FLOODING ALONG THE BALCONES ESCARPMENT, CENTRAL TEXAS

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> A few days before the rains began to fall, a band of Tonkawa Indians that were camped in the river valley just below old Fort Griffin moved their camp to the top of one of the nearby hills. After the flood, on being asked why they moved to the top of the hill, the chief answered that when the snakes crawl towards the hills, the prairie dogs run towards the hills, and the grasshoppers hop towards the hills, it is time for the Indian to go to the hills. (Oral testimony attributed to an unnamed weather observer in Albany, Texas, following a memorable flood on the Clear Fork of the Brazos River in the late 1870's; recounted by Vance, 1934, p. 7.)

ABSTRACT

High-magnitude floods occur with greater frequency in the Balcones Escarpment area than in any other region of the United States. Rates of precipitation and discharge per unit drainage area approach world maxima. The intensity of rainstorms is compounded by rapid runoff and limited infiltration, producing episodic flooding. Effects of urbanization may be superimposed on meteorologic and physiographic factors, thereby increasing flood hazards in metropolitan areas throughout the region.

INTRODUCTION

The Balcones Escarpment area, comprising parts of the Edwards Plateau, Hill Country, and northern and westernmost Coastal Plains (fig. 1), is one of the most severely flooded regions of the United States (Leopold and others, 1964, fig. 3-16; Baker, 1975; Beard, 1975, fig. 13; Crippen and Bue, 1977, fig. 12, table 1; Patton and Baker, 1976, p. 945, fig. 5). Floods of record include the catastrophic 1954 inundation of the lower Pecos River valley where peak instantaneous discharge approached 1,000,000 cubic feet per second (cfs), or more than 600 billion gallons per day (International Boundary and Water Commission, 1954). This reach of the Pecos normally is an intermittent stream completely dry for several months each year. But during the 1954 event, its rate of discharge was more than 1 1/2 times mean flow of the world's third longest river, the Mississippi (table 1). What's more, only part of the Pecos drainage basin had received significant rainfall and provided runoff; the contributing area was less than 0.3 percent of the Mississippi's watershed.

The 1954 Pecos River flood was a remarkable occurrence, estimated to represent the 2,000-yr recurrence interval flood (0.05 percent yearly-probability flood) in that basin (Kochel and others, 1982, p. 1179). This and other major discharge events are easily and instructively compared by examining the ratio of peak discharge (in cfs) to contributing drainage area (in mi^2). During the 1954 flood of the Pecos, this ratio was approximately 261:1, compared to 0.5:1 for mean discharge of the Mississippi (table 1). Although the rate of peak discharge of the Pecos was exceptional, floods yielding comparable discharge:drainage area ratios have been recorded in most drainage basins and subbasins in Central Texas. Intense rainstorms over small watersheds throughout the region have produced numerous examples of discharge in excess of 100,000 cfs. Flooding of this magnitude exacts a heavy toll from area residents who incur the high cost of flood-control structures on trunk streams (fig. 1), but also sustain casualties and damages associated with floods on small, unregulated or under-regulated tributaries.

CAUSE OF MAJOR FLOOD EVENTS

Baker (1975; 1977) and Patton and Baker (1976) described a number of factors that contribute to flooding in the Balcones Escarpment area. Principal among these are: (1) the intensity of sporadic rainstorms, particularly those associated with incursions of tropical storms and hurricanes; and (2) the high-percentage yield and rapidity of runoff from the steep bedrock slopes that characterize much of the region. (NOTE: Meteorologic conditions in the Central Texas region are discussed in greater detail in another section of this guidebook and in references cited here.) To these factors may be added the many drainage problems inherent in urban areas including large municipalities along the Balcones Escarpment (fig. 1). Although not unique to Central Texas, the role of urbanization in flood enhancement is especially significant when superimposed on adverse characteristics of the natural environment of this region.

Meteorologic Factors

Easterly Waves

The climatic provenance and topography of Central Texas, and its proximity to the Gulf of Mexico, combine to make the incidence of torrential rains in the area extremely high. The region lies within the zone of convergence of polar air masses and easterly waves (Orton, 1966, p. 10-11). Polar air is characterized by cool temperatures, high pressures, and low moisture. Easterly waves, which are westward-moving troughs of low pressure, convey warm, moist air of tropical origin. When a well-developed easterly wave approaches a lobe of high-pressure, such as that associated with a strong polar surge into middle latitudes, pronounced instability and heavy rains may result.

in Abbott, Patrick L. and Woodruff, C.M., Jr., eds., 1986, **The Balcones Escarpment, Central Texas:** Geological Society of America, p. 1-14

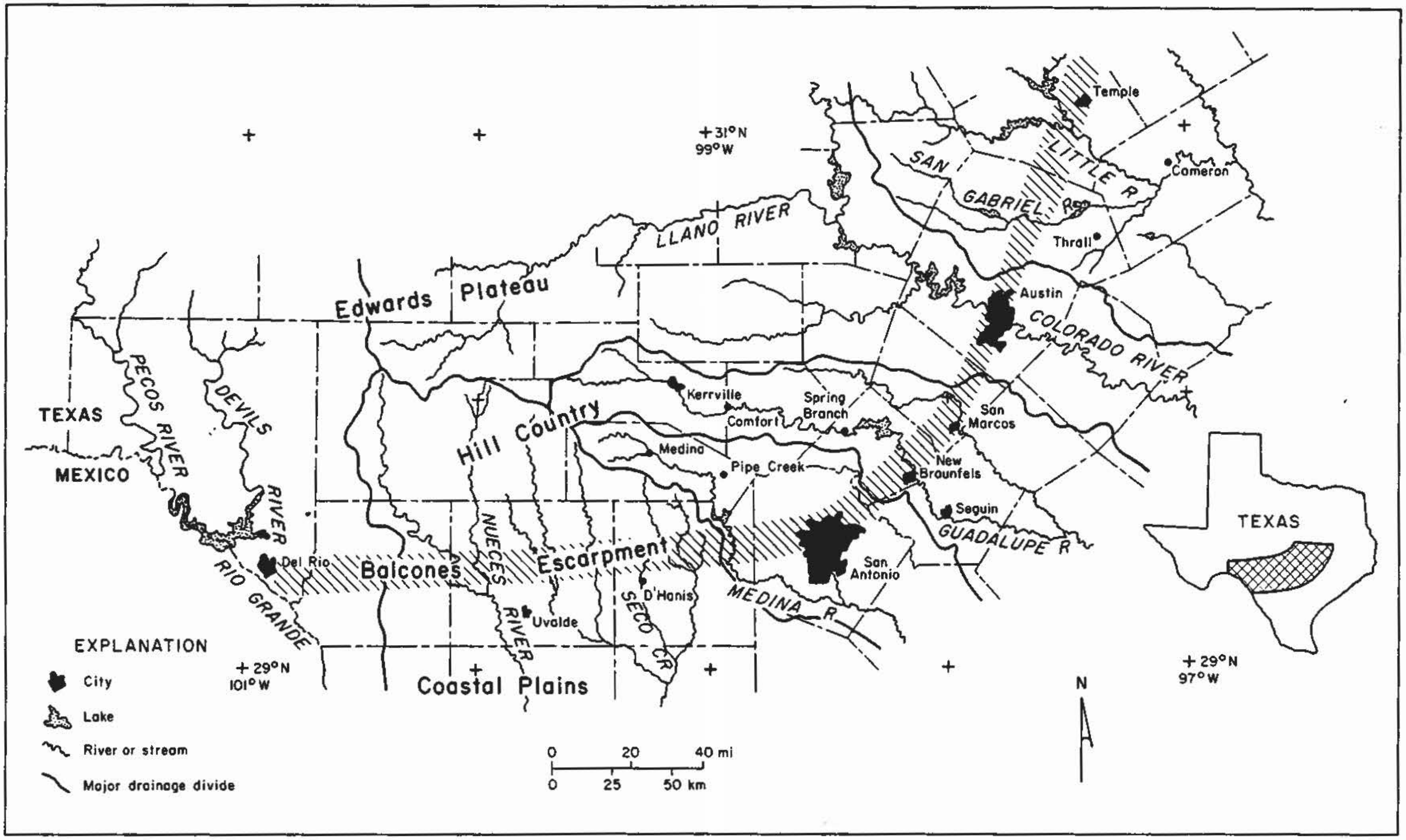


Figure 1. Balcones Escarpment area, Central Texas. Only major streams and those mentioned in text are named. Relief across the Balcones Escarpment varies from 100 to 500 ft.

Table 1. Representative flood discharge of Central Texas streams compared with mean discharge of some of the world's great rivers

River/stream	(A) Drainage area (x 10^3 mi^2)	(B) Discharge (x 10^3 cfs)	Ratio B:A
Amazon[1]	2,722.[a]	4,200[b]	2:1
Nile[2]	1,293.[a]	110[b]	0.1:1
Mississippi-Missouri[3]	1,243.7[a]	620[b]	0.5:1

Texas

(Source: International Boundary and Water Commission, 1954; Crippen and Bue, 1977; Schroeder and others, 1979; Moore and others, 1982)

Pecos (U.S. Hwy 90, 1954)	3.7[c]	967[d]	261:1
Little (Cameron, 1921)	7.1[c]	647[d]	91:1
North Prong of Medina (Medina, 1978)	0.07[c]	123[d]	1,800:1
Medina (Pipe Creek, 1978)	0.5[c]	281[d]	600:1
Guadalupe (Comfort, 1978)	0.8[c]	240[d]	300:1
Guadalupe (Spring Branch, 1978)	1.3[c]	158[d]	122:1
Seco (D'Hanis, 1935)	0.14[c]	230[d]	1,500:1
Walnut (FM Hwy 1325, 1981)	0.01[c]	15[d]	1,500:1

[1] World's largest drainage area and discharge; second longest
[2] World's longest; fourth largest drainage area; tenth largest discharge
[3] World's third longest; fifth largest drainage area and discharge
(Source: National Oceanic and Atmospheric Administration, 1971)

[a] Entire basin
[b] Mean discharge at mouth
[c] Contributing portion of drainage area
[d] Flood discharge at point of measurement

This combination is comparatively uncommon but has produced extremely heavy rains and associated flooding. The most severe rainstorm ever recorded in the continental United States occurred under these conditions on September 9 and 10, 1921, in Thrall, Williamson County (Jennings, 1950; Bowmar, 1983, p. 69) (fig. 1,2). A total of 36.4 inches of rain fell in 18 hr, which is the world's record for this period. The 24-hr total was 38.2 inches, exceeding in one day the expected precipitation of an entire year (Larkin and Bowmar, 1983, p. 18). At the town of Cameron, Milam County, a few miles northeast of Thrall, peak discharge of the Little River was 647,000 cfs from a drainage area of 7,088 mi^2 (Crippen and Bue, 1977, table 1) (figs. 1, 3; table 1). This storm, which spread over a large area of Central Texas, produced 215 deaths and 19 million dollars in property damage (Bowmar, 1983, table E-3).

Orographic Effects

The easterly wave that produced the Thrall storm of 1921 was augmented by topographic conditions in the region. Relief across most of the Balcones Escarpment ranges from 100 to 500 ft (fig. 1 caption). Warm, moisture-laden air from the Gulf of Mexico is pushed northward across the gently sloping Coastal Plains by dominant southerly winds. As these winds encounter the escarpment they rise abruptly to higher altitude. If the Gulf air is nearly saturated at lower elevations, rainstorms may occur along the escarpment because of orographic cooling of the air mass. The climate of Central Texas is semiarid; drought years offset wet periods, thereby reducing mean annual precipitation. But cumulative rainfall increases sharply at the escarpment compared to adjacent regions (fig. 4), and rains may be extremely intense for periods of

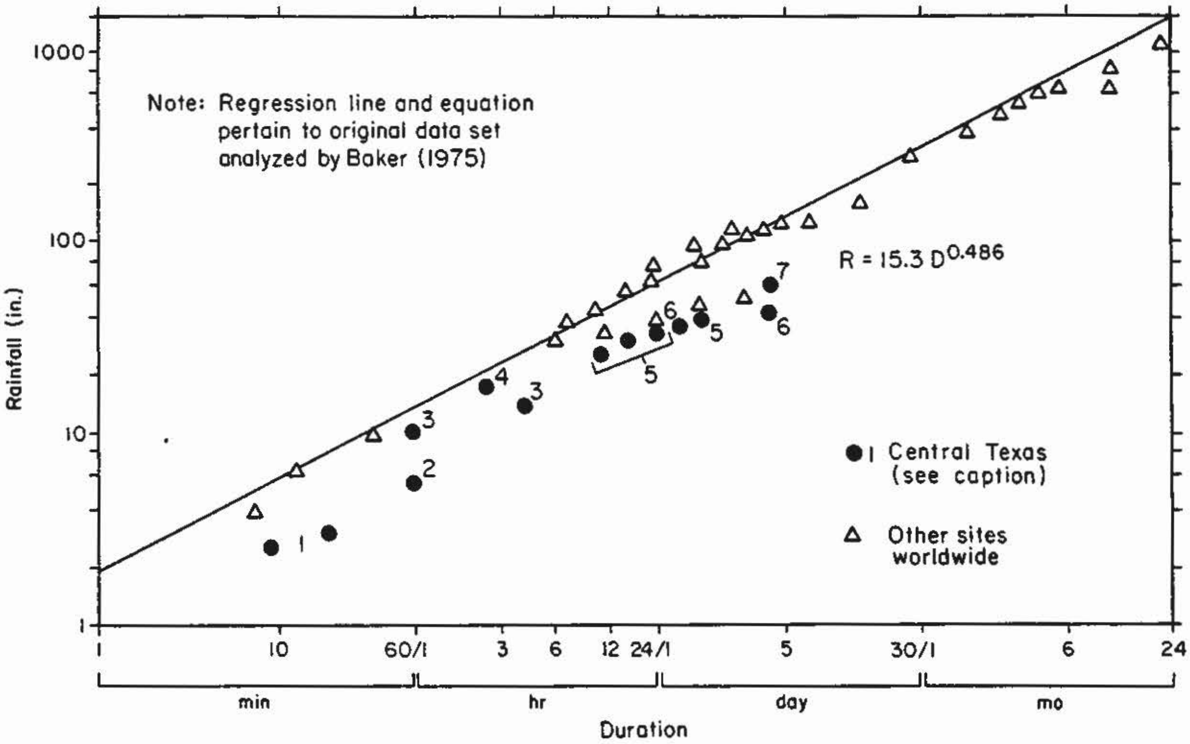


Figure 2. Magnitude-duration relationships of the most intense rainstorms in Central Texas and the rest of the world. Sites in Central Texas: (1) Trough Creek, 1973; (2) Austin, 1981; (3) New Braunfels, 1973; (4) D'Hanis, 1935; (5) Thrall, 1921; (6) Voss Ranch, 1978; (7) Manatt Ranch, 1978. Adapted from Baker (1975, fig. 2). Additional data sources: Hansen (1979); Massey and others (1982, table 2); Moore and others (1982, figs. 2.2, 2.4); and sources cited by Baker (1975, fig. 2).

hours to days over small areas (Carr, 1967, p. 20-21; Bowmar, 1983, p. 56). An astonishing example of this orographic effect is the storm of May 31, 1935, near D'Hanis, Medina County (Jennings, 1950; Morgan, 1966, p. 37, 40) (fig. 2). A total of 22 inches of rain fell in just 2 hr and 45 min, which is the world-record precipitation for that period. At a point a few miles above D'Hanis, Seco Creek has a drainage area of only 142 mi^2 yet briefly discharged at a rate of 230,000 cfs (Crippen and Bue, 1977, table 1) (table 1; fig. 3).

Tropical Disturbances

Tropical storms and hurricanes are regular seasonal occurrences over the warm waters of the Caribbean and Gulf of Mexico. Their paths do not often extend far inland but occasional storms penetrate well into the interior of the state and beyond. Some of the Central Texas region's heaviest rainfalls are products of these events. A recent example is tropical storm Amelia, which produced catastrophic flooding throughout the area in August, 1978. The largest three-day total rainfall ever recorded in the United States occurred on the Manatt ranch, Medina County, where more than 48 inches of rain fell during the period August 1 to 3 (Hansen, 1979) (fig. 2). Near this ranch, on the North Prong of the Medina River, peak discharge was 123,000 cfs from a drainage area of 67.5 mi^2 (Schroeder and others, 1979, p. 6) (table 1; fig. 3). Farther downstream, discharge of the Medina River near Pipe Creek was 281,000 cfs from a drainage area of 474 mi^2 (Schroeder and others, 1979, p. 111). Medina Lake near San Antonio overflowed its spillway as storage increased by 93,000 acre-feet in 35 hr (Schroeder and others, 1979, p. 6). Flood stages at 13 stations exc
previous records and/or projected stages of floods wit
recurrence intervals greater than 100 yr (Sullivan, 198
47).

Physiographic Factors and Urbanization

Climatic factors control precipitation but once ra
reaches the ground it is the character of the land its
that controls runoff. The Balcones Escarpment area
steep sparsely-vegetated slopes, narrow valleys, thin u
soils on limestone bedrock, and, in the Coastal Plain
with low infiltration capacity (Baker, 1975, 1976, 197
Patton and Baker, 1976) (fig. 5). Each of these fac
increases runoff and, therefore, discharge per unit dra
area. Development practices in metropolitan areas al
tend to increase runoff but may reduce flow through
stream channels, as well. Urbanization generally incr
(1) impervious cover (that is, the areal extent of roo
parking lots, and roadways that reduce infiltration); (
channel rectification (reduces channel storage thereby
increasing discharge farther downstream); (3) channel
obstruction (causes damming behind bridge abutments
water crossings, waterside recreational facilities, etc.);
(4) floodplain development (inhibits high-water throug
(Leopold and others, 1964; Costa, 1978; Morisawa ar
LaFlure, 1979; Rahn, 1984). Espey and others (1966
demonstrated that land-use practices alone can increa
Central Texas peak flood discharges by as much as
percent.

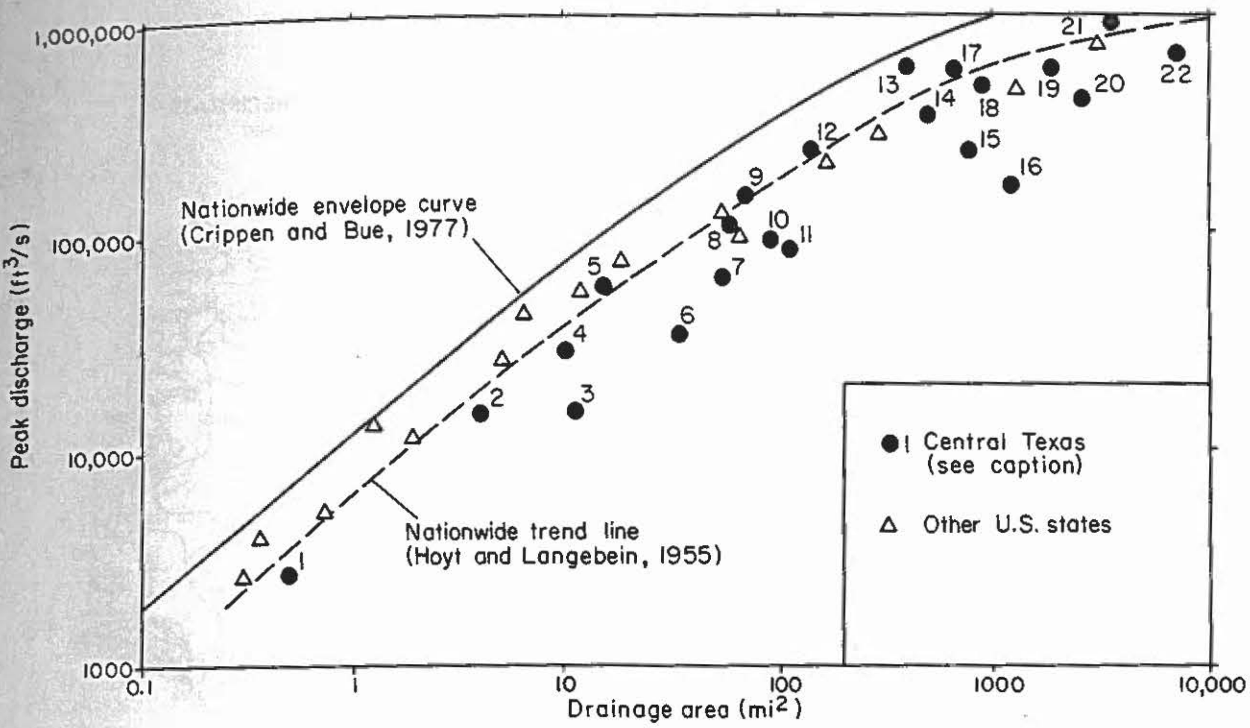


Figure 3. Discharge-watershed relationships of the most severe floods in Central Texas and other U.S. states. Sites in Central Texas: (1) Trough Creek near New Braunfels, 1972; (2) Bunton Creek at Kyle, 1936; (3) Walnut Creek at Austin, 1981; (4) Little Red Bluff Creek at Carta Valley, 1948; (5) Calaveras Creek near Elmendorf, 1946, Blieders Creek near New Braunfels, 1972, and Spring Creek near Fredricksburg, 1978; (6) Purgatory Creek near San Marcos, 1972; (7) Sink Creek near San Marcos, 1972; (8) North Prong of Medina River near Medina, 1978; (9) Mailtrail Creek at Loma Alta, 1948; (10) Guadalupe River at New Braunfels, 1972; (11) Hondo Creek near Hondo, 1919; (12) Seco Creek near D'Hanis, 1935; (13) West Nueces River near Kickapoo Springs, 1935; (14) Medina River near Pipe Creek, 1978; (15) Guadalupe River at Comfort, 1978; (16) Guadalupe River near Spring Branch, 1978; (17) West Nueces River near Brackettville, 1935; (18) Pedernales River near Johnson City, 1952; (19) Nueces River below Uvalde, 1935; (20) Devils River near Del Rio, 1932; (21) Pecos River at U.S. Highway 90, 1954; (22) Little River at Cameron, 1921. Adapted from Baker (1975, fig. 4) and Crippen and Bue (1977, figs. 2, 12). Additional data sources: Schroeder and others (1979, p. 11); Massey and others (1982, table 1); and source cited by Baker (1975, fig. 4).

Urban flooding is a serious problem in many Central Texas communities (Baker, 1975, 1976). For example, within the small, largely rural Guadalupe River basin, the Federal Emergency Management Agency has designated 17 cities with significant flood hazards (Texas Department of Water Resources, 1984, p. III-18-6). Annual flood losses throughout the Balcones Escarpment area remain high despite a network of flood-control structures (fig. 1). During the "Memorial Day" flood of May 24 to 25, 1981, the city of Austin sustained 13 deaths and 35.5 million dollars in damages from flooding along small unregulated urban streams (Moore and others, 1982, p. 15). In response, the city constructed several discharge-retention dams and completely revamped its procedures for assessing flood hazards and issuing warnings. But although this system may reduce future casualties and property losses it represents a significant infrastructural investment that few area communities could make. Better planning at an earlier stage of urban development might have prevented foreseeable problems experienced during the 1981 flood and eliminated costly retrodesign.

Urbanization merely compounds the natural tendency of Central Texas streams to produce damaging floods with greater frequency than do comparable drainage basins elsewhere. But the causes and effects of flooding in rural and urban settings differ in important ways. Two case studies, one concerning an undeveloped stream reach, the other an area undergoing urban growth, are reviewed in order to assess these differences.

CASE STUDIES

Rural Flooding: Guadalupe River, 1978

A striking example of flooding in a rural watershed is the August, 1978 event on the upper Guadalupe River, which was associated with the deep inland incursion of tropical storm Amelia. Amelia's climatic history was described in detail by Bowmar (1978, 1979, 1983) and the National Weather Service (1979). One of the most severe droughts in more than 20 yr was underway just prior to

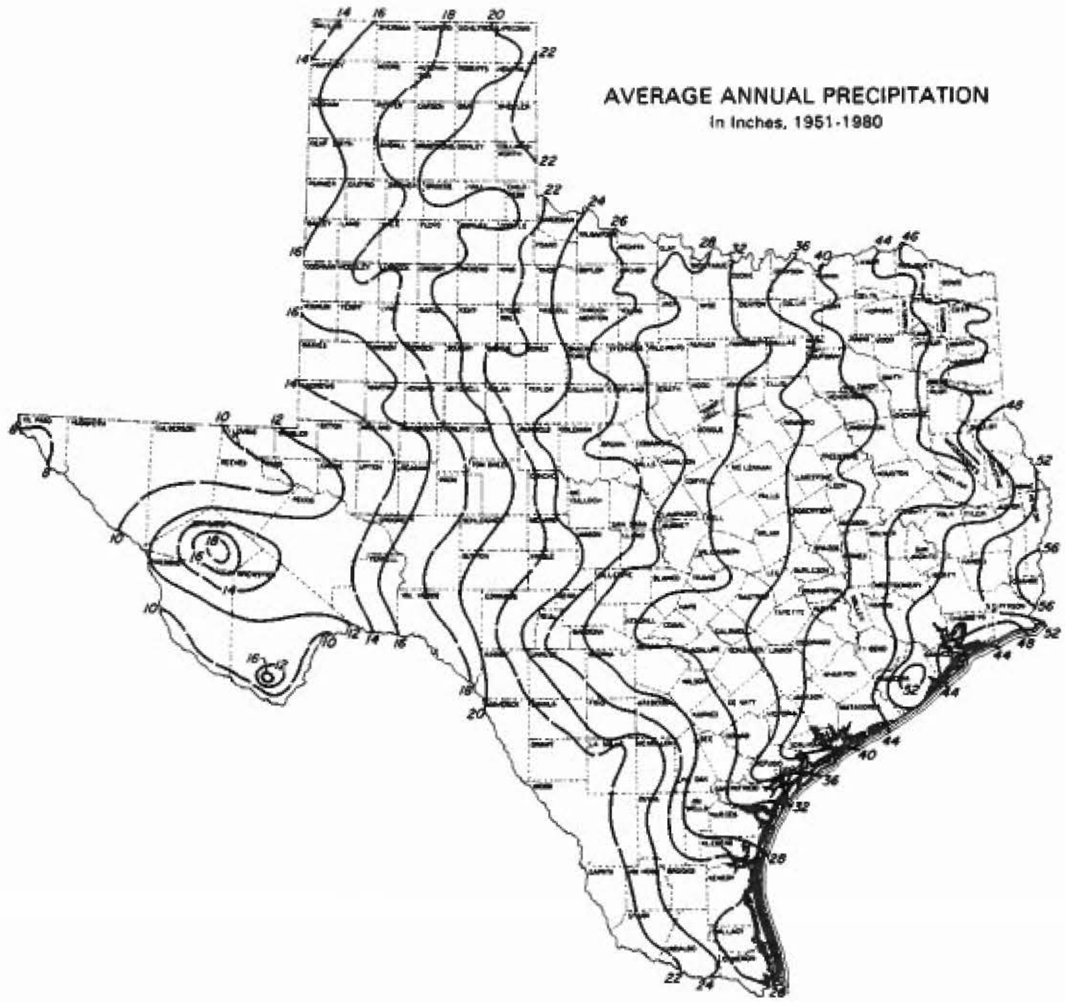


Figure 4. Mean annual precipitation in Texas. Note westward deflection of isohyet contours in Balcones Escarpment area, indicating increased rainfall relative to adjacent areas. From Larkin and Bowmar (1983, p. 18).

the advent of this storm. A subtropical ridge of high pressure had maintained dry conditions across much of the state throughout the summer. This ridg did not begin to deteriorate until the end of July when tropical storm Amelia formed in the Gulf of Mexico less than 50 mi off the southernmost Texas coast. Amelia was a minimal tropical storm (technically an "extratropical storm" because it originated north of the Tropics) when it made landfall in South Texas, causing little damage along the coast.

But as the storm moved northwestward, eventually crossing the Balcones Escarpment near San Antonio, it began producing extremely heavy rains. Amelia followed a path "virtually unique in Texas' weather" (Bowmar, 1979, p. 29). This slow-moving storm drifted over the escarpment and eastern Edwards Plateau, inundating small drainage basins. Rains exceeded 10 inches in 48 to 72 hr across a large area of Central Texas. The heaviest rains were those at the Manatt ranch near Medina, Bandera County, which set the U. S. 3-day rainfall record of more than 48 inches (Hansen, 1979) (fig. 2). Amelia remained a significant cyclonic system for six days following landfall, producing very intense rains all along its track into North-Central Texas.

Flooding associated with tropical storm Amelia v
severe. Records of flood discharge in the Medina Riv
basin are summarized above (under "Tropical
Disturbances"). For a more complete discussion see
Schroeder and others (1979), Sullivan (1983), and Bal
(1984). Remarkable stage heights and discharge peak
were attained on the upper Guadalupe River, as well.
Comfort, Kendall County, water level rose to nearly 4
breaking the previous record established in July, 1869
(Schroeder and others, 1979, p. 106). Drainage area
this location is 838 mi^2 and peak discharge was 240,
cfs (table 1; fig. 3). Farther downstream, the U. S.
Highway 281 bridge was flooded even though it stanc
ft above stream bed (Bowmar, 1983, p. 52). Near S
Branch, Comal County, where the contributing drainag
is 1,315 mi^2, stage height was greater than 45 ft.
However, discharge in this reach had attenuated to 1
cfs (Schroeder and others, 1979, p. 107) (table 1; fig
Even this figure is phenomenal; 158,000 cfs is substa
greater than mean discharge of the Nile at its mouth
the upper Guadalupe has only 1/1000th the Nile's
watershed area. And yet, the Amelia flood was only
third largest recorded at the Spring Branch station.
highest stage, observed in 1869, was approximately 5

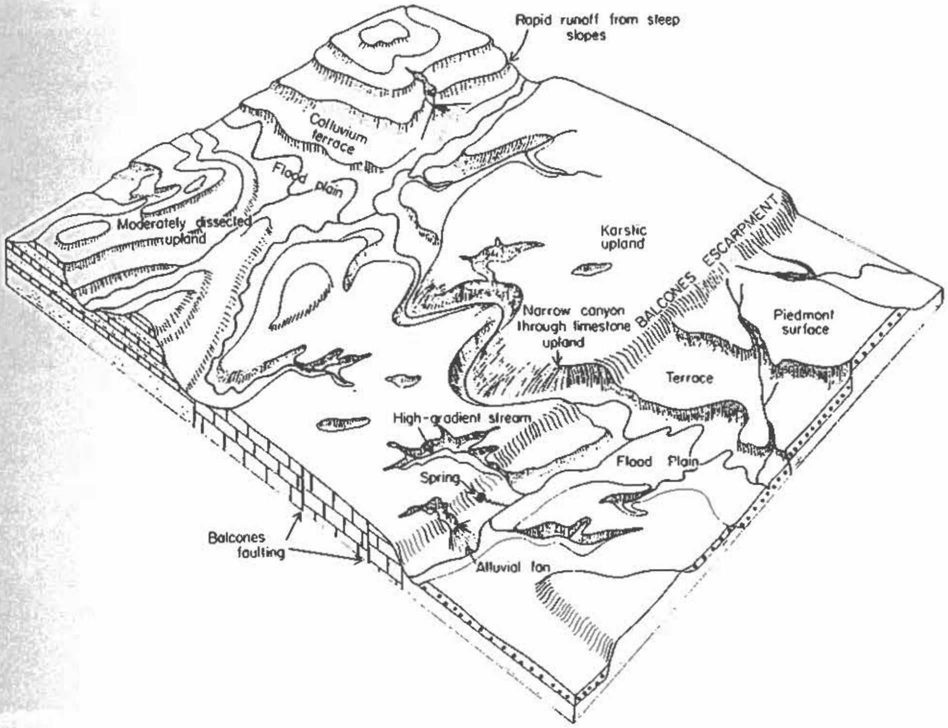


Figure 5. Block diagram representing geomorphic features that affect flood potential in the Balcones Escarpment area. From Baker (1975, fig. 3).

Damage resulting from the Amelia flood was enormous. In Central Texas, 25 persons were killed, 150 were injured, and 50 million dollars in property losses were sustained (Bowmar, 1979, p. 29). Another six persons were killed in North-Central Texas. All flood waters in the upper Guadalupe River watershed were contained by Canyon Lake reservoir in Comal County. Fortunately, lake level was low prior to the storm. Water storage increased by 226,200 acre-feet or approximately 74 billion gallons (Schroeder and others, 1979, p. 6). Areas downstream were not subjected to flooding but the lake afforded no protection of sites higher in the basin where rains were heaviest.

Geomorphic effects of the flood were pronounced. Devegetation, channel and flood-plain scour, large-scale deposition, modification of channel form, and temporary avulsion of meanders were common. Along both the Guadalupe and Medina Rivers, riparian woodlands including bald cypress trees six feet in diameter were scoured from miles of channel. Sullivan (1983, table 8) estimated 62 to 92 percent reduction of tree-crown cover in some reaches of the Medina. Van Auken and Ford (in preparation) will present a detailed account of effects of the Amelia flood on plant communities along the upper Guadalupe.

Baker (1977, p. 1069-1070) discussed the dynamic relationship between riparian vegetation and hydrologic characteristics of channels in flood. This discussion serves to illustrate effects of the Amelia flood on the upper Guadalupe River. Baker's model notes that dense stands of woody plants typically occupy the lower terraces, channel margins, and even the point bars of area streams. As water level begins to rise during a flood, the irregular floor of the low-flow channel is submerged. Boulders and bedrock outcrops that obstruct base flow are completely covered, which reduces resistance or channel roughness. With further increase in depth the stream, now "bankfull", overtops the sinuous low-flow channel, lowest terraces, and vegetated bars. Plants below the level of inundation increase roughness and tend to retard flow, but stream velocity actually increases in response to heightened discharge as the flood crest advances. Within the constricted bedrock channels common to this region, increased discharge is accommodated by rapid increase in stream depth. At this point, the mid-water zone of maximum velocity, the thalweg, shifts laterally inward across the slip-off bars, thereby increasing the effective channel radius and straightening the flood course around meanders.

Transition to the next phase of stream flow is governed by a critical threshold that in turn is dependent on the height and density of vegetation. If plants do not choke the flood channel, and if tree canopies remain above water there may be little additional damage. However, if canopies are submerged or flow is greatly restricted trees are uprooted, toppled, or sheared by the force of the water and impact of transported debris. Partial clearing of the channel reduces drag and increases local flow velocities. Rapid flow around remaining obstructions creates macroturbulence, causing intense scouring of gravel bars and low terraces at peak discharge. The coarsest sediment, including boulders and megaboulders, is transported only a short distance. Chute bars and gravel berms form at the downstream ends of bends on which scour was initiated. Valley-bottom scour is selective, partly because the combined resistance of the gravel fill and anchoring vegetation is variable. Following peak stage, as flow subsides, dragged and floated vegetation is deposited in the stream bed where it may inhibit waning discharge.

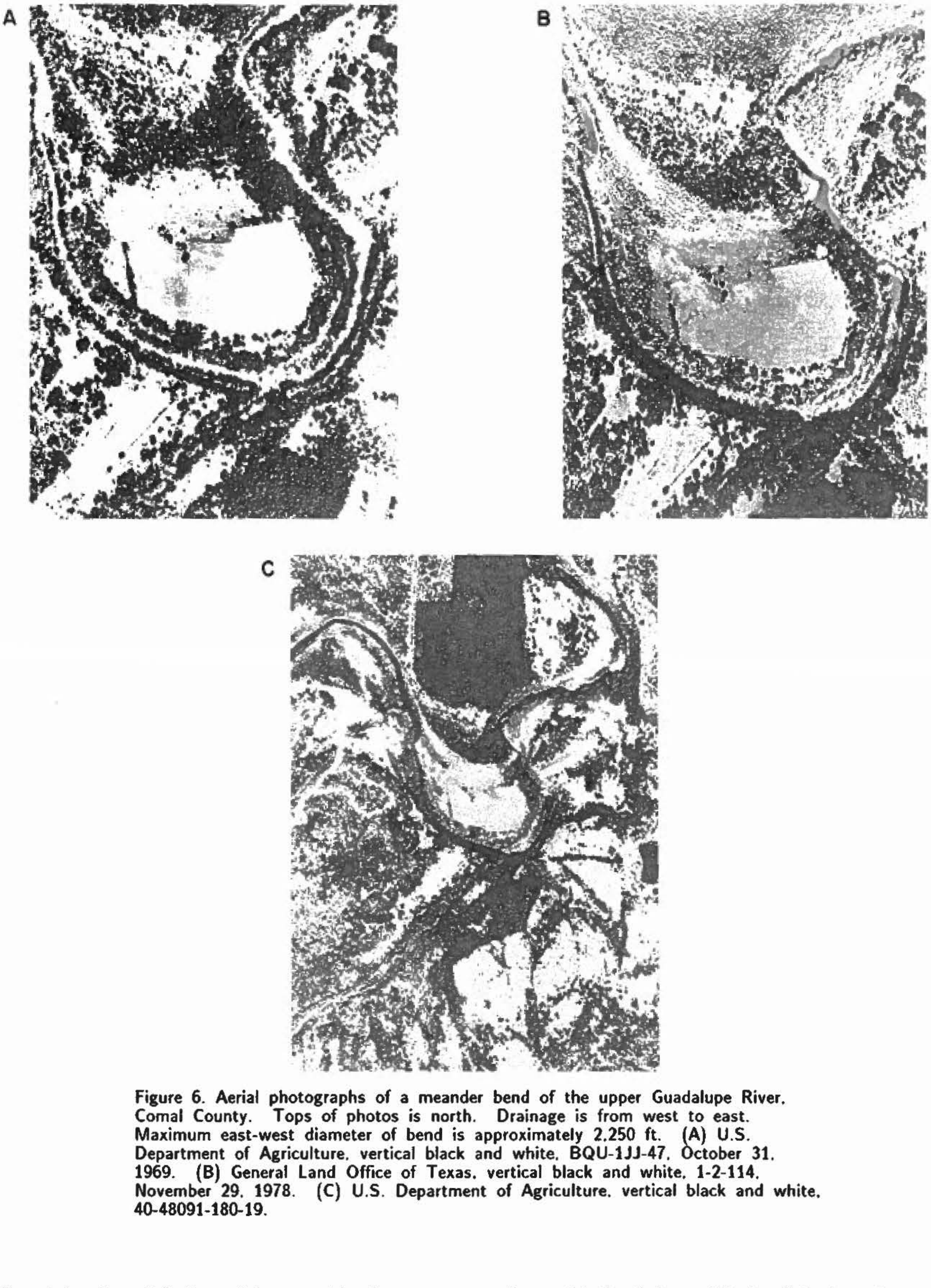


Figure 6. Aerial photographs of a meander bend of the upper Guadalupe River, Comal County. Tops of photos is north. Drainage is from west to east. Maximum east-west diameter of bend is approximately 2,250 ft. (A) U.S. Department of Agriculture, vertical black and white, BQU-1JJ-47, October 31, 1969. (B) General Land Office of Texas, vertical black and white, 1-2-114, November 29, 1978. (C) U.S. Department of Agriculture, vertical black and white, 40-48091-180-19.

A variation from Baker's model occurred in the Guadalupe basin approximately eight miles upstream from the U. S. Highway 281 bridge in western Comal County. Water depth in this area exceeded 50 ft. As predicted by the model, the thalweg shifted radially inward across th slip-off bar. However, this shift completely cut off the neck of the meander. Figure 6B shows scoured chutes chute bars, large-scale gravel ripples, and aligned fallen trees at the cutoff. Peak flow bypassed this bend entirely. Consequently, this was one of the few reaches that sustained no serious loss of riparian vegetation such as large bald cypress and other trees. In fact, slack-water deposits began filling this channel segment at the same time contiguous areas were being scoured. A dam of fine sediment and plant debris temporarily blocked the mouth of Honey Creek, a tributary entering this bend from the south.

Effects of high-magnitude, low-frequency floods are much greater and more enduring in the bedrock-channel streams of Central Texas than in fine-grained alluvial channels of humid regions. Wolman and Miller (1960) have shown that, in stream systems of the latter type, relatively frequent low-magnitude events are most significant. In contrast, post-flood monitoring of Elm Creek (Comal County) and other streams in the Balcones Escarpment area indicate hydrologic characteristics typically are affected for years and perhaps decades (Baker, 1977).

A sequence of aerial photographs (fig. 6) shows the avulsed meander bend of the Guadalupe before, shortly after, and two years after the Amelia flood. Evidence of older (pre-1969) cutoffs at yet higher elevations attest to the episodic nature of these events (fig. 6A). Following the 1978 flood, the river occupied a deep, sharply-defined base-flow channel against the cutbank (fig. 6B). This channel cuts through gravel bars that in 1969 nearly blocked the river at several twists and tributary junctures. Coarse, open-work gravel deposits on slip-off slopes and low terraces show little evidence of reworking or revegetation between 1978 and 1980 (fig. 6C). Low adventitious plants such as grasses and forbs had completely covered the deep cutoff chute by 1980 but no large woody plants had been established. Trees that had fallen or been stranded at this meander bend in the 1978 flood were still in place in 1980. As of summer, 1986, changes in channel geometry and alignment and vegetation patterns that were effected in this reach by the Amelia flood had not been significantly modified.

Urban Flooding: Walnut Creek, 1981

Urban flooding generally is more complex than that in rural settings because it often results from failure or inadequacy of engineered drainage systems as well as excessive rains. A recent example of urban flooding in the Balcones Escarpment area is the "Memorial Day" flood of May 24 to 25, 1981, in Austin, Travis County (fig. 1). Bowmar (1981) presented a detailed review of the meteorologic causes of this flood. Late in the afternoon of May 24, warm moist air from the Gulf of Mexico was moving rapidly northwestward into Central Texas at middle levels of the atmosphere. Near-surface air had been heated throughout the day making the lower third of the atmosphere convectively unstable. Only 10,000 ft of additional vertical movement of surface air was needed to form significant thunderstorms.

An upper-level trough of low pressure moved through Central Texas early in the evening and provided the needed lift. Cloud tops reached 40,000 to 45,000 ft and remained in that range for more than 7 hr. Heavy rains began falling at about 9:30 p.m. Within a few hours, 8 to 10-inch rains had covered a large area of the city. The most intense rainfall and greatest total precipitation in the area were measured at stations in northern and northwestern Austin in the watersheds of Shoal and Walnut Creeks (Massey and others, 1982, fig. 6, table 2; Moore and others, 1982, figs. 2.2-2.4). One site near the headwaters of Walnut Creek recorded almost 6 inches of rain in one hour and 10 inches in 2 1/2 hours, which are intensities approaching the trend of worldwide precipitation maxima (fig. 2).

The effect of so much rainfall in a short period was severe flooding of parts of the city. Conditions were worsened by lighter but substantial rains of the day before which had saturated the ground (Moore and others, 1982, p. 4). A high percentage of impervious land cover is characteristic of urban areas and reduces further the potential soil infiltration. Under these circumstances, runoff was nearly complete. A remarkable aspect of the 1981 storm was the concentration of moisture in small, relatively stationary cells. Rains produced by these cells were highly localized within a widespread pattern of general though less intense rainfall. Small drainage basins were overwhelmed, producing massive flooding. Massey and others (1982) analyzed flood hydrographs and field observations and reconstructed areas of inundation along parts of Shoal, Little Walnut, and Walnut Creeks. The following discussion pertains to the headwaters of Walnut Creek, which were beyond the area covered by Massey and others.

Some of the most intense flooding resulting from this storm occurred in the uppermost reaches of Walnut Creek. The stream skirts well east of the Balcones Escarpment except in the upper part of the basin. There, tributaries drain off a segment of the escarpment which has subdued relief (fig. 7). These short but steep bedrock slopes enhance runoff onto adjacent Coastal Plain surfaces with low-permeability soils (Werchan and others, 1974). In addition, the small watersheds of these tributaries are areas of residential and small commercial development with 25 to perhaps 50 percent impervious cover (U.R.S./Forrest and Cotton and others, 1977, table 2-5). Each of these factors tends to amplify runoff.

Only a few years prior to the 1981 flood, upper Walnut Creek basin primarily comprised cultivated fields and rangeland. Until the late 1970's, the area was outside the corporate limits of Austin and other communities and therefore was not governed by construction codes sensitive to flood hazards. Earlier landowners evinced little voluntary concern; for example, initial construction had predated widespread recognition of risks inherent in development on flood plains. Railroads had been constructed along contours on high linear berms that obstruct movement of runoff. Rural roads with low narrow bridges, low-water crossings, and no storm culverts had been only partly replaced by urban streets and drains designed for 25 to 50-yr recurrence floods. Old and new roads and drainage ways were poorly integrated. Few of these problems had been corrected because urbanization was incomplete at the time of flooding. The area was a patchwork of modern urban streets, storm drains, housing, and businesses interspersed with undeveloped tracts, unimproved roads, and small industrial sites adjacent to streams. These conditions exaccerbated meteorologic and topographic factors associated with the flood of May, 1981.

Eight to ten inches of rain fell over most of the upper Walnut Creek drainage between 9:30 p.m. and midnight on May 24 (Massey and others, 1982, fig. 6, table 2). At FM Highway 1325 (Burnet Road), water level reached 19.5 ft, corresponding to 15,000 cfs discharge from a drainage area of 12.6 mi^2 (Massey and others, 1982, table 1) which approaches the nationwide trend line for high-discharge events (table 1; figs. 3, 7). Numerous homes and buildings were damaged by rising water along the channel or unchanneled flow on nearby slopes. At Waters Park Road just upstream from Burnet Road, a few commercial buildings on the flood plain were completely destroyed or badly damaged. One small manufacturing plant was submerged by more than 15 ft of very rapidly moving water. This high-velocity macroturbulent flow transported heavy industrial equipment, large commercial trucks, and passenger cars more than one mile downstream from the plant site (figs. 8A, 9). To accomplish this the stream carried some of its load over a 15-ft high railroad trestle partly blocking the channel just downstream.

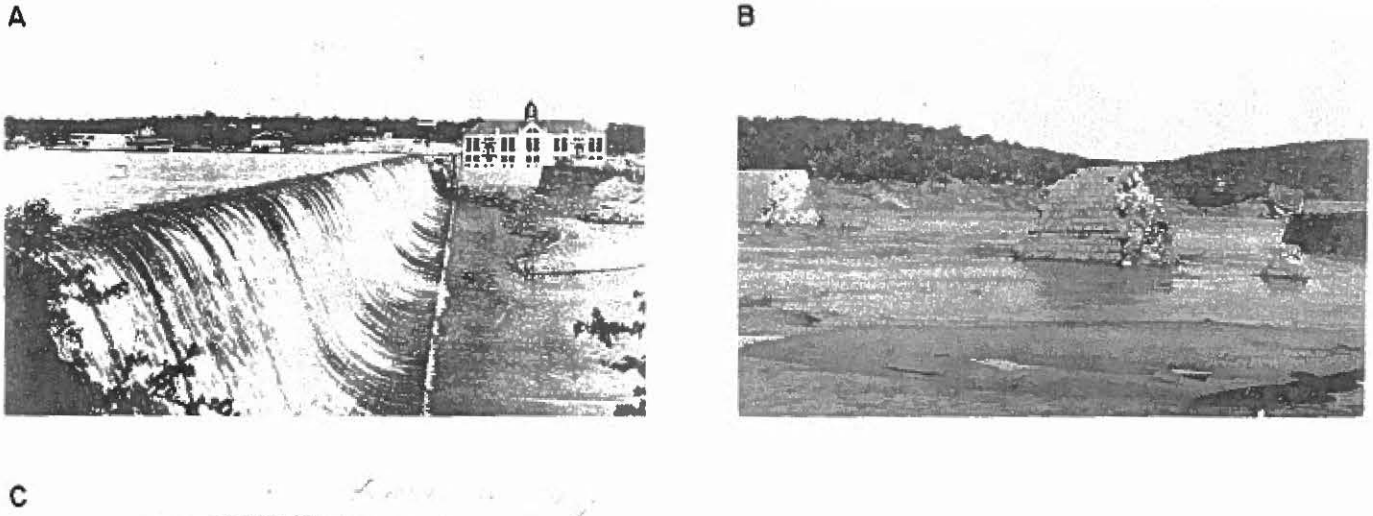
An unnamed tributary of Walnut Creek that has a drainage area of approximately 2.5 mi^2 probably was entirely within one of the zones of 10-inch rainfall depicted by Massey and others (1982, fig. 6). Only part of this drainage area contributed to a reach where flood waters damaged a bridge and washed out a railroad berm along Dorsett Road (fig. 7, 8B). Just downstream, a woman was killed when her automobile was submerged at a newly constructed bridge on Duval Road (Massey and others, 1982, p. 22; fig. 3.1 of Massey and others is in error). Twelve additional fatalities occurred along other streams which also destroyed homes and businesses.

CATASTROPHIC DAM FAILURE: AUSTIN, 1900

Floods have posed serious hazards throughout the history of Central Texas. In an effort to control flooding and harness the Colorado River for water supplies, recreation, and hydroelectric-power generation, the city of Austin and, later, the Lower Colorado River Authority constructed and maintained a dam in western Austin. The present structure, known as Tom Miller Dam, impounds Lake Austin. An earlier dam at this site was the world's largest masonry structure when it was completed in 1893 (Lower Colorado River Authority, undated). The reservoir formed by this early dam was called Lake McDonald (fig. 10A). Design problems and controversy surrounding the advisablity of the site raised some concern although the dam appeared stable (Taylor, 1930, p. 25). But on April 7, 1900, a major flood in the Colorado watershed caused the dam to fail, draining Lake McDonald. Sections of the dam were displaced downstream yet remained upright (fig. 10B). Other sections were washed away entirely. The dam was reconstructed, only to fail a second time in 1915 (Lower Colorado River Authority, undated). Further construction was delayed. Another flood in 1935 did additional damage (fig. 10C). Finally, in 1938, the existing structure was completed and has operated with few interruptions since that time.

CONCLUSIONS

The Balcones Escarpment area is one of the most flood-prone regions of the world. Intense rainstorms occur in the area with surprising frequency. Physiographic factor produce rapid runoff which results in phenomenal stream discharge. Urbanization reinforces these natural conditions and increases the probability of casualties and property losses. Numerous flood-control structures throughout the region provide some measure of security but heavy rains are so localized that catastrophic floods may occur almost anywhere else in the drainage basi.. Small, completely unregulated streams may undergo enormous increases in discharge, posing a considerable threat particularly in urban settings. Within the Balcones Escarpment area, the distribution of major flood-producing storms in time and space is random. Therefore, the only completely effective approach to flood protection is avoidance of geomorphically defined flood plains and channels.



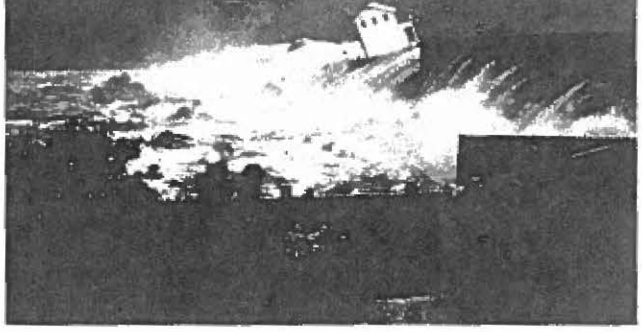


Figure 10. Historic photographs of Austin Dam (now call Tom Miller Dam). Photos courtesy of Austin History Center. In all photos drainage is from north to south. (A) Photo number Chal 8484. Dam soon after construct (photo taken about 1895). View is toward east. Note paddlewheel steamboat Ben Hur at left. (B) Photo num Chal 1613. Remnants of dam soon after flood of Augus 7, 1900 (photo taken about 1900). View is toward northwest. Section in center has been displaced downstream. Note wreak of Ben Hur at right. (C) Ph number Chal 65. Dam during flood of June 15, 1935. View is toward west.

ACKNOWLEDGMENTS

Personnel of the Texas Natural Resources Information System, particularly Charles Palmer and Lou Falconieri, assisted in compiling aerial photographs used in preparation of this article. The Austin History Center provided historic photographs of Austin. Kerza Prewitt, Joel Lardon, and Ted Samsel of the Bureau of Economic Geology drafted the final figures. Jim Morgan of the Bureau of Economic Geology rephotographed aerial photos for use as figures. Special thanks go to each of these individuals and institutions.

REFERENCES

Baker, V. R., 1975, Flood hazards along the Balcones Escarpment in Central Texas--alternative approaches to their recognition, mapping, and management: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 75-5, 22 p.

_____1976, Hydrogeomorphic methods for thr regional evaluation of flood hazards: Environmental Geology, v. 1, no. 5, p. 261-281.

_____1977, Stream-channel response to floods, with examples from Central Texas: Geological Society of America Bulletin, v. 88, no. 8, p. 1057-1071.

_____1984, Flood sedimentation in bedrock fluvial systems, in Koster, E. H., and Steel, R. J., eds., Sedimentology of gravels and conglomerates: Canadian Society of Petroleum Geologists Memoir 10, p. 87-98.

Beard, L. R., 1975, Generalized evaluation of flash-flood potential: The University of Texas at Austin, Center for Research in Water Resources Technical Report CRWR-124, 27 p.

Bowmar, G. W., 1978, An analysis of weather conditions relative to the occurrence of flash flooding in Central Texas (during the period of July 30 to August 4, 1978): Austin, Texas Department of Water Resources LP-69, 37 p.

_____1979, 1978--drought in the east, floods out west: Austin, Texas Department of Water Resources LP-89, 37 p.

_____1981, Appendix--Report on meteorological aspects of the Austin flash flood of May 24-25, 1981, in Moore, W. L., and others, The Austin, Texas, flood of May 24-25, 1981: Washington, D. C., National Academy Press, p. 39-49.

_____1983, Texas weather: Austin, University of Texas Press, 265 p.

Carr, J. T., Jr., 1967, The climate and physiography of Texas: Austin, Texas Water Development Board Report 53, 27 p.

Costa, J. E., 1978, The dilemma of flood control in the United States: Environmental Management, v. 2, no. 4, p. 313-322.

Crippen, J. R., 1977, Maximum floodflows in the conterminous United States: Washington, D. C., U.S. Department of the Interior, Geological Survey Water-supply Paper 1887, 52 p.

Espey, W. H. K., Morgan, C. W., and Masch, F. D., 1966, Study of some effects of urbanization on storm runoff from a small watershed: Austin, Texas Water Development Board Report 23, 110 p.

Hansen, E. M.,1979, Study of the reported 48+ inch rainfall in the storm of August 1-3, 1978, near Medina, Texas: Silver Springs, Maryland, National Oceanic and Atmospheric Administration, Weather Service unpublished report, 12 p.

Hoyt, W. G., and Langbein, W. B., 1955, Floods: Princeton, New Jersey, Princeton University Press, 469 p.

International Boundary and Water Commission, 1954, Flow of the Rio Grande: Washington, D. C., Water Bulletin 24, 60 p.

Jennings, A. H., 1950, World's greatest observed point rainfalls: Monthly Weather Review, v. 78, no. 1, p. 4-5.

Kochel, R. C., Baker, V. R., and Patton, P. C., 1982, Paleohydrology of southwestern Texas: Water Resources Research, v. 18, no. 4, p. 1165-1183.

Larkin, T. J., and Bowmar, G. W., 1983, Climatic atlas of Texas: Austin, Texas Department of Water Resources LP-192, 151 p.

Leopold, L. B., Wolman, M. G., and Miller, J. P.,1964, Fluvial processes in geomorphology: San Francisco, W. H. Freeman and Company, 522 p.

Lower Colorado River Authority, undated, Lake Austin and Tom Miller Dam: Austin, brochure.

Massey, B. C., Reeves, W. E., and Lear, W. A., 1982, Floods of May 24-25, 1981, in the Austin, Texas, metropolitan area: Washington, D. C., U.S. Department of the Interior, Geological Survey Hydrologic Investigations Atlas HA-656 (2 sheets).

Moore, W. L., Cook, Earl, Gooch, R. S., and Nordin, C. F., Jr., 1982, The Austin, Texas, flood of May 24-25, 1981: Washington, D. C., National Academy Press, 54 p.