Hydrogeomorphic Methods for the Regional Evaluation of Flood Hazards

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ABSTRACT / The "upstream" approach to flood hazard evaluation involves the estimation of hydrologic response in small drainage basins. This study demonstrates the application of geomorphology to such studies in a region of unusually intense flooding in central Texas. One approach to flood hazard evaluation in this area is a parametric model relating flood hydrograph characteristics to quantitative geomorphic properties of the drainage basins. A preliminary model uses multiple regression techniques to predict potential peak flood discharge from basin magnitude, drainage density, and ruggedness number. After mapping small catchment networks (4 to 20 km^2) from remote sensing imagery, input data for the model are generated by network digitization and analysis by a computer-assisted routine of watershed analysis.

The study evaluated the network resolution capabilities of the following data formats: (1) large-scale (1:24,000) topographic maps, employing Strahler's "method of v's", (2) low altitude black-and-white aerial photography (1:13,000 and 1:20,000 scales), (3) NASA-generated aerial infrared photography at scales ranging from 1:48,000 to 1:123,000, and (4) Skylab Earth Resources Experiment Package S-190A and S-190B sensors (1:750,000 and 1:500,000 respectively). Measured as the number of first order streams or as the total channel length identified in small drainage areas, resolution is strongly dependent on basin relief. High-density basins on the Edwards Plateau were poorly depicted on orbital imagery. However, the orbital network definition of low-relief basins on the inner Texas Coastal Plain is nearly as accurate as results from large-scale topographic maps.

Geomorphic methods are also useful for flood hazard zonation in "downstream" flood plain areas. Studies of the Colorado River valley near Austin, Texas, easily distinguished infrequent (100- to 500-year recurrence interval), intermediate (10- to 30-year), and frequent (1- to 4-year) hazard zones. These mapping techniques are especially applicable to the rapid regional evaluation of flood hazards in areas for which there is a lack of time and money to generate more accurate engineering-hydraulic flood hazard maps.

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Introduction

Flood hazard evaluation can be approached from two viewpoints. The "upstream" approach consists of evaluating the interaction of rainfall inputs and physiographic factors in producing flood responses from small watersheds. The "downstream" approach consists of mapping flood hazard zones in the broad alluvial valleys which rivers develop after collecting the flow of numerous tributaries. Demonstrated in this study are hydrogeomorphic techniques that allow a rapid, relatively inexpensive regional evaluation of flood hazards in both upstream and downstream problem areas. Examples from central Texas will be used because of that region's variety of hydrologic settings and its historically high potential for damaging floods (Baker 1975).

An Environment for Floods

Central Texas includes parts of two major physiographic provinces—the gently undulating Gulf Coastal Plain in the south and southeast, and the uplifted Edwards Plateau in the north and northwest. The plateau, which is underlain by interbedded, soft limestone, dolomite, and marl, has been deeply eroded to produce locally steep slopes. The boundary between these two physiographic provinces is marked by a sharp change in elevation at the Balcones Fault Zone. The precipitation falling on the plateau drains across the fault zone into the major rivers—the Guadalupe, Colorado, Brazos, and Trinity—of the Gulf Coastal Plain.

The controlling factors for flooding in central Texas are climate and physiography. Land use practices add to the problem. Mean annual precipitation along the escarpment that marks the Balcones Fault Zone varies from 83 cm at Austin to 56 cm at Bracketville (Fig. 1). Climatically the area is located in the zone where the middle-latitude, humid subtropical climate of the east grades into

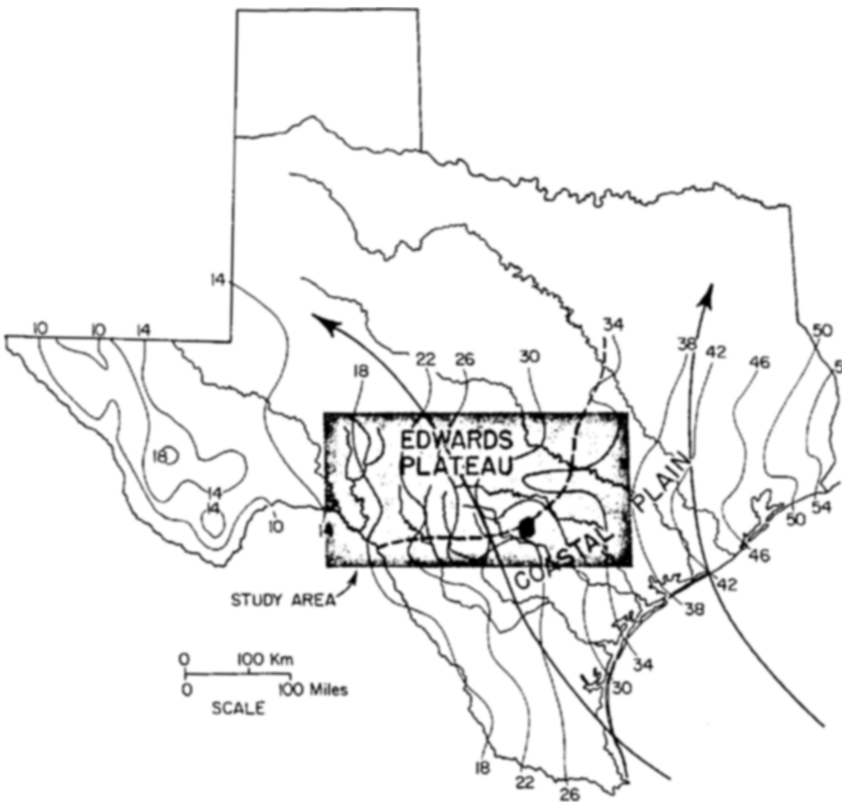


Figure 1. Isohyets of mean annual precipitation in inches for Texas (Carr 1967). Large arrows show major tropical storm tracks from the Gulf of Mexico; the broken line shows the general location of the Balcones Fault Zone.

the middle-latitude steppe climate to the west (Strahler 1965). Humid air masses can penetrate the area at any time of the year, but lack of triggering events during long periods lead to very dry conditions. In any one year the border between humid subtropical climate and middle-latitude steppe may shift completely across the region. As a result annual rainfall is highly variable, ranging from more than 150 cm to less than 35 cm. Even in the dry and hot summers tropical disturbances can bring very heavy rainfall and rapid runoff from high gradient "Hill Country" streams flowing on bedrock. Great variation in stream flow is characteristic both seasonally and annually.

Air masses of tropical marine origin are responsible for the greatest flood-producing storms. These storms result from easterly waves which develop along the Intertropical Convergence Zone that in summer extends into the Gulf of Mexico. The air masses in these waves are warmed and they pick up great quantities of moisture as they pass over thousands of kilometers of warm tropical seas (Orton 1966). A typical storm occurred on September 9 and 10, 1952, when almost simultaneously over central Texas a pressure surge from the northeast met an easterly wave trough. The warm moist tropical air of the trough was lifted over the combined barriers of the Balcones Escarpment and the steep pressure gradient from the northeast. Rainfall totals of 50 to 66 cm were recorded in a localized area over the upper Pedernales and Guadalupe Rivers. Heavy rains fell throughout the area (Lott 1952). A particularly intense cell between Stonewall and Johnson City produced a peak flood stage at the Johnson City bridge on the Pedernales of 14.6 m as recorded by local residents. Hydraulic calculations (Breeding and Montgomery 1954) indicated a peak discharge of 12,490 m^3/sec (441,000 cfs) at that bridge location. Water depths of up to 18 m and flow velocities exceeding 6 m/sec were recorded on smaller streams in the Guadalupe Basin. The advancing flood wave of the Colorado River drainage was stopped by Mansfield Dam. Otherwise,[it is estimated that] the flood stage at Austin, Texas, would have been at least 14 m (21,240 m^3/sec = 750,000 cfs). This would have exceeded all flows since at least 1833 (Orton 1966).

Rainfall is also produced by convective thunderstorms which occur when thermally unstable air is lifted along orographic barriers, weather fronts, and isobaric convergences. A spectacular example of this type of "cloudburst" thunderstorm occurred on May 31, 1935, near D'Hanis, Texas. A tongue of unusually moist, warm air protruded from the Gulf of Mexico into this area (Morgan 1966). The orographic effect of the Balcones Escarpment on this unstable air produced 56 cm of rainfall in 2 hours and 45 minutes.

The flood peak discharges that result from these storms in central Texas are known to exceed those recorded from drainage basins of similar size elsewhere in the United States. By examining the relationship between the magnitude of flood discharge and contributive drainage basin area, it is possible to define an envelope curve for the greatest floods in the region(Fig. 2). It is impossible to predict the occurrence of such storms or even measure accurately their frequency. By careful analysis of the morphology of the drainage basins developed in the area, however, it is possible to predict probable peak discharges and suggest economic and cultural development of the basins which would reduce the magnitude of flooding and insure tha human activities are assigned to topographic positions which are safe from floods.

Upstream studies of small drainage basins

Many interrelated factors control the shape and dimensions of a flood hydrograph, the graph of storm runoff as a function of time. These factors can be separated into two main categories, transient and permanent (Rodda 1969). Transient controls for the most part represent climatic factors, and permanent controls are associated with physical characteristics of the drainage basin. Because virtually all of the controls are dependent in some way on one another, the task of identifying and quantifying individual factors provides a major difficulty in establishing meaningful statistical relationships between various controls. The usual solution to this problem involves selecting variables which are as physically independent as possible. The importance of quantitative geomorphology is obvious because the most easily obtained data is that which can be quantified from maps, aerial photographs, and remote-sensing imagery.

Hydrogeomorphology and floods in small drainage basins

Hydrogeomorphology (Coates 1971; Scheidegger 1973) can be thought of as that part of geomorphology that directly concerns hydrological problems. The discipline involves practical applications of a basic science in much the same way as hydrometeorology is an application of meteorology to flood prediction and other water resources problems. Such applications were probably first recognized by Horton (1945) and Langbein (1947), who pointed out that drainage basin morphology could be quantified for hydrological use. Horton's morphometric work has been extended by many investigators, but relatively little research has aimed at relating flood hydrograph properties to permanent hydrogeomorphic controls. Two reasons have contributed to this lack of progress: (1) the resolution capabilities of various types of maps, photographs, and remote-sensing imagery, and (2) the tedious nature of quantitative drainage network analysis. Before discussing the problems, however, it would be well to demonstrate the methods.

Many physical characteristics of channel form and drainage network geometry have been related to differing magnitudes of flood runoff (Gregory and Walling 1973; Baker and others 1974). Drainage area has been the most often employed correlation with discharge. Its ease of measurement and obvious physical significance allow meaningful correlation with runoff in both humid and arid regions. Drainage density, the length of channel per unit of drainage area, is another frequently employed parameter that has been correlated with base flow (Carlston 1963; Trainer 1969) and the mean annual flood (Carlston 1963; Hadley and Schumm 1961). Drainage density has also been used in multiple regression models for estimating peak flood discharge (Maxwell 1960; Patton and Baker in press). Stream order has also been directly correlated with discharge by numerous workers (Blyth and Rodda 1973; Rodda 1969; Stall and Fok 1967). The frequency of first-order streams (Shreve magnitude) has been correlated with peak flood discharge (Morisawa 1962; Patton and Baker in press). A variety of basin shape factors has also been correlated to flood runoff.

This broad variety of geomorphic data is best employed in a parametric model of flood response that is tailored to a specific study region. The investigator should very carefully assess the hydrologic processes in his study region that govern which variables are most appropriate to his area. The functional relationships that exist between the important hydrogeomorphic parameters in his study area and flood response are then established by multiple regression analysis. A standard logarithmic expression would take a form as follows:

$$Q_t = aX_1 + bX_2 + cX_3 + \cdots$$

where Q_t = the peak discharge with return period t (or some other flood hydrograph property such as lag time), $a, b, c, \cdots$ = regression coefficients, and $X_1, X_2, \cdots$ = factors controlling the flood response.

In practice this approach has resulted in many "flood formulas," nearly all of

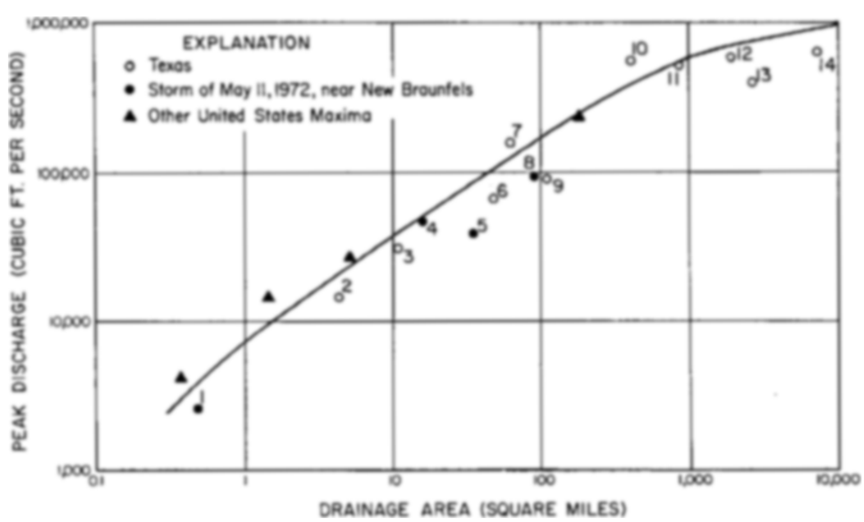


Figure 2. Maximum flood discharges recorded in central Texas in relationship to contributing drainage area. The trend line represents the U.S. national maximum according to Hoyt and Langbein (1955).

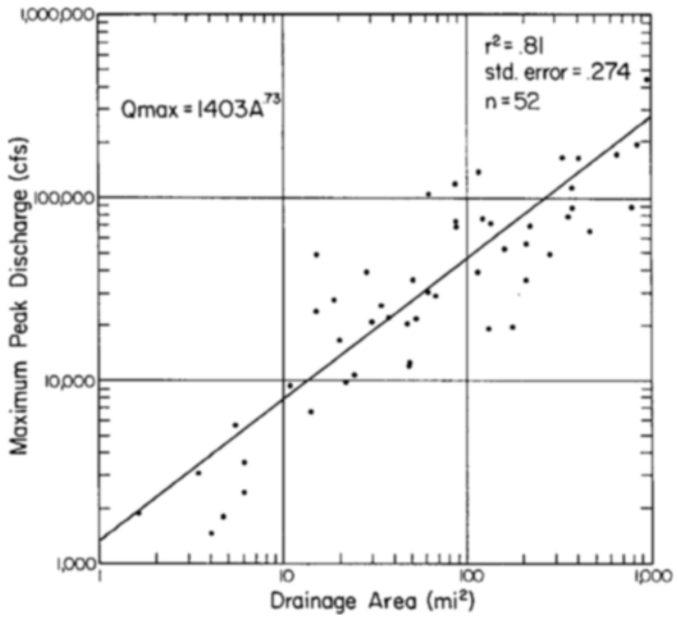


Figure 3. Maximum peak discharge versus drainage area for locations in central Texas. English units were used because of the original data sources (conversions: cfs × .02832 = m³/sec, mi² × 2.590 Km²).

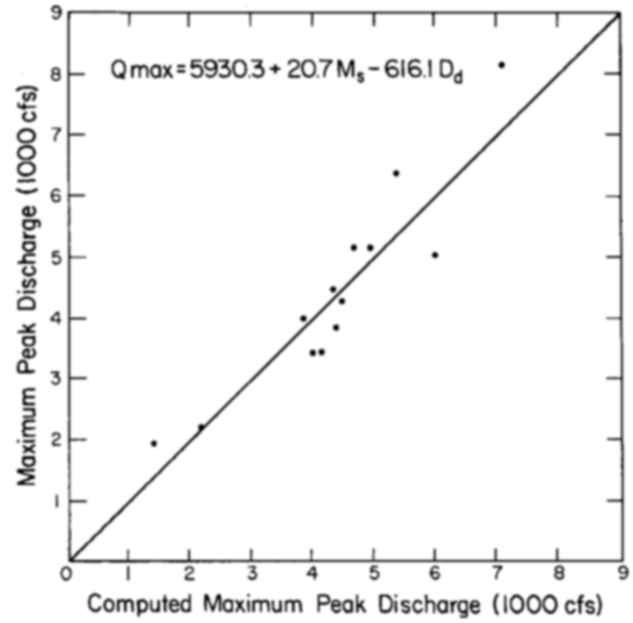


Figure 4. Comparison of measured maximum peak discharge values versus maximum discharge computed from the equation $Q_{max} = 5930.3 + 20.7\ M_S - 616.1\ D$. The 45° line represents perfect agreement.

which include basin area as one of the variables. Problems with the parametric approach include (1) interpreting the interdependence of variables, and (2) explaining the physical reality of the variables included in the analysis. The investigator often finds that unless many variables are held constant, no single variable will account for a large percentage of the variability in flood response.

A Parametric Model for Peak Discharge in Central Texas

As an illustration, a parametric model was formulated from morphometric data collected from topographic maps of study basins in central Texas. All but three of the basins selected for analysis were covered by 1:24,000 scale topographic maps with contour intervals not exceeding 20 feet. The remaining three basins were measured from 1:62,500 scale topographic maps which also had contour intervals less than 20 feet. The drainage networks for these basins were quantified by performing a Horton analysis (Horton 1945) so that quantitative comparison between basins and remote-sensing imagery could also be accomplished. Stream lengths were determined by the crenulation method (Horton 1945; Morisawa 1957) and streams were ordered by both the Strahler (1957) and Shreve (1966) methods. The following variables were recorded for each basin: drainage area, Strahler order, Shreve magnitude or number of first-order streams, number of streams of a given order, total stream length, basin length, relief, main stream length, and number of segments of all orders. From these variables additional measures of the drainage basin were calculated, as follows: drainage density, relief ratio, ruggedness number,[1] and first-order channel frequency. Linear measurements were made with a map wheel. Areal measurements were made with a polar planimeter.

The hydrologic response component of the model was generated from a data base collected from 25 stream gaging stations in central Texas. Runoff data was only available for eight of the study basins that formed the data base. To extend this data, maximum discharge was estimated from the least squares relationship between drainage area and peak discharge derived from 52 sites in central Texas (Fig. 3). Although there is considerable deviation from the best fit line, this relationship was considered more applicable than regional frequency equations because the frequency of the maximum runoff events for streams in central Texas varies considerably.

The morphometric and runoff data were entered into a correlation analysis, and morphometric variables highly correlated with area (total stream length, basin length, and main stream length) and area were eliminated from further

[1]Ruggedness number is the product of relief and drainage density where both parameters are expressed in the same units.

Table 1 Correlation Matrix of Morphometric Data and Runoff Data for Central Texas

	Drainage area	Strahler order	Shreve magnitude	Total stream length	Drainage density	Basin length	Relief	Relief ratio	Total number stream segments	Main stream length	Ruggedness number	Maximum peak discharge
Drainage area[1]	1.000											
Strahler order	.499	1.000										
Shreve magnitude	.470	.842	1.000									
Total stream[1] length	.715	.872	.905	1.000								
Drainage[1] density	−.390	.517	.570	.360	1.000							
Basin length[1]	.896	.396	.323	.639	−.368	1.000						
Relief	.455	.737	.795	.808	.434	.385	1.000					
Relief ratio	−.156	.423	.526	.333	.632	−.307	.737	1.000				
Total number stream segments	.327	.875	.920	.882	.727	.295	.763	.523	1.000			
Main stream[1] length	.911	.387	.371	.654	−.367	.941	.454	−.158	.318	1.000		
Ruggedness number	.177	.695	.847	.712	.686	.093	.918	.845	.813	.170	1.000	
Maximum peak[1] discharge	.999	.500	.470	.714	−.389	.895	.453	−.157	.327	.910	.175	1.000

[1]Log_{10}

analysis to avoid spurious results (Table 1). The eliminated variables may be important estimators of runoff magnitude, but because the runoff data were generated from an equation employing area the resulting high coefficient of determination (R^2) for a regression equation employing these variables would directly reflect the high correlation coefficients with area. Morphometric variables related to discharge, Shreve magnitude, drainage density, ruggedness number (relief times drainage density), and total relief were entered into a step-wise multiple regression analysis. The multiple regression technique allows for the selection of that variable which initially explains the most variability in the dependent variable, in this case, maximum peak discharge.

In descending order of importance, the additional variables are included in the regression until there is no significant increase in the variability explained. The resulting relationship was:

$$Q_{\max} = 5930.3 + 20.7\ M_S - 616.1\ D$$

where $Q_{\max}$ = maximum flood discharge of record (cubic feet/second), M_S = Shreve magnitude of the basin, and D = drainage density (miles/miles^2).

Problems of drainage network resolution and quantification

The sources of data for hydrogeomorphic studies in small drainage basins can be divided into three broad groups: topographic maps, aerial photography and remote-sensing imagery, and orbital remote-sensing imagery. Many complex factors contribute to the degree of network resolution achieved from data imagery sources. These factors are best illustrated by considering selected results from individual study basins in central Texas.

Bee Creek is a small tributary of the Colorado River developed on deeply dissected marl and limestone bedrock near Austin, Texas. The relief ratio (ratio of basin relief to basin length) is 0.03. The basin is characterized by steep slopes, brushy vegetation, and thin, discontinuous soils. Orbital imagery of the basin revealed the considerable resolution capabilities of the Skylab EREP earth terrain camera over the EREP multispectral photographic camera (Fig. 5). At least 44 first-order streams were identified with the terrain camera in the 8.2 km^2 basin. The S-190A multispectral image revealed only 14 first-order streams. The topographic map analysis (Fig. 6), in contrast, shows the interpretive advantages of contour crenulation analysis and of large-scale formats (1:24,000) for network interpretation. Resolution of various scales and types of imagery can be further quantified by the use of Horton's law of stream numbers (Fig. 7).

A question arises in deeply dissected

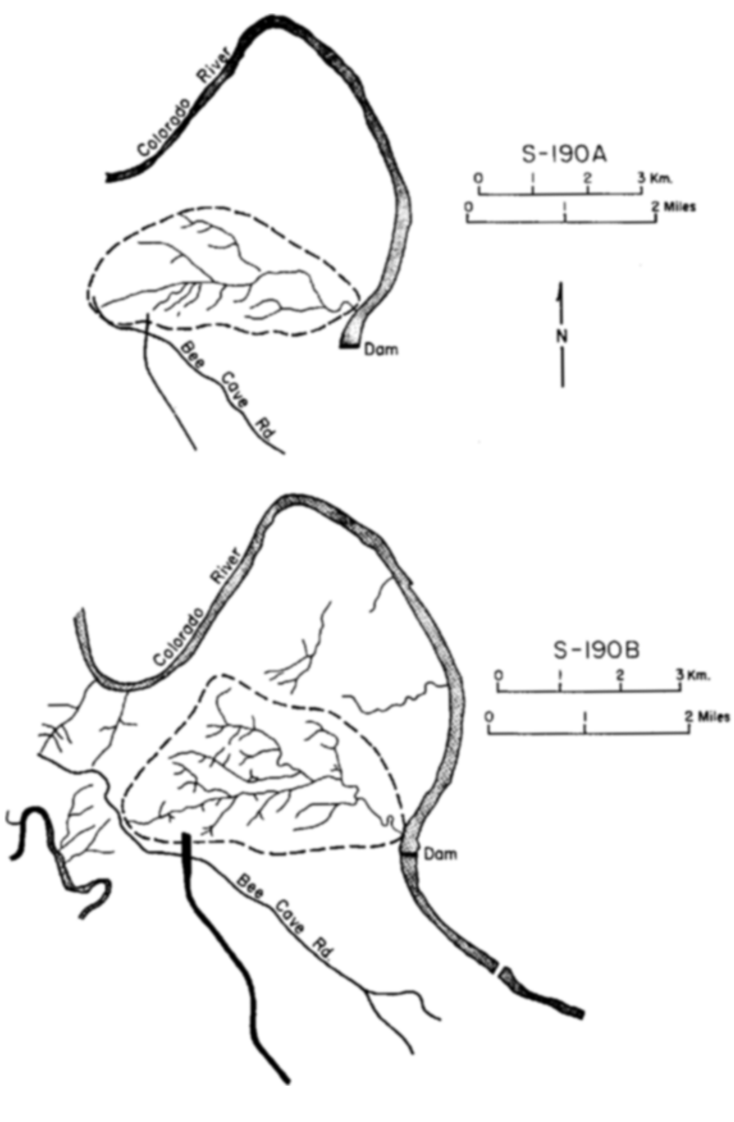


Figure 5. Drainage maps of the Bee Creek basin: (a) Skylab S-190A, high resolution color film SO-356 with FF filter, enlarged to scale 1:56,000; (b) Skylab S-190B, roll 94, frame 123; the original 9 × 9″ transparency was enlarged to 1:48,480 scale.

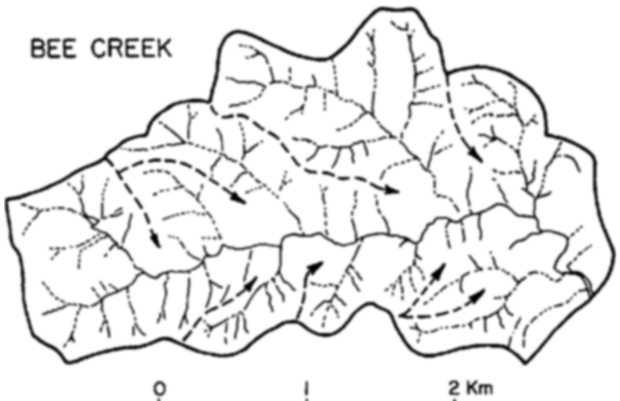


Figure 6. Drainage map of Bee Creek, constructed by the "method of V's" using the Austin West 7.5′ topographic quadrangle map (1:24,000).

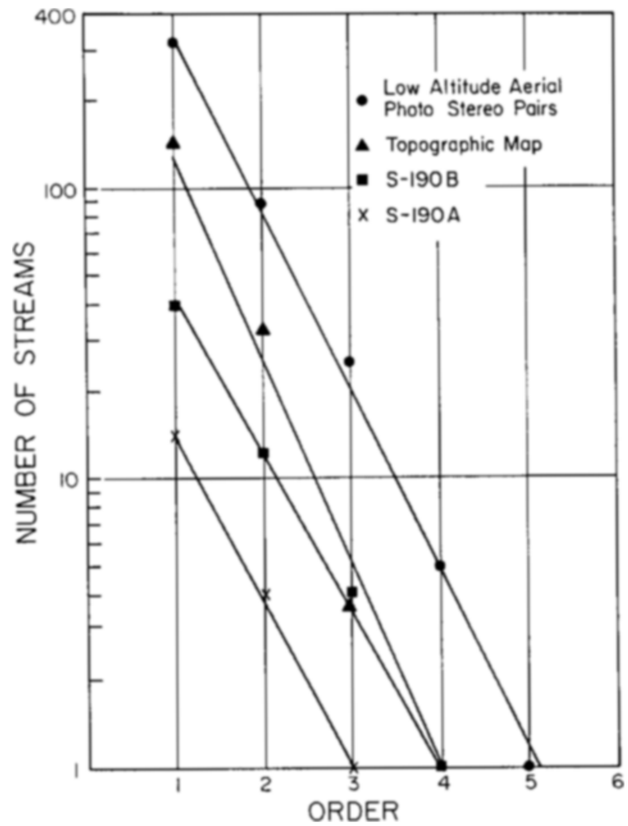


Figure 7. Horton's law of stream numbers for Bee Creek networks mapped from various imagery sources.

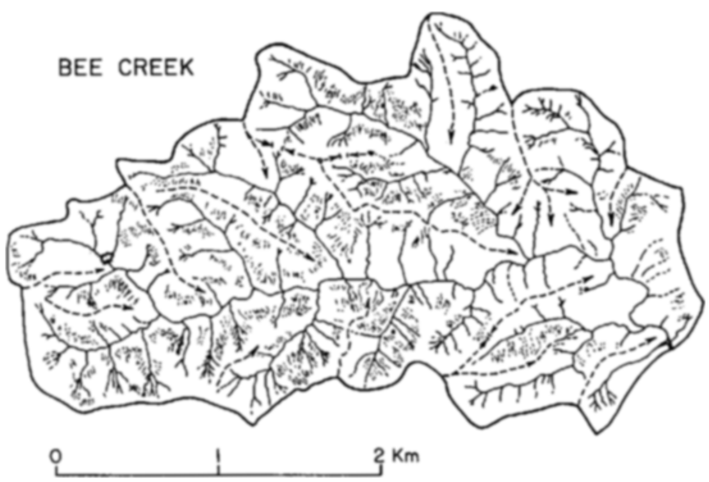


Figure 8. Drainage map of Bee Creek constructed by detailed stereoscopic interpretation of low altitude black-and-white aerial photographs at 1:13,000 scale. (Map prepared by Dr. M. M. Penteado.)

basins such as Bee Creek concerning the detail of the actual network and the significance of that detail for flood runoff. A precise stereoscopic interpretation of low altitude black-and-white aerial photographs revealed that numerous small gullies develop on hillslopes in the Bee Creek basin as an adjunct to the continuous channel network (Fig. 8). A detailed field study showed that these gullies averaged 30 m in length. This and other field studies suggest that all forms of imagery for drainage network mapping fail adequately to depict the high-density gully systems that may occur in high-relief study basins. Most of the gullies studied in the field would result in an order of magnitude increase in first-order stream frequency for a given basin. However, the hydrologic significance of the gullies is probably much less than that of the continuous channel network. The gullies constitute a channel flow component of local hillslope hydrologic systems. Their high channel roughness and irregular gradients clearly distinguish them from the more efficient stream channel system that is accurately displayed on smaller-scale imagery.

Dry Prong Deep Creek basin is developed on interbedded sandstone and shale units. It has a relief ratio of 0.021. As in the case of Bee Creek, a topographic map and suborbital imagery (Fig. 9) proved to be much more accurate for network resolution than did Sky-

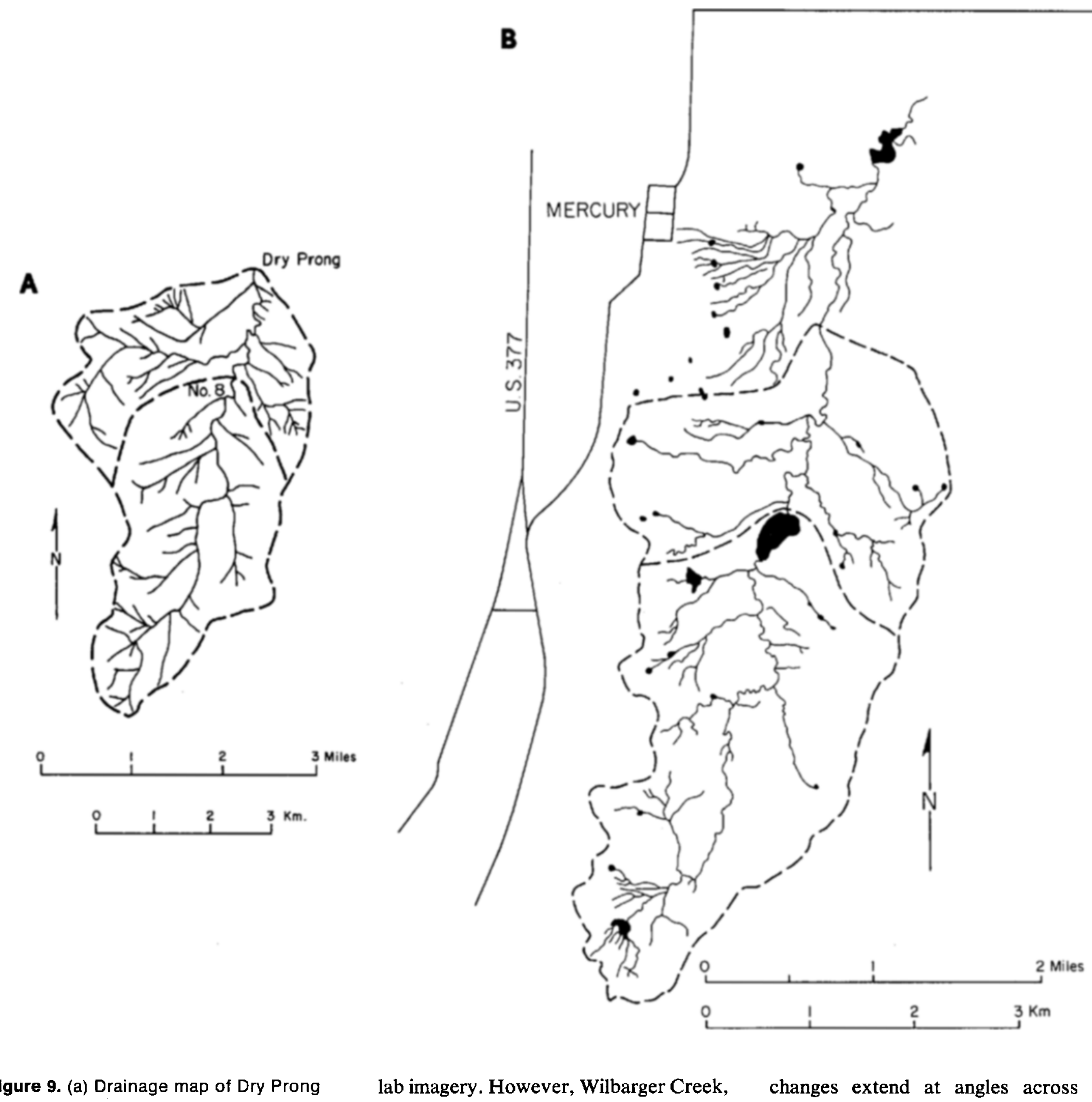


Figure 9. (a) Drainage map of Dry Prong Deep Creek constructed by the "method of V's" using a 1:62,500 scale topographic map. (b) Drainage map of Dry Prong Deep Creek constructed from a NASA color infrared image in 9 × 9" format at 1:24,768 scale (Aircraft mission 261, image RL13-DO17).

lab imagery. However, Wilbarger Creek, a coastal plain basin with a relief ratio of only 0.01 was quite accurately depicted by the orbital earth terrain camera (Fig. 10). This basin occurs in an agricultural area with thick soils developed on the relatively permeable Austin Chalk. Channels with their attendant land use changes extend at angles across th more regular tones, textures, and pa terns of the cultivated land. The angul trend of these linears frequently allow an interpreter to trace a stream chann to a bifurcation point which might g unnoticed, especially among low stream orders. Wilbarger Creek's drai age density is only 2.1 km/km² in contrast to Bee Creek's density of 7.8 km/km². Bee Creek's more detailed pattern is partly obscured by tall, brushy vegetation and strong shadows that mask the photographic expression of the channels.

Although drainage network resolution appears to be controlled by a complex of factors including scale, vegetation, land use, shadow tone, and texture, basin relief acts in an integrating fashion. For drainage basins of similar-size, Shreve magnitude (the total number of first-order streams) calculated from various imagery formats is a clear function of relief ratio (Fig. 11). In general, the large-scale topographic maps gave the highest resolution of first-order streams, while the orbital S-190A imagery provided the least. Furthermore, with increasing relief ratio the number of first-order streams "lost" in this sequence increases, as the decreasing slope of the

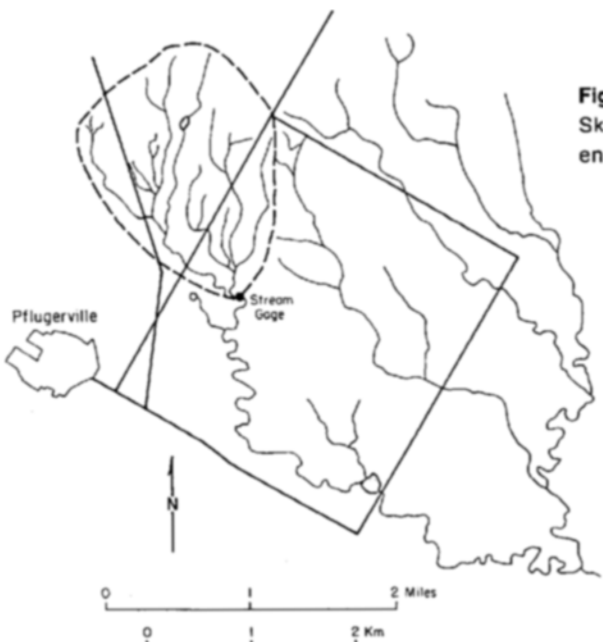


Figure 10. Drainage map of Wilbarger Creek based on analysis of Skylab S-190B imagery, roll 94, frame 123, 9 × 9" transparency enlarged to 1:48,480 scale.

Figure 11. Shreve magnitude versus relief ratio for similar-sized central Texas drainage basins with morphometric data supplied from differing imagery formats. Basins are indicated by number as follows: (1) Deep Creek no. 8, (2) Dry Prong Deep Creek, (3) Wilbarger Creek, (4) Dry Creek at Buescher Lake, (5) Upshaw Creek, (6) Bee Creek. Basin areas vary from 8 to 20 km².

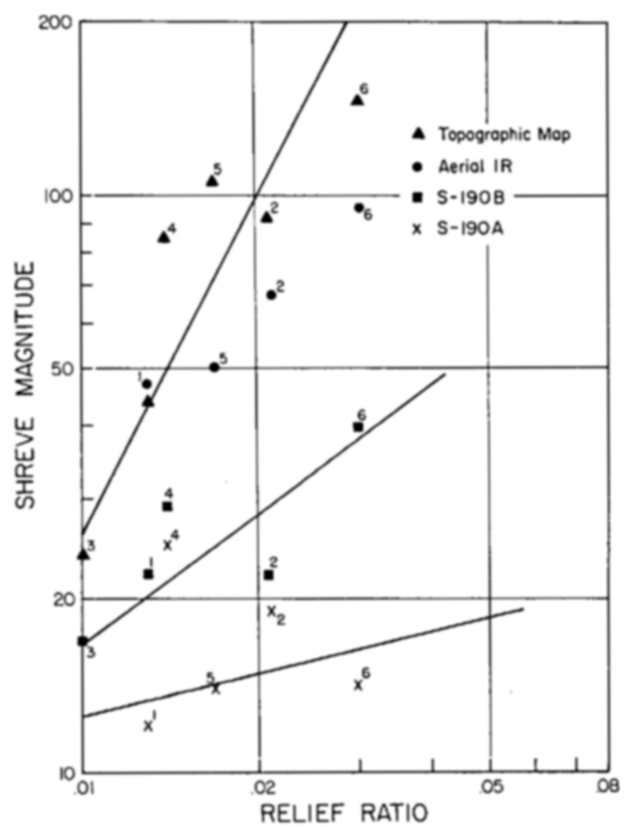
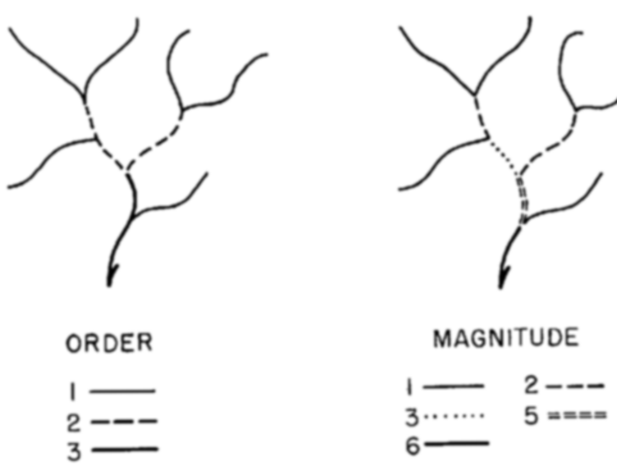


Figure 12. Assignment of Strahler orders and Shreve magnitudes.



individual lines demonstrates. Probably many of the first-order streams in regions of steep relief are the small gullies of hillslope systems that are easily obscured by vegetation and not enhanced by shadow effects.

Once a network pattern has been interpreted from a data source the various stream junctions, sources, and link midpoints need to be reduced to morphometric parameters. To avoid the tedious nature of manual morphometric analysis from photographic or cartographic data sources, the current research trend is toward incorporating machine-assisted digitization of drainage networks and computer reduction of data into a systematic analytical procedure (Penteado and Hulke 1974).

The W.A.T.E.R. System, a computer program for watershed analysis developed at Purdue University and the University of Toronto (Coffman and others 1971) was used to calculate quantitative geomorphic parameters from digital input data. The transformation of spatial data (drainage maps) to digital data can be accomplished by selecting points within the drainage network which describe the branching pattern of the network (network topology) and assigning cartesian coordinates to these points to resolve their spatial position (Fig. 12). Network topology can be described by a sequence of numeric codes which define the function of selected data points.

Aside from recording data point function codes sequentially, it is necessary to record the spatial positions (cartesian coordinates) of the points in the same sequence. (X and Y coordinates of the end-of-data dummy point are ignored.) These positions were automatically digitized with an accuracy of ± 0.005 inches (0.013 cm) using a d-mac pencil follower. Output from the pencil follower was recorded on 7-track magnetic tape. Input data to the W.A.T.E.R. System were the three sequential arrays of X and Y coordinates, associated function codes of the data points, and the scale of the digitized drainage network.

It is obvious that the method outlined above creates a schematic digital of a drainage network. A more detailed model can be defined by inserting "midpoints" which break up curving segments of the network into several short straight segments rather than one long straight segment. The W.A.T.E.R. System can also perform three-dimensional analysis if the elevation is included as a Z coordinate in defining the spatial position of data points.

After the recording of coordinates for each data point on magnetic tape, a series of operations ensues to determine accuracy in the data array, to edit, and finally to interface the data with the W.A.T.E.R. System (Fig. 13). The RCUHELP program was used to transfer data to punch cards or permanent disc file. The KAREDIT program was used to properly align data words as stored in the permanent file. The MIXER program was used to read word storage to transform data back to a graphical output for error detection. Errors were located on CALCOMP plots of network data at the same scale as the original spatial input (Fig. 14). By overlaying the two spatial formats, data errors were quickly recognized.

From the edited numeric data, the W.A.T.E.R. System assigns the Strahler orders to all segments of the drainage network, determines segment lengths, basin perimeter and area, and calculates basin statistics. Shreve magnitudes, link lengths, and basin statistics are likewise calculated. The output of the W.A.T.E.R. System characterizes a drainage network geometry as interpreted from a specific imagery source.

Downstream studies: mapping the flood plain

The accelerating national demand for flood hazard information in downstream areas makes imperative an evaluation of alternative techniques to standard engineering flood line and regional flood analyses (Wolman 1971). Different mapping techniques may be appropriate to different localities depending on the local

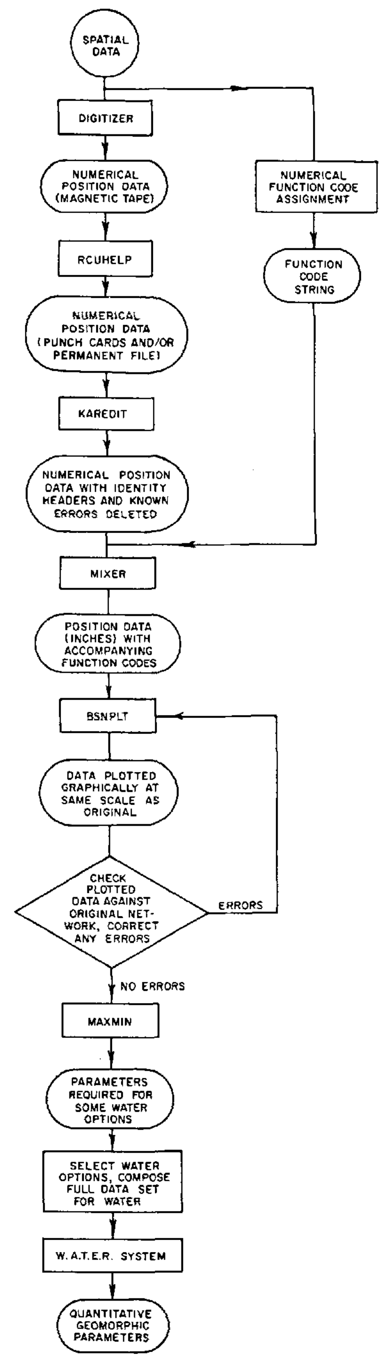


Figure 13. Flow chart of operations to transform spatial drainage network data to quantitative geomorphic parameters using the W.A.T.E.R. System (modified from Hulke 1976).

hydrologic regimen, the level at which planning is being performed, and the funds available to finance the study. A geomorphic approach to flood hazard mapping can be used effectively at the state-wide or regional scale to provide interim information prior to detailed hydrologic and hydraulic studies on a local basis. If included within an overall program of regional environmental geological mapping, morphological flood plain mapping can provide a relatively inexpensive by-product of a general program of environmental inventory based on the interpretation of remote sensing imagery.

Figure 14. CALCOMP plot of drainage network data used for detecting machine or operator errors encountered in the digitizing operation.

Alternative Approaches to Flood Hazard Mapping

Wolman (1971) noted that flood plains can be mapped by occasional flood, botanic, pedologic, and physiographic approaches. Traditional engineering hydraulic-hydrologic methods are generally considered to be the most desirable for planning and management purposes in urban areas (Wiitala and others 1961). However, these methods also tend to be the most expensive, costing as much as $1,000 per mile for delineating flood profiles by backwater curve analysis of large-scale topographic maps (Wolman 1971, p. 1384). In contrast, the mapping of topographic features or soil associations that may correlate to flood levels could cost as little as $1 to 4 per mile of channel (Wolman 1971).

The occasional flood method. This approach involves establishing flood lines on the basis of aerial photographs taken during flood events, historic evidence of floods, and local observation of flood heights (Wolman 1971). Remote sensing offers many advantages for providing wide coverage of inundated areas. Unfortunately, however, poor weather may inhibit aerial surveys of floods. Orbital space platforms for earth resource sensors have an important advantage in this regard. Their multidate photographs allow continuous monitoring of river conditions without necessitating emergency plans for aerial surveys of broad areas.

A striking example of the use of satellite imagery for occasional flood mapping occurred in the spring of 1973, when severe flooding affected the entire alluvial valley of the Mississippi River. Special optical data-processing techniques were used to produce a variety of multispectral composites of ERTS-1 imagery taken before, during, and after overbank flooding (Deutsch and Ruggles 1974). The entire lower Mississippi River from St. Louis to the Gulf of Mexico could be depicted in a single view. An important discovery was that the effects of flooding on the reflectance characteristics of the flood plain allow the delineation of areas from which flood water has recently receded. This eliminates the need for continuous monitoring of the flood crest (Deutsch and Ruggles 1974).

The botanic approach. Regional ecological studies (Blair 1950; Tharp 1926) suggest that some zonation of vegetatation occurs along the river valleys of the Edwards Plateau. The most distinctive zonal forms are baldcypress *(Taxodium distinchum)* and pecan *(Carya illinoensis)*. Baldcypress is hydrophilic with shallow, abundant roots that require a constant moisture supply, usually by submergence. The species only occupies the low-flow channel banks of streams with a permanent base flow. (Lines of dead baldcypress occasionally mark former channels isolated by meander cutoffs.) Pecan is a dominant species in the alluvial zones bordering low-flow channels. Pecan is confined to areas of well-drained loamy soils not subject to prolonged flooding, termed "pecan bottoms," by local residents. At Stonewall, Texas, one such pecan bottom was completely removed from the point bar of a Pedernales River meander by the 1952 flood. Trees and supportive soil were scoured, leaving a flat bedrock surface.

American sycamore *(Platanus occidentalis)*, eastern cottonwood *(Populus deltoides)*, and black willow *(Salix nigra)* grow in close proximity to stream bottoms, but unlike baldcypress they occur along ephemeral tributaries. The shallow roots of the black willow require a constant moisture supply during the growing season. Unlike the pecan, American sycamore may extend from flat-lying bottomlands up relatively steep slopes where the water supply is sufficiently abundant. The alluvial soil zones, including wetter terraces and well-drained flats on active flood plains, contain pecan, hackberry *(Celtis laevigata)*, Spanish oak *(Quercus shumardii)*, elm *(Ulmus americana)*, black walnut *(Juglans nigra)*, and large live oaks *(Quercus vir-*

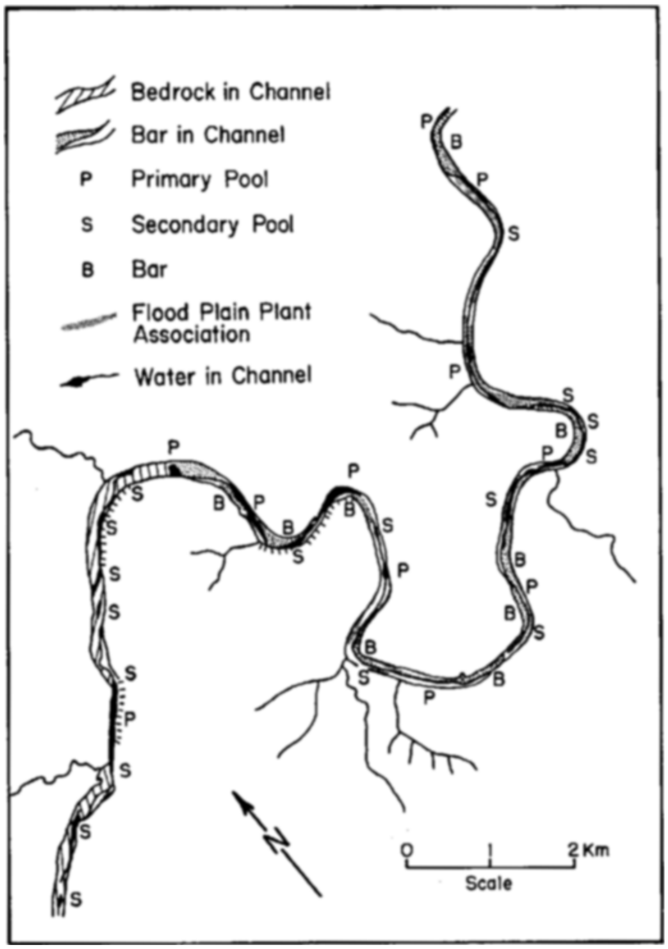
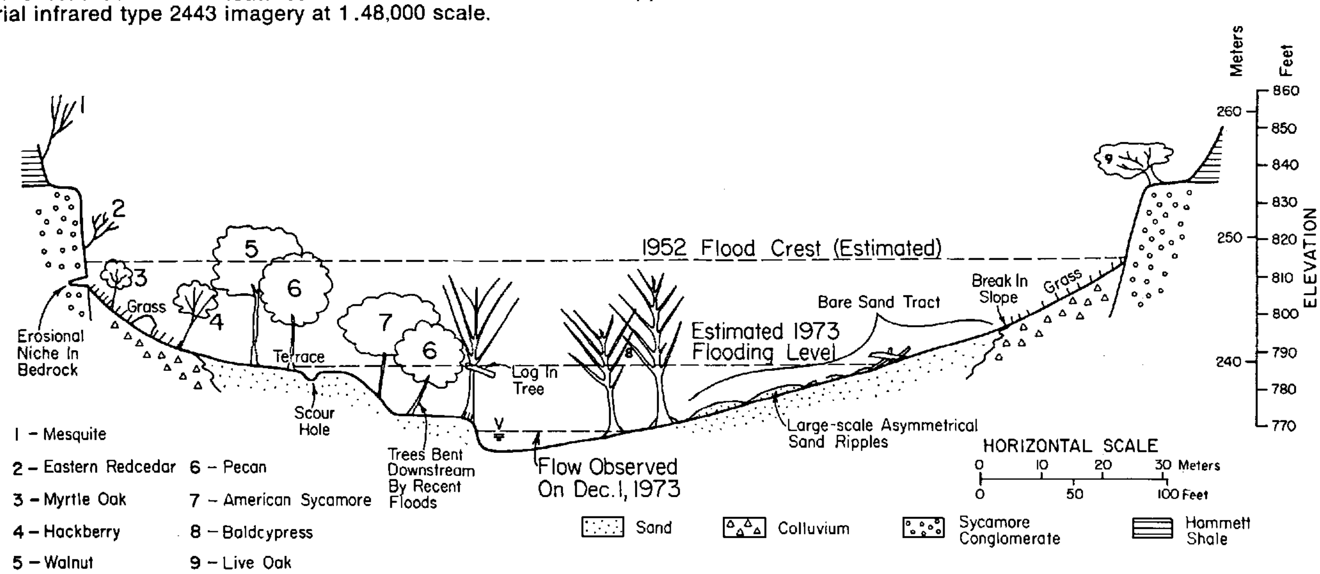


Figure 15. Flood-related features in the Pedernales Falls area mapped from NASA aerial infrared type 2443 imagery at 1.48,000 scale.

Figure 16. Schematic cross-section of Pedernales River valley at Trammel Crossing, Pedernales Falls State Park; vegetation associations and geomorphic features based on field observations by V. R. Baker, P. C. Patton, and P. A. Smith.



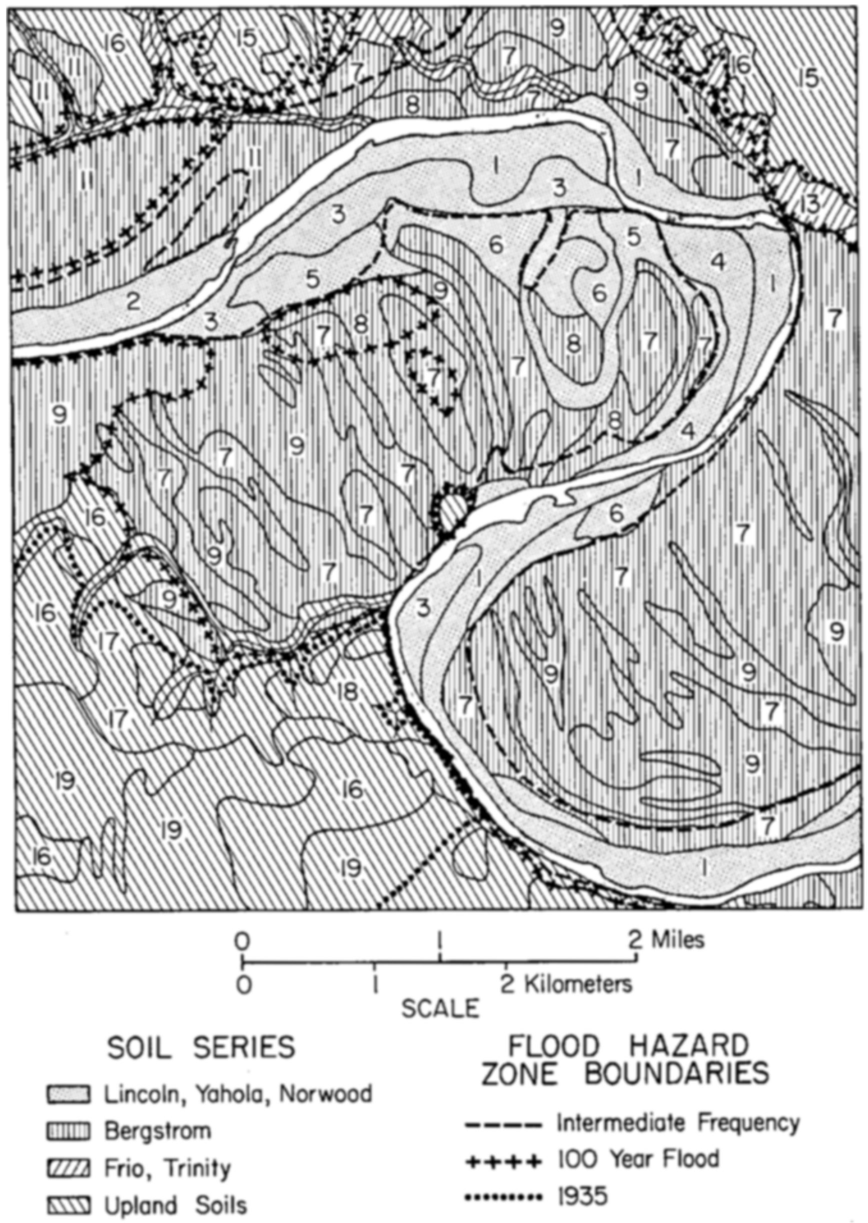


Figure 17. Soils of Montopolis Bend area, Colorado River valley near Austin, Texas. Soil associations are compiled and grouped from mapping by Werchan, Lowther, and Ramsey (1974). Soil series are as follows: (1) Lincoln loamy fine sand; (2) Lincoln soils under urban land; (3) Yahola very fine sandy loam; (4) Yahola soils, channeled; (5) Norwood silty clay loam; (6) Norwood soils, channeled; (7) Bergstrom silt loam, 0–1% slopes; (8) Bergstrom silt loam, 1–3% slopes; (9) Bergstrom silty clay loam, 0–1% slopes; (10) Bergstrom silty clay loam, 1–3% slopes; (11) Bergstrom soils and urban land; (12) Frio silty clay loam; (13) Ferris-Heiden complex, 8–20% slopes; (14) Trinity clay; (15) Travis soils and urban land, 1–8% slopes; (16) Houston Black soils; (17) Heiden clay; (18) Dougherty loamy sand; (19) Lewisville silty clay.

giniana). However, not all these species are distinctive. The live oaks extend up nearby limestone ledges, where they mix with Spanish oak, white ash *(Fraxinus americana),* red mulberry *(Morus rubra),* and Texas black walnut *(Juglans microcarpa).* They also occur on the vast limestone interfluves in association with juniper *(Juniperus virginiana),* prickly pear *(Opuntia lindheimeri)* and mesquite *(Prosopis glandulosa).* Black walnut tolerates thinner soils and lower moisture than pecan, while Texas black walnut tolerates even drier habitats such as the limestone ledges adjacent to bedrock streams. Spanish oak, in contrast, remains in the well-drained soils of alluvial terraces and colluvium near active streams.

Preliminary biologic assemblage mapping by The University of Texas Bureau of Economic Geology (Wermund and Waddell 1974) has shown that the bottomland cypress-pecan assemblage can be easily recognized in the process of environmental geologic mapping from aerial photography. However, the factors which control the zonation of vegetation on Texas river bottom environments are quite complex. Particular combinations of soil conditions and water supply appear to be the dominant controls. Because flooding is not a cause of the zonation, botanical flood studies must be combined with other techniques for flood hazard evaluation.

In the Pedernales Falls area (Fig. 15) the flood plain botanic association was clearly visible as a light pink response on aerial infrared photography. Pools of deep water along the discontinuous river course could also be easily mapped from their distinctive deep blue response. Areas of exposed bedrock in the channel bottom and bars of sand and gravel appeared bright white on the imagery. These frequently flooded zones presented a dramatic contrast to the dull green of adjacent grassy hillslopes and the maroon response of local clusters of juniper and live oak in the uplands. Field investigations near Pedernales Falls revealed that the principal trees giving the pink response were American sycamore, pecan, water hickory, and myrtle oak. The darker, maroon response of vegetation on the hillslopes and interfluves was given by eastern redcedar, juniper, and live oak. A generalized cross section showing the field-botanic associations and past flood levels is given in Figure 16.

Soils method. Wolman (1971) suggested that locally both soils and topography may correlate with specific flood heights. Distinctive flood plain soils have been studied by Cain and Beatty (1968), Ruhe (1971), and Reckendorf (1973). Reckendorf (1973) found that the soils technique did an adequate job of delineating areas in Oregon flooded by the 100-year return period event when individually mapped soils or groups of soils were compared to hydrologic studies of flood frequency. The principal use of the technique was in extending information from points of known gage data or historical flood elevations to other localities characterized by the same soil-geomorphic associations. Reckendorf concluded, however, that a better extrapolation could be obtained by geomorphic mapping of stair-stepped flood plain surfaces on the basis of "typical flood plain morphologic features."

Detailed soil survey maps prepared by the U.S. Soil Conservation Service often provide information on various grades of wetness related to soil permeability or to surface and subsurface drainage conditions. Although the maps do not show actual coverage of water during floods of known frequency and elevation, local correlations can sometimes be drawn. The 100-year flood for the Colorado River near Austin, Texas, for example, shows considerable correlation to certain soil series mapping units (Fig. 17).

Geomorphic method. Geomorphic techniques for flood plain mapping should not be confused with simple physiographic correlation of specific topographic features with flood discharges of known frequency (e.g., Kilpatrick and Barnes 1964; Woodyer 1968). These involve the more extensive investigation of morphology, sedimentology, distinctive erosional features (Baker 1974), time sequences of channel abandonment, and the compilation of existing pedologic, botanic and hydrologic information. This concept is similar to Reckendorf's "combination

Figure 18. Location of the Colorado River flood hazard mapping projects.

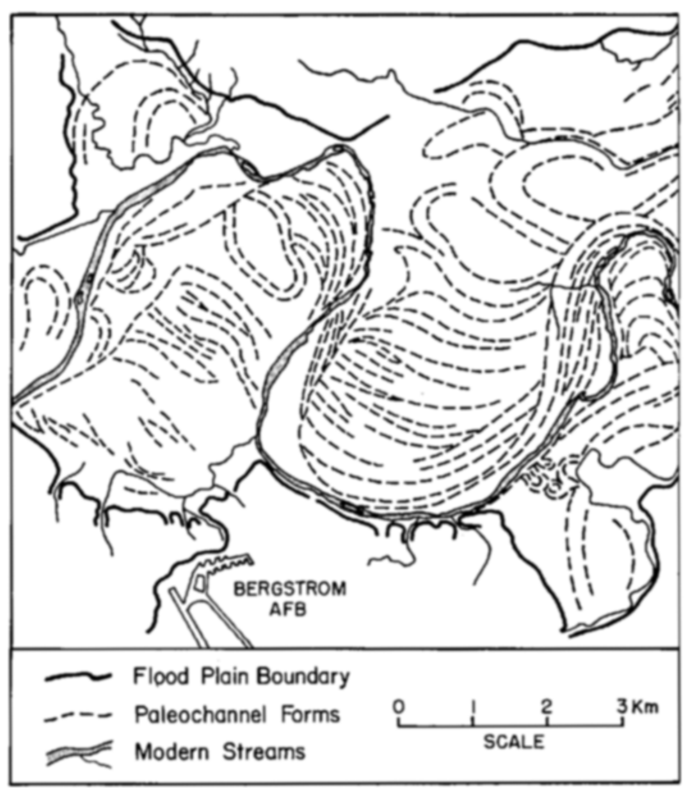


Figure 19. Colorado River flood plain features near Austin, Texas, mapped from high altitude color aerial infrared imagery (Film Type SO-117). Mission was flown by the NASA Colorado River-Brazos River Experiment on December 11, 1969, using the RC8/4R sensor.

method" for the construction of flood plain maps in Oregon (1973). Reckendorf developed a base map by mapping typical geomorphic flood plain features (*see* Fisk 1944; Jahns 1947; Lueder 1959) and associated terraces from aerial photography and selected field studies. The available soils, vegetational, historical flood, and hydrologic-hydraulic information can then be superimposed on the geomorphically delineated flood plain. The skilled investigator will use each technique to check and balance the other. Reckendorf found that there is in general a strong correlation between geomorphic flood plain surfaces and river stages for floods of particular frequencies, especially the 100-year average recurrence interval event. The geomorphic approach to flood hazard delineation should include inventories of historical flood marks on the ground surface, aerial photographs of actual flood events, and local interpretations of existing stream gaging data. It should also be a subjective appraisal of all existing physiographic, botanic, pedologic, occasional flood, and regional hydrologic studies to be done by skilled scientists as a part of a regional environmental inventory.

An Illustration of Hydrogeomorphic Flood Hazard Mapping Using Orbital Remote-Sensing Imagery

As a test of the hydrogeomorphic method of flood plain mapping, a study was initiated of the Colorado River valley between Austin and La Grange, Texas (Fig. 18). The channel forms of the Colorado's valley were mapped from NASA-generated high altitude color aerial infrared (Type SO117) photography (1:116,000 scale). The map (Fig. 19) revealed crosscutting relationships for distinct assemblages of channel patterns associated with multiple levels of the Colorado River flood plain. The imagery easily distinguished these channel forms from upland physiography and from modern active channels of the Colorado River.

Comparison of the mapped channel forms to historic and hydrologic regional flood lines (Fig. 20) shows that the low sinuosity channels on the older terraces

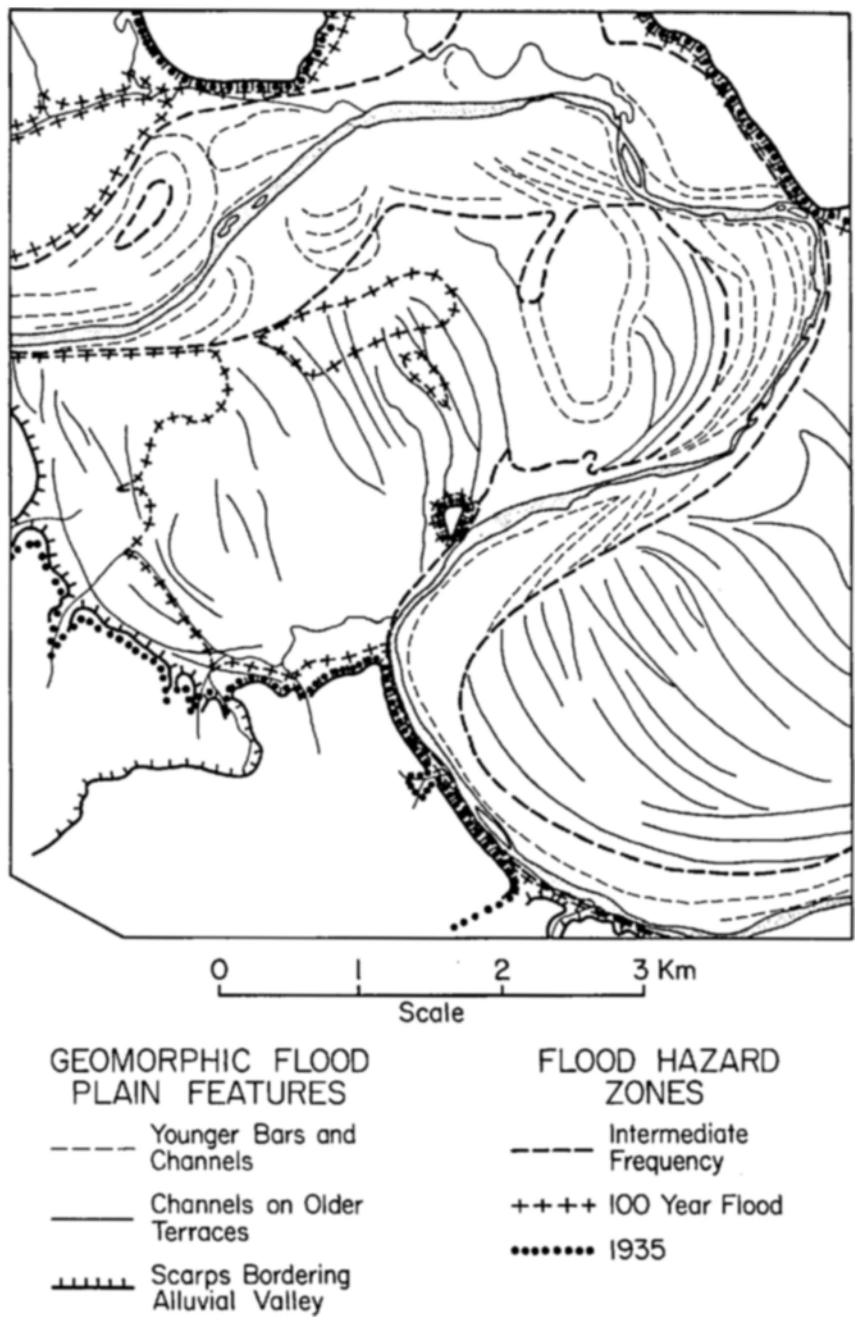


Figure 20. Comparison geomorphic flood plain features of the Colorado River to regional flood lines from historic and hydrologic surveys.

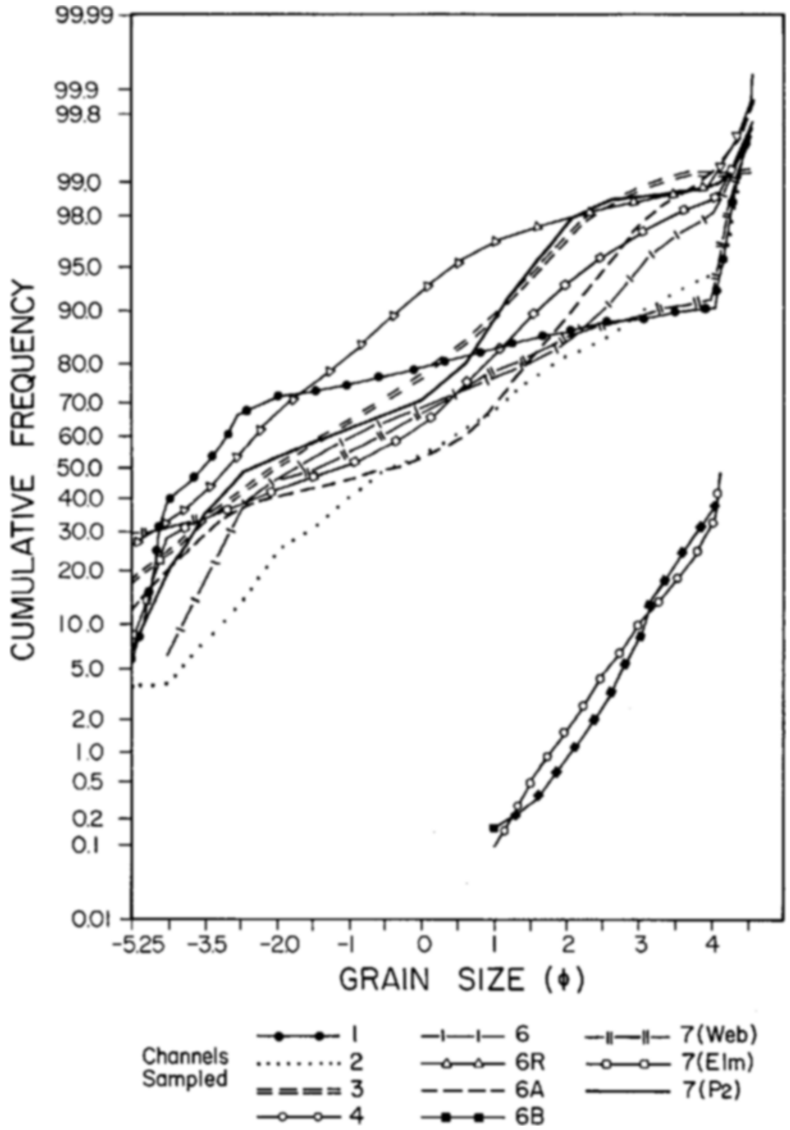


Figure 21. Cumulative frequency curves of grain size for ancient channels of the Colorado River near Austin, Texas.

are flooded by extremely rare, high magnitude events (e.g., the 100-year flood). The distinctive younger bars and channels are flooded with much greater frequency, probably in the 2 to 15-year recurrence interval range. An upper boundary to flood hazard zone is provided by the scarps bordering the alluvial valley of the Colorado River. Water from the largest historic Colorado River flood reached this margin in 1935.

The channel patterns (Figs. 19 and 20) appear to result from the variation in soil types (Fig. 17). Grain size variations were controlled by the changing regimen of the ancient Colorado River (Baker and Penteado 1975). Figure 21 illustrates the contrast in sediment load transported by high sinuosity phases (4 and 6B) and by low sinuosity phases (1, 2, 3, and the channel 6 and 7 complexes). Coarser sediments result in greater permeability, lower soil moisture, and, therefore, a lighter response on infrared imagery. Finer sediments result in lower permeability, higher soil moisture retention, and, therefore, a darker response on infrared imagery.

Other hydrogeomorphic flood plain studies using remote-sensing imagery

A striking opportunity for the application of multi-date photography to a flood event was afforded by the flooding of May 11 and 12, 1972, near New Braunfels, Texas. Around 8:00 p.m. on May 11, 1972, a series of intense thunderstorms formed southwest of New Braunfels, Texas, and moved northeastward along the Balcones Escarpment. The center of the storm had about 40 cm of rainfall. Reports from local residents indicated that the storm only lasted four hours and spread an average of perhaps 20 cm over 800 km². Fragmentary evidence of the time distribution of the rainfall indicates that nearly 75 percent fell during the most intense hour, between 8:40 p.m. and 9:40 p.m. on May 11.

The stream gage on the Comal River recorded much of the storm runoff (Fig. 22). Some of the most intense rail fell on the catchment of Blieders Creek, a tributary to the Comal River. Blieders Creek was the closest of the streams contributing runoff from the Balcones Escarpment to the stream gage. The gage recorded the passage of the flood crest from Blieders Creek at 11:45 p.m. on May 11. This represents a lag time of approximately 3 hours between the centers of mass for the rainfall distribution, and for the flood hydrograph respectively. The crest rose 2.3 meters in 15 minutes, and 9.1 meters in 1 3/4 hours. The second peak on (Fig. 22) was caused by runoff that followed the longer flow path along Dry Comal Creek to the stream gage. That crest was delayed until 5:30 a.m. (May 12).

A field study of flood scour and deposition for the 1972 New Braunfels flood revealed spectacular effects along Blieders Creek. Prior to the thunderstorm cloudburst the valley floor was mostly covered by an organic soil and turf layer 15 to 25 cm in thickness that had developed on coarse stream gravels marginal to the low-flow channel. Low brush, scrub oak, and large deciduous trees characterized the channelway (Fig. 23a). The estimated peak flood discharge of 1370 m^3/sec (48,400 cfs) for the 39 km^2 catchment area resulted in widespread devastation to the vegetation and soil cover. The combination of scour, along with coarse cobble and boulder deposition, created a bare valley bottom exposing white limestone bedrock and fresh alluvium (Fig. 23b). Preflood and postflood channel cross sections show that scour occurred in the deeper portions of the channel, probably at mean flow velocities of 2 – 3 m/sec. Deposition of gravel berms, similar to those observed by Scott and Gravlee (1968) occurred along the channel margin. Pebble counts revealed that the mean intermediate diameter of the deposited bedload was 2.5 to 5 cm. Boulders as large as 2 m in diameter were transported for short distances by the flood flows.

The Blieders Creek erosion has not been modified by subsequent lower discharges as has been described for the effects of Hurricane Agnes flooding in the humid northeastern United States (Costa 1974). The morphology of the rock channel of Blieders Creek appears to be adjusted to relatively infrequent, high magnitude controlling discharges. Tinkler (1971) suggested that the mor-

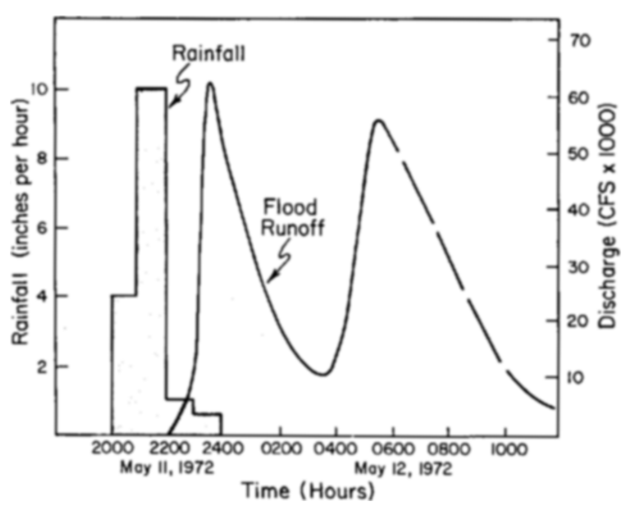


Figure 22. Rainfall and runoff for Comal River at New Braunfels, Texas, flood of May 11 and 12, 1972. Rainfall distribution assumes that 40 cm recorded maximum was time-distributed according to a unit distribution of storm rainfall recorded at Canyon Dam (Colwick, McGill, and Erichsen 1973). Runoff was computed by the U.S. Geological Survey from visual observations of water surface elevations at regular time intervals.

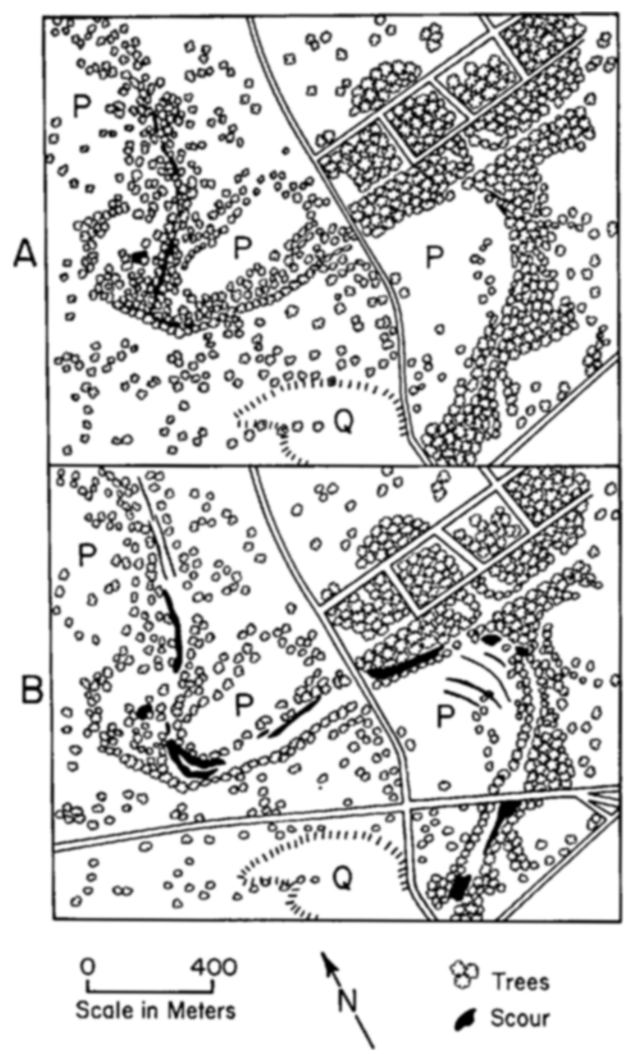


Figure 23. Geomorphic effects of the 1972 flood along Blieders Creek, (a) as mapped from a vertical aerial photograph (U.S.D.A. BQU-2v-161) of Blieders Creek taken in February 1958. The active channel is somewhat obscured by grass and soil. Note the extensive brush and tree vegetation along the stream course. Lower portion (b) as mapped from a high altitude infrared photograph.

Figure 24. NASA infrared aircraft imagery of the Guadalupe River canyon below Canyon Dam and upstream from New Braunfels, Texas. The bright response areas are alluvium and scour in tributary stream valleys resulting from flooding of May 11 and 12, 1972. Frame depicts a scene 3 × 5 km.

phology of central Texas streams, especially their meander wavelength, was adjusted to flood discharges that have a recurrence interval between 10 and 50 years.

The striking bright response of recently flooded stream bottoms in the New Braunfels area (Fig. 24) indicates that many post-flood effects remain clearly visible by remote sensing as much as 2 years after a flood event. The coarse, white limestone debris transported by a flood remains as a channel lag and is not appreciably modified by lower discharges. The response of this debris is clear enough to even be recognized by orbital imagery. (Fig. 25).

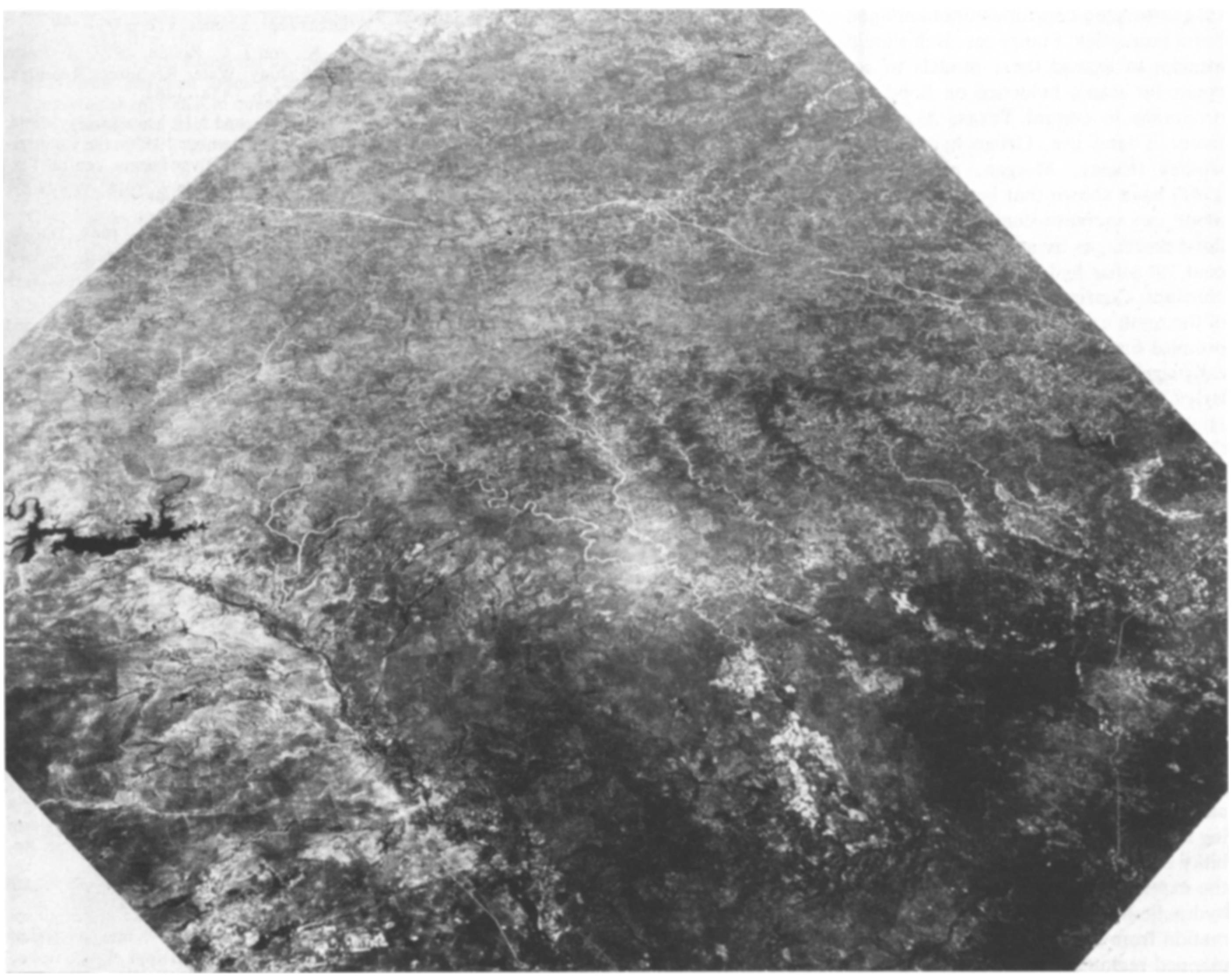
Conclusions

Central Texas is a region of high magnitude and variable flood responses that has posed many problems for the evaluation of flood potential by traditional hydrological methods (Benson 1964). A rational model, emphasizing the permanent hydrogeomorphic controls on flood hydrographs, may be a practical alternative. The basis of the approach is the measurement of drainage basin, network, and channel characteristics from various kinds of remote-sensing imagery. By the use of machine-assisted measurement and computer processing of data, many of the objections to this hydrogeomorphic approach can be overcome. The most significant hydrogeomorphic controls were found to be drainage density, drainage area, and Shreve magnitude.

Measures of network resolution such as drainage density and basin Shreve magnitude indicated that large-scale topographic maps (1:24,000) offered greater resolution than small-scale suborbital imagery (1:48,000 and 1:123,000) and orbital imagery. However, detailed field surveys of high-relief drainage basins revealed that even networks developed from topographic maps failed to record some second-order and many first-order streams. The disparity in network resolution capabilities between orbital and suborbital imagery formats (including topographic maps) depends on factors such as imagery scale, rock type, vegetation, land use and valley morphology. For a given relief ratio, drainage network results from Skylab Orbital orbital imagery appear to conform proportionately to the topographic map base data. Moreover, in the low-relief basins of the inner Coastal Plain, such as Wilbarger Creek, orbital network definition is nearly as accurate as topographic map definition.

Geomorphic analysis of remote sensing imagery has a broad range of uses in a variety of flood plain mapping approaches. Studies of the Colorado River valley near Austin, Texas, easily distinguished the boundary between upland physiography and active flood plain. In addition, the recognition of paleochannel patterns associated with higher, less active portions of the flood plain allowed a distinction to be made between infrequent, intermediate, and frequent hazard zones. NASA-generated aerial infrared imagery, type 2443, at a scale of 1:48,000 was found to be useful for botanic and geomorphic flood hazard

Figure 25. Oblique S-190A photograph of the Balcones Escarpment from Lake Amistad (left) to San Antonio (right). Bright response of river channels on the Edwards Plateau clearly delineates effects of recent flooding. Frame depicts a scene 320 km across.



mapping along both the deeply entrenched bedrock streams of the Edwards Plateau and the broad alluvial flood plain or the Colorado River east of the Balcones Fault Zone. These mapping techniques can provide rapid regional evaluation of flood hazards much more quickly than standard engineering-hydraulic approaches. Where a significant economic threat is identified in a local area, the regional remote-sensing studies can be supplemented by the time-consuming, but more accurate engineering approaches.

This study concentrated on the natural geomorphic controls on network and basin properties. Future research should attempt to extend these models to account for man's influence on flood hydrographs in central Texas. A critical factor is land use. Urban hydrological studies (Espey, Morgan, and Masch 1966) have shown that land use factors alone can increase central Texas peak flood discharges by as much as 300 percent, all other hydrological factors held constant. Continuous orbital monitoring of the earth's surface holds considerable promise for the depiction of hydrologically significant land use factors, particularly in areas of rapid change such as the Highland Lakes region of central Texas. Other factors which require evaluation in such regional hydrological studies include: (1) wavelength of valley and channel meanders, (2) distribution, type and density of vegetation, (3) distribution of exposed bedrock and caliche, (4) estimation of relief, and (5) distribution of roads, fence lines, drainage ditches, and other human disruptions of the natural drainage geometry.

Hydrogeomorphic methods offer a powerful potential to aid certain aspects of solving the "map gap" that plagues flood plain management. Specifically, it can aid in the following ways: (1) depicting features that indicate flood susceptibility over very large areas, (2) allowing the extension of detailed but expensive hydraulic-hydrologic flood plain information from local areas into larger unmapped regions, (3) providing the basic flood hazard information in hydrologically data-sparse regions, and (4) establishing "upstream" flood-response models.

The true promise of hydrogeomorphic analysis will probably be realized when the output of aircraft and satellite scanning equipment will feed directly into a computer system capable of automatic drainage network recognition and automatic computation of morphometric parameters. This will eliminate the need for operator scanning of imagery, even when assisted by pencil following and digitizing equipment. Before this is feasible, however, considerable manual testing will be required to establish the ground truth for apparent drainage network patterns on the imagery and to evaluate the effects of scale on the hydrological utility of hydrogeomorphic parameters.

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