesn't exist

        &severity &error &routine error


/*  We will be using the file "watersheds.done" as the input file to generate
/*  the names of the watersheds on which we will be working...

/*  First, set up the filestats to be used in the routine

        &sv file1 := [open watersheds.done openstat -read]

&label uphere

        &sv ijunk = 0


/*  Now get the values from each of these files, and assign them to
/*  variables to be used in the cellvalue command

        &sv water = [read %file1% readstat]

/*  Now set up the grid operators by determining what the name of the grid
/*  to be worked on is...

        &sv gridname = ws%water%
                &if %ijunk% = 1 &then &goto downhere

/*  Go through all the grid functions needed to create a flowlength grid

        %gridname%_elev = %gridname% * nofill10 / %water%
```

```
    %gridname%_dir = flowdirection (%gridname%_elev)
        kill %gridname%_elev all

    %gridname%_length = flowlength (%gridname%_dir)
        kill %gridname%_dir all


/*  Now do the zonalstats on the _length file



%gridname%.sta = zonalstats (%gridname%_length, nofill10, all)

/*  Pipe the name of the watershed and the relevant information into a text file

    &sys echo -n %gridname% >> max_elev.tab

&data ARC INFO
    ARC
        SELECT %gridname%.STA
            OUTPUT ../max_elev.tab
            DISPLAY MAX PRINT
    Q STOP
&end

&label downhere

/*  Go back up and do it again if it was not the end
kill %gridname%_length all
    &if %water% = 622 &then quit

        &goto uphere


/*  This is a subroutine that makes sure the aml won't crash when an error is
/*  encountered

    &routine error
        &sv ijunk = 1
        &severity &error &ignore
        &return
    &end
```

APPENDIX E
DISTANCE.AML

APPENDIX E

DISTANCE.AML

```
/*  This is an aml that runs through all the subwatersheds that have been
/*  created for the sample points I used for my thesis on Walnut Gulch
/*  Experimental Watershed.  This program is designed to go through
/*  the subwatersheds and create an output grid that contains cellvalues
/*  of the distances from all points on the subwatershed to their
/*  respective outlets.  It then retrieves this information from the
/*  location of the centroid of the watershed.
/*  Updated 5-12-95 by Scott Miller

/*  First, set it up so that the routine won't crash if it runs into a
/*  filename that doesn't exist

        &severity &error &routine error


/*  We will be using the file "centroid.ws" as the input file to generate
/*  the names of the watersheds on which we will be working...

/*  First, set up the filestats to be used in the routine

        &sv file1 := [open centroid.ws openstat -read]
        &sv file2 := [open centroid.x openstat -read]
        &sv file3 := [open centroid.y openstat -read]

&label uphere

        &sv ijunk = 0


/*  Now get the values from each of these files, and assign them to
/*  variables to be used in the cellvalue command

        &sv water = [read %file1% readstat]
        &sv xlocat = [read %file2% readstat]
        &sv ylocat = [read %file3% readstat]

/*  Now set up the grid operators by determining what the name of the grid
/*  to be worked on is...

        &sv gridname = ws%water%
                &if %ijunk% = 1 &then &goto downhere
```

```
/* Go through all the grid functions needed to create a flowlength grid

     %gridname%_elev = %gridname% * nofill10

     %gridname%_dir = flowdirection (%gridname%_elev)
          kill %gridname%_elev all

     %gridname%_length = flowlength (%gridname%_dir)
          kill %gridname%_dir all


/* Take the distance value from the _length coverage's centorid value and
/* paste it into the distance.txt file...

          &sys echo -n %gridname%_length >> distance.txt
          &sys echo -n "   " >> distance.txt
          &sys echo [show cellvalue %gridname%_length %xlocat% %ylocat%] >>
distance.txt

     kill %gridname%_length all


 &label downhere

/* Go back up and do it again if it was not the end

     &if %water% = 622 &then quit

          &goto uphere


/* This is a subroutine that makes sure the aml won't crash when an error is
/* encountered

     &routine error
          &sv ijunk = 1
          &severity &error &ignore
          &return
     &end
```

APPENDIX F
STREAMLENGTH.AML

APPENDIX F

STREAMLENGTH.AML

```
/*  This is an aml designed to create stream maps for each
/*  of the subwatersheds of my thesis area.  It will multiply
/*  the final stream order map by each watershed, create a
/*  line coverage, superimpose a route system, and then output
/*  the length of each stream order into a file.
/*  Updated 6-24-95 by Scott Miller.

/*  First, set up the files from which the names of the watersheds will
/*  be taken, using the file watersheds.done as that which has the watershed names.

     &sv file1 = [open watersheds.done openstat -read]

          &label uphere
          &sv junk = 0

/*  Now get the variable from this file & assign it to a watershed name

     &sv watershed = [read %file1% readstat]
          &sv gridname = WS%watershed%

/*  turn the grid into a polygon coverage & clip out the streams within

      gridpoly %gridname% %gridname%_poly
         clip final_ord %gridname%_poly %gridname%_arcs line

/*  Use the frequency command to tabulate the lengths by order

     frequency %gridname%_arcs.aat %gridname%_arcs.fre
        order
                end
        length
                end

/*  Now go into info & spit the correct info out to the files

        &sys echo -n %gridname% >> density.tab
        &sys echo -n "  " >> density.tab
```

```
&data ARC INFO
ARC
SEL %gridname%_ARCS.FRE
OUTPUT ../density.tab
DISPLAY ORDER,LENGTH PRINT
Q STOP
&end

/*  Clean up after yourself

        kill %gridname%_poly all
        kill %gridname%_arcs all

/*  Go back up and do it again if it is not the end

          &if %watershed% = 622 &then quit

          &goto uphere
```

APPENDIX G
VARIABLES CITED IN TEXT

APPENDIX G

VARIABLES CITED IN TEXT

Variable	Explanation
A_c	cross-sectional area at a channel link (m^2)
$\bar{A}_O$	average cross-section width for that order (m^2)
A_p	area:perimeter ratio (m)
A_{Sn}	area of soil type n (m^2)
A_w	watershed area (m^2)
C_{Sn}	clay content of soil type n
D	mean channel depth (ft)
$\bar{D}$	average depth of channel link (cm)
$\bar{d}_n$	average depth measured at a cross-section (cm)
$d(x)$	distance between break points (cm)
h	maximum change in elevation within a watershed (m)
h_o	mean - minimum elevation within a watershed (m)
K	fraction of the total length between break points
$K\bar{y}$	weighted depth between successive break points (cm)
L	maximum length of a basin (m)
L_a	average length of first order streams (m)
l_c	number of channel lengths within a watershed (m)
L_l	stream length of a given order (m)
L_m	maximum flow length within a watershed (m)
l_O	total channel length for that order (m)
n	number of cross-sections measured along the channel link
N_o	number of streams per order
o	order of a given class of tributaries
p	watershed perimeter
Q	mean annual discharge (cu. ft/sec)
Q_v	measure of streamflow
R_b	bifurcation ratio
R_l	cumulative channel length within a watershed (m)
R_r	relief ratio
s	order of the main channel
S	basin slope
S_b	basin shape
S_c	soil clay content
S_o	stream order

V	mean channel velocity (ft/sec)
V_o	excavated channel volume for a given order (m^3)
W	mean channel width (ft)
$\overline{W}$	average width of a channel link (cm)
w_n	channel cross-section width (cm)
x_p	measured distnace from origin at each break point (cm)
$\overline{y}$	average depth between successive break points (cm)
y_p	measured depth at each break point (cm)
a, c, k	coefficients
u, b, f, m	exponents

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