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Paleoflood Hydrology

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Assessing the risk of rare, large magnitude floods is generally very difficult when conventional methods of flood frequency analysis are used (*1*). A major problem is that return periods of large floods may be much longer than the length of historical records. Floodplain zoning laws and flood control projects are designed on the basis of statistical analyses of relatively short-term historical records of stream flow and precipitation (*2*).

Summary. The difficult task of estimating recurrence intervals for large floods has long plagued hydrologists because statistical measures fail when return intervals of floods exceed the length of historical data sets. Sediments deposited in the backwaters of large floods may accumulate thick sequences in tributary mouths. Stratigraphic and sedimentologic studies of these sequences combined with radiocarbon dating have established a 10,000-year paleoflood record for the lower Pecos and Devils rivers in southwestern Texas. This technique is rapid and relatively inexpensive and can be used where historical records are short or entirely absent.

In semiarid and arid regions flood frequency analyses are complicated by additional factors. Conventional analyses, such as that with the logarithm of annual maximum discharges (the log Pearson type III method) or Gumbel extreme value theory, may provide misleading information if the study period coincides with a period of anomalous rainfall-runoff conditions (*3*). There are severe problems with extreme value theory in treating negatively skewed annual flood distributions such as those that are characteristic of semiarid regions. To further compound the problems, these regions have short-term historical records and a low spatial density of recording stations.

The historical flood record (1900 to 1981) for the lower Pecos River in southwestern Texas illustrates the difficulty encountered in assessing recurrence intervals for large magnitude floods. In 1954 a flood occurred with a peak discharge of 27,400 cubic meters per second; this was about an order of magnitude greater than any flood in the previous 54-year record. Conventional flood frequency methods failed to predict this outlier. Conventional flood frequency estimates yield recurrence intervals ranging from 81 years to more than 10 million years for the 1954 event.

We describe a new technique for assessing long-term flood frequency analyses by paleohydrologic interpretation of slack-water flood deposits. Slack-water sediments are generally fine-grained sand and silt that accumulate in areas of reduced velocity during flood flows. Slack-water deposits were first recognized in tributaries to outflow channels that contained the catastrophic Pleistocene Spokane floods in eastern Washington (*4*). Paleohydrologic analyses of stratigraphic sequences of slack-water deposits yield estimates of paleoflood stage and discharge. Radiocarbon dating of organic materials in these sediments is used to establish recurrence intervals for the large floods. Our investigations of slack-water sediments along the lower Pecos and Devils rivers in southwestern Texas have established a paleoflood record that spans the last 10,000 years.

In addition to their direct application to engineering problems, estimates of the frequency and magnitude of paleofloods are important in studies of channel morphology and development. In some regions, a rare flood may dominate fluvial morphologic adjustment, whereas frequently occurring flows of lesser magnitude are ineffective in reshaping channel morphology (*5*). Other studies indicate that geomorphic effects of catastrophic floods are minor (*6*). The geomorphic effects of large, infrequent floods are complex (*7*). Frequency data would clarify the frequency-magnitude problem and allow geomorphologists to assess the importance of infrequent floods in the adjustment of fluvial morphology and the recovery rate.

To obtain data on the recurrence intervals of rare floods, the methods must extend flood records well beyond the range of historical data. Geomorphic evidence of paleofloods has been obtained by (i) botanical studies of floodplain vegetation (*8*), (ii) palynological studies of floodplain sediments (*9*), (iii) analysis of floodplain soil development (*10*), (iv) study of flood bars and coarse-grained overbank deposits and dating of organic materials entrapped in the deposits (*11*), (v) dating of landforms truncated by flood flows (*12*), and (vi) paleostratigraphy of flood sediments in prehistoric rock shelters (*13*). The morphostratigraphic study of slack-water sediments is widely used to extract paleoflood data from Holocene floodplain sediments.

Slack-Water Sediments and Flood Frequency

Slack-water sediment accumulation sites. Slack-water sediments accumulate where floodwater velocities are minimal. Each successive flood with a stage capable of inundating previously accumulated slack-water sediments will deposit a

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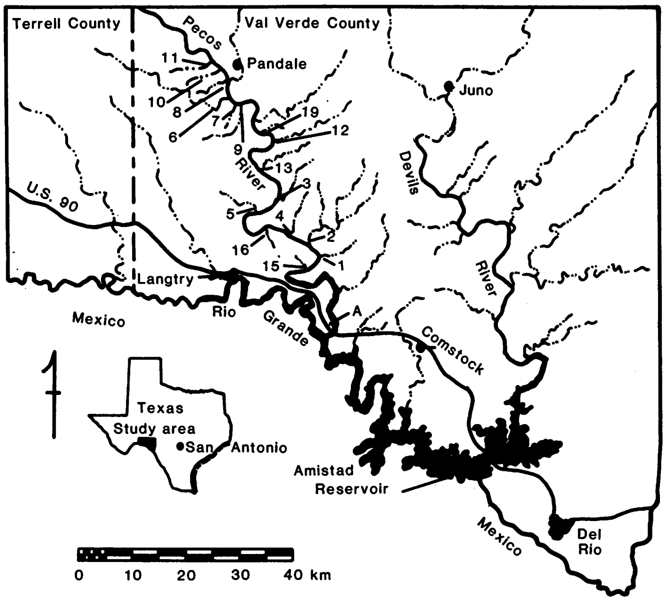

Fig. 1. Location of the study area and tributary mouth slack-water deposits in the lower Pecos River, Texas. Canyons at numbered localities are: (1) Shackelford, (2) Lewis, (3) Zixto, (4) Still, (5) House, (6) Big Fielder, (7) Rowland, (8) Cash, (9) Little Fielder, (10) Davis, (11) Brushy, (12) Cedar, (13) Everett, (15) Ladder, (16) Unnamed, and (19) Little Live Oak. Site A is the Arenosa Shelter.

new layer on top of the old sediment sequence. If these depositional sites are protected from erosion by subsequent floods, lengthy records of large floods are preserved. Tributary mouths are the most common sites for the accumulation and preservation of slack-water deposits (Figs. 1 and 2, A and B). Here, deposits accumulate during backflooding of the tributary by flood waters from the main stream. In western Texas, backflooding processes are accentuated because tributaries peak rapidly, typically before the main stream. Major floods fill bedrock channels of main streams to depths of up to 30 m. Surges of sediment-laden water move up tributary canyons and deposit sediment in the mouth of the main stream (Fig. 2, A and B). Reverse surges have also been observed during floods in humid areas (*14*). If the tributary basin also floods, a couplet of sediments will result from each event. The basal layer is typically coarse-grained tributary alluvium. This is overlain by finer-grained slack-water sediment from the main stream. Along the Pecos River the basal layer is limestone gravel derived from tributaries underlain by Cretaceous limestones. In contrast, Pecos River slack-water sediments are fine-grained, tan quartz sand and silt, derived from sandy units several hundred kilometers upstream.

Not all tributary canyons contain thick slack-water sequences. Morphologic characteristics of tributary canyons that permit accumulation and preservation of slack-water deposits include (i) drainage basin morphometry that is not conducive to the production of flash floods, which could erode slack-water sediments—that is, low drainage density, elongate shape, low first-order stream frequency, low

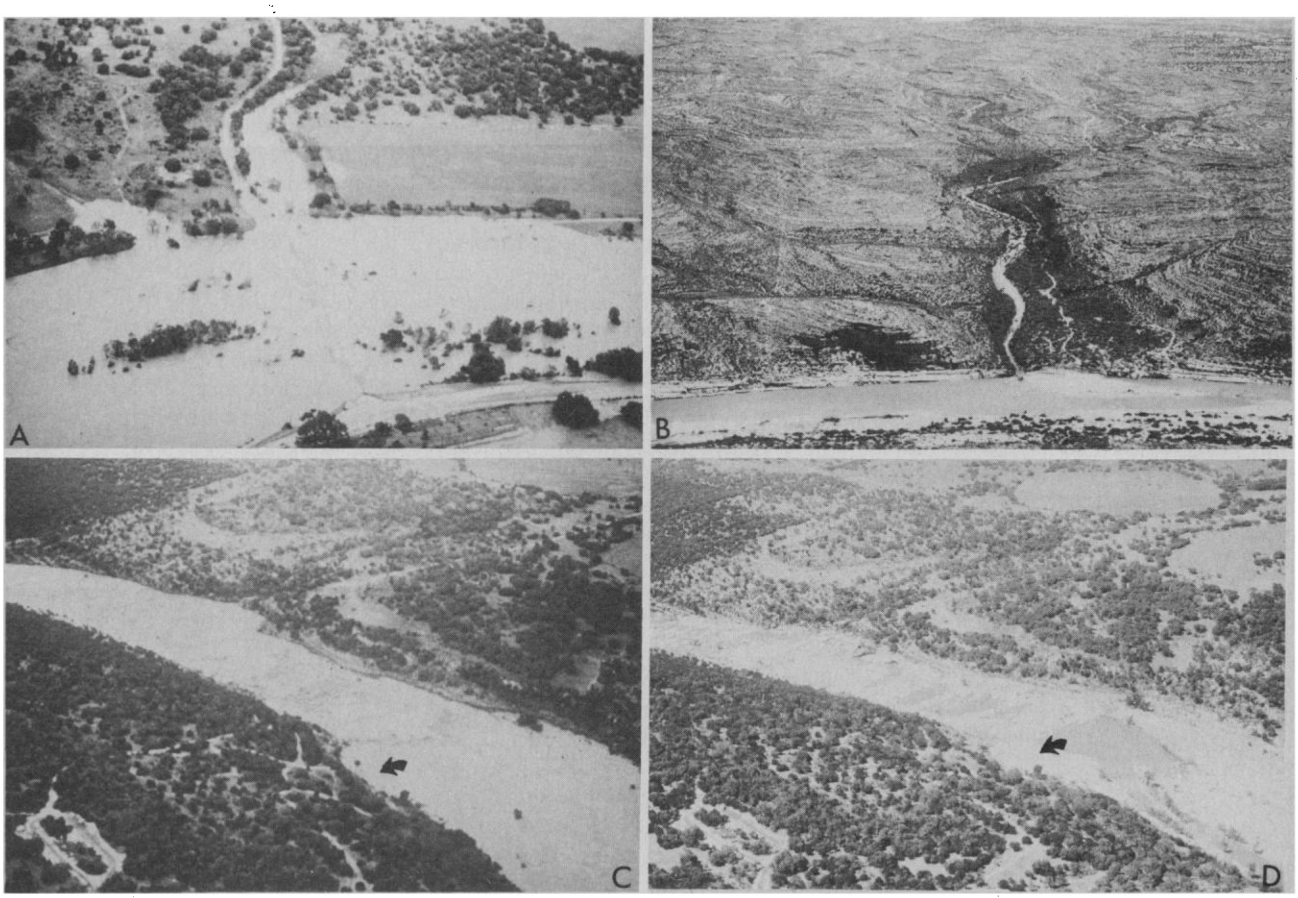

Fig. 2. Sites of slack-water sediment accumulation. (A) Aerial view of reverse surge and slack-water deposition in tributary mouths along the Pedernales River, Texas, in August 1978 [photograph by C. Chandler]. (B) Slack-water deposit in the mouth of Cedar Canyon along the lower Pecos River. Slack-water sand from backflooding by the Pecos (flowing left to right) supports a stand of mesquite. (C) Pedernales River in flood on 3 August 1978 (flow is left to right). Arrow denotes a large slack-water eddy where the channel widens abruptly [photograph by C. Chandler]. (D) Same location as (C) on 17 August 1978. Note the fresh accumulation of slack-water sand at the former eddy site.

ruggedness number, and low channel gradient (*15*); (ii) accumulation sites in areas most protected from erosion by tributary floods, that is, along the insides of tributary meanders, shallow caves in bedrock walls, and the leeward side (with respect to tributary flow) of bedrock protrusions and talus blocks; (iii) junction angles with the mainstream flow vector between 70° and 90° that permit easy access for reverse surges without allowing excessive velocity; and (iv) minimal vegetative cover on the deposits, which limits bioturbation of the stratigraphy and facilitates hand-shovel trenching of the site.

Along confined bedrock channels of central and southwestern Texas streams, abrupt changes of channel width are common. In these sites flood velocity decreases as reverse eddies form along channel margins (Fig. 2C). Slack-water deposits accumulated in this manner are shown in Fig. 2D. Other sites along bedrock channels where slack-water deposits accumulate include the leeward sides of bedrock spurs and talus blocks, joints along channel walls, shallow caves (rock shelters) along channel walls, and low terraces along channel margins.

Slack-water sediment sequences. Figures 3 and 4 illustrate a typical tributary mouth slack-water deposit along the lower Pecos River (Fig. 1, site 3). The deposit in the mouth of Zixto Canyon contains eight slack-water flood sedimentation units composed of tan quartz sand and silt. The sequence rests on gray limestone. The number of floods in this section decreases in the up-canyon direction in the tributary because backwaters from only the largest floods are able to inundate distal areas (Fig. 4). Sediments fine and flood units thin away from the Pecos River. Most slack-water sediments are horizontally bedded or structureless, but some cross-bedding occurs. Cross-bedded foresets indicate that the paleoflow direction was up the tributary canyon, away from the Pecos River.

Between six and ten floods are preserved in slack-water sequences of the lower Pecos River tributary mouths. Thickness of individual flood units ranges from 5 centimeters to 1.5 meters. Frequently, units are capped by drapes of silt or fine-grained organic detritus. The organic detritus is normally carried in the upper few meters of the floodwater and is the last sediment deposited as the water recedes. Other criteria useful in delineating flood events include abrupt stratigraphic breaks, preservation of buried paleosols, rapid changes in the induration of sediments, abrupt reversals of vertical grain-size trends, color changes, relict mud cracks, and colluvial horizons.

Paleoflood stage and discharge. Paleoflood discharge and slack-water flood sediment thickness appear to be directly related at a given depositional site. However, there is considerable variation in sediment thickness between sites. We believe that this can be explained by the geometry of tributary mouth sites and their junction angles with the main stream. Sites with the narrowest cross sections and lowest junction angles typically contain the thickest sections of slack-water sediments from specific floods.

The height of slack-water sediments in tributary canyons can be extrapolated to the main stream to make a conservative estimate of the peak paleoflood stage. Comparisons of such extrapolated values with historically documented flood peaks in the lower Pecos River indicate that the estimates are too low by 10 to 20 percent. Once the peak flood depth is known, the slope-area method (*16*) can be used to estimate paleoflood discharge. Field data needed for slope-area calculations include channel cross sections, estimates of floodplain and channel roughness, estimates of water surface slope, and flood depth. Average velocity is computed from the Manning equation

$$\bar{v} = \frac{1}{n} R^{2/3} S^{1/2} \qquad (1)$$

where $\bar{v}$ is mean velocity (meters per second), n is the roughness factor (*17*), R is the hydraulic radius (meters), and S is

Fig. 3. Slack-water deposit in the mouth of Zixto Canyon (Fig. 1, site 3). Light-colored quartz sand and darker silty colluvial strata alternate in the deposit. The log in the central sand layer has been dated at 530 ± 60 years. The ruler is 1.5 m.

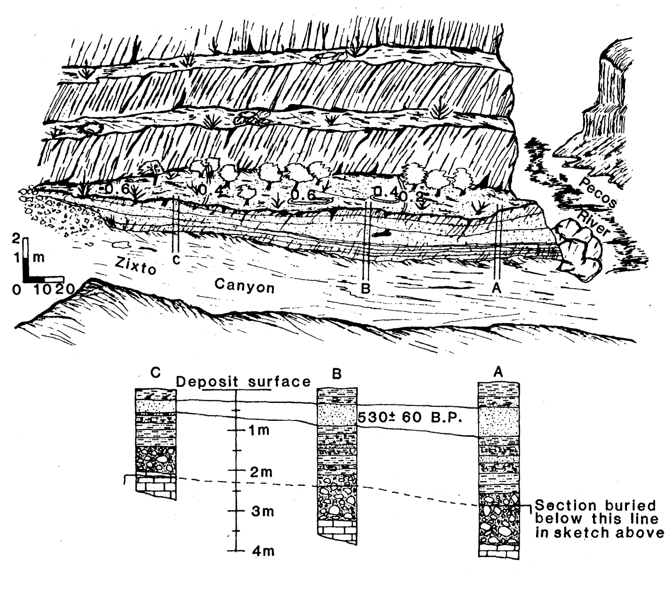

Fig. 4. Schematic drawing of the slack-water deposit in Zixto Canyon. Contours are at 0.2-m intervals on the deposit surface. Note that some units pinch out up the tributary canyon.

the water surface slope (*18*). Discharge is computed as the product of area and $\bar{v}$. To check the accuracy of the calculations, comparisons were made with known discharges at the International Boundary and Water Commission gaging station on the Pecos River near Langtry, Texas. The estimates were consistently within 10 percent of measured discharges.

In using slack-water sediment elevations to estimate paleoflood discharge, it is assumed that (i) the top of the slack-water deposits corresponds to the top of the floodwater surface; (ii) significant aggradation or degradation of the channel did not occur over the period of slack-water accumulation; (iii) the channel was not significantly scoured or filled during large flood events (*19*); and (iv) the tops of slack-water sediment sequences are within the modern flood regime of the river. Historical flood data indicate that slack-water sediments provide conservative estimates of peak flood stage. Along the lower Pecos River, slack-water sediment heights are typically 2 or 3 m below the peak flood stages measured during the 1954 and 1974 floods. Since the peak flood stages were about 30 m, the error is less than 10 percent. The 1954 and 1974 floods inundated all slack-water sequences in the area; hence, the sites are in the modern flow regime.

Radiocarbon-dated flood chronology. Radiocarbon dating of organic materials entrapped in slack-water sediments establishes an absolute frequency relation for large floods. Materials sampled for radiocarbon dating of Pecos and Devils river slack-water sediments include charcoal, wood, fine-grained organic detritus (twigs and seeds), organic-rich buried paleosols, and peaty deposits. Because logs were probably broken from trees and shrubs by floodwaters, radiocarbon ages determined from wood samples may not always correspond with the precise timing of the flood that incorporated them into its deposit. In semiarid climates, wood can remain intact on the surface for decades before being transported to depositional sites. This also increases the likelihood of error if the wood used for dating was displaced during recycling of previously deposited sediments by later floods. In slack-water unit 3 of the Ladder Canyon section (Fig. 1, site 15), radiocarbon dates of logs and fine-grained organic detritus were compared. Logs typically yielded dates 50 to 100 years older than the detritus, indicating that radiocarbon dates from logs may be in error by up to 100 years. Where possible, samples of the fine-grained organics were used to obtain more reliable estimates of the timing of flood events. These materials are usually found in the upper few centimeters of a sedimentation unit, and the samples provide dates nearly synchronous with the flood because they would decay rapidly unless they were buried.

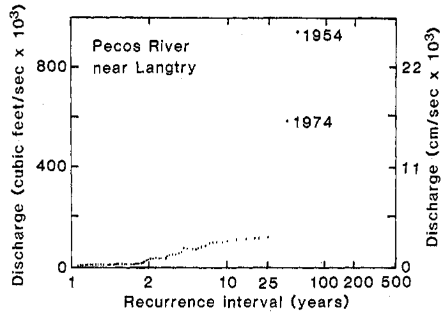

Fig. 5. Flood frequency plot for the Pecos River near Langtry, Texas, for the period 1900 to 1980. Note that the 1954 and 1974 floods occur as extreme outliers. Data from International Boundary and Water Commission (*24*).

If buried soils contain sufficient organic material, they provide mean residence times for the period of soil formation. Soil dates are minimum time intervals between the deposition of underlying sediments on which the soil formed and deposition of the overlying flood sediment. In the southwestern United States the organic content of paleosols is usually low, and several kilograms within a thin stratum are needed for radiocarbon dating. Radiocarbon dates of soil represent the entire period of soil accumulation (*20*) because the accumulation of organic matter in soils is a continuous, nonlinear process (*21*). Three soil fractions are datable: total soil humus, soluble humic acid, and insoluble residue. If all fractions yield similar ages, contamination is probably minor, and the date can be respected as a minimum age of soil formation.

Table 1. Radiocarbon dates determined in this study; B.P., before present.

TX number (*25*)	Sample	Canyon	Stratum*	Uncorrected ^{14}C date (years B.P.)	Corrected† ^{14}C date (years B.P.)	Sample nature
3192	PR 3/13	Zixto	6	500 ± 50	530 ± 60	Wood
3195	PR 2/12	Lewis	2	1940 ± 60	1955 ± 70	Fine organics
3196	PR 4/15	Still	5 and 6	240 ± 50	240 ± 50	Fine organics
3482	PR 6/7	Big Fielder	2a	0 ± 150	0 ± 150	Fine organics
3483	PR 6/8	Big Fielder	1	470 ± 100	479 ± 126	Fine organics
3484	PR 7/23	Rowland	2	Ultramodern	Ultramodern	Fine organics
3485	PR 7/24	Rowland	3	Ultramodern	Ultramodern	Fine organics
3486	PR 7/27	Rowland	5	Ultramodern	Ultramodern	Fine organics
3487	PR 7/29	Rowland	6	Ultramodern	Ultramodern	Fine organics
3488	PR 8/11	Cash	4b	Ultramodern	Ultramodern	Fine organics
3489	PR 8/14	Cash	4b	Ultramodern	Ultramodern	Fine organics
3490	PR 10/20	Davis	5a	1080 ± 380	1101 ± 381	Wood
3491	PR 10/21	Davis	5b	730 ± 70	730 ± 70	Fine organics
3492	PR 11/20	Brushy	6	610 ± 60	618 ± 67	Wood
3679	PR 15/20	Ladder	8	Ultramodern	Ultramodern	Fine organics
3680	PR 15/21	Ladder	6	Ultramodern	Ultramodern	Fine organics
3681	PR 15/22	Ladder	5	Ultramodern	Ultramodern	Fine organics
3682	PR 15/23	Ladder	3	300 ± 40	367 ± 55	Fine organics
3683	PR 15/24	Ladder	3	480 ± 70	533 ± 80	Wood
3715A	PR 19/20	Little Live Oak	5	450 ± 50	440 ± 50	Buried soil
3715B	PR 19/20	Little Live Oak	5	330 ± 90	366 ± 98	Humid acid fraction
3717	PR 19/21	Little Live Oak	2	790 ± 60	816 ± 58	Buried soil
3718	PR 19/22	Little Live Oak	1	910 ± 70	933 ± 77	Buried soil

*Refers to sections in Fig. 6 numbered from bottom to top. †Corrected for dendrochronology, isotopic fractionation, and 5730-year half-life of carbon-14.

Radiocarbon dates of flood sediments in slack-water sequences can be used to establish a time-series analysis for estimating the frequency of flood events by

$$RI = \frac{n + 1}{m} \qquad (2)$$

where RI is the recurrence interval in years, n is the period of record in years, which is established from the radiocarbon dates to bracket intervals of flood history, and m is the rank of the floods considered in each bracketed interval (22). Regional flood frequency analyses are possible if correlations can be made between slack-water sites along the river. When combined with slope-area determinations of paleoflood discharge, the dated sequences provide a detailed history of the frequency and magnitude of large floods for thousands of years. The major limiting factor is the frequency with which slack-water sediment sequences are eroded by mainstream or tributary stream floods. Mainstream backwater flows can erode tributary mouth slack-water sequences if high velocities are achieved. This occurs only when junctions between the axes of the tributary streams and the downstream flow vector of the main stream form angles less than 30°. More frequently, slack-water sequences are eroded by floods that originate in the tributary drainage basin. Slack-water sediment stratigraphies exhibiting erosional episodes were eliminated from correlation studies. In most cases, however, slack-water sediments accumulated in sites protected from erosion and showed no erosional unconformities.

Only floods whose backwaters are capable of overtopping previously existing slack-water sediments produce a lasting sedimentation unit in tributary mouth sequences. Floods of lesser magnitude deposit slack-water sediment as an inset terrace in the tributary canyon, and the inset sediments are rapidly reworked by subsequent flows from the tributary drainage.

Pecos River Paleoflood History

The lower Pecos and Devils rivers of southwestern Texas (Fig. 1) were selected to illustrate the use of slack-water sediments in unraveling Holocene paleoflood hydrology. Physiographically, southwestern Texas is ideal for this technique. Rivers occur in bedrock canyons deeply entrenched in the Edwards Plateau. In these boxlike canyons, increases in discharge result in tremendous rises of water stage Therefore, during large

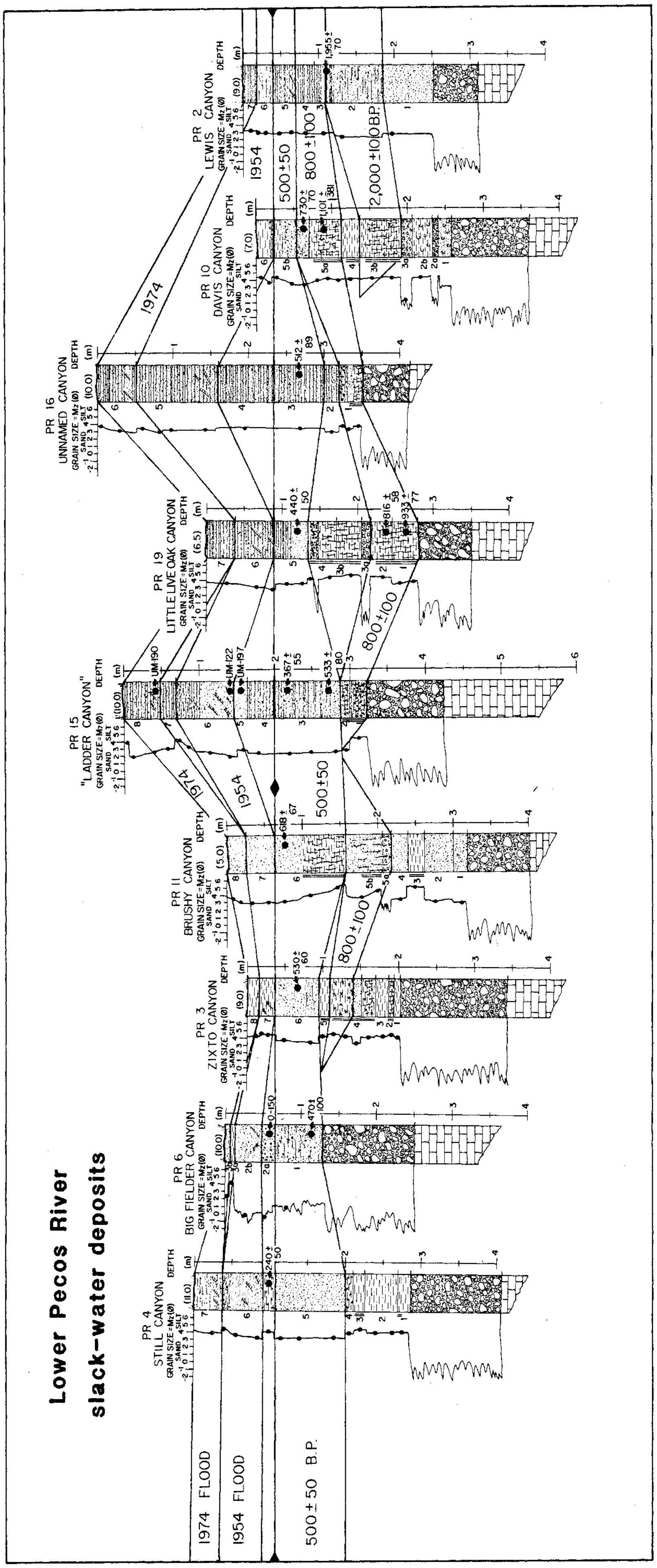

Fig. 6. Correlation of lower Pecos River slack-water sediment stratigraphies over the region. Only canyons with radiocarbon-dated sediments are shown. Locations of canyons are from Fig. 1. Mz = mean grain size; ϕ = negative logarithm to base 2 of the millimeter diameter of particles.

Table 2. Calculations of flood recurrence intervals by Eq. 2 (*13*) for stratigraphy at Arenosa Shelter (Fig. 7) (*28*); B.P., before present.

Time interval (years B.P.)	Number of floods	River stage (m)	Estimated discharge (m^3/sec)	Recurrence interval (years)
1970 ± 110 to present	3	14.8	11,320	655 ± 35
		15.4	12,450	985 ± 55
		24.4	27,735	1970 ± 110
4450 ± 150 to 4150 ± 130	4	10.1	5,095	75 ± 70
4150 ± 130 to 3330 ± 85	4	11.0	6,095	205 ± 50
3220 ± 70 to 3640 ± 80	2	11.4	6,790	210 ± 75
3220 ± 70 to 2230 ± 80	5	12.6	8,490	200 ± 30
2440 ± 140 to 1970 ± 110	1	14.1	10,755	470 ± 250

floods, slack-water sediments are deposited at high levels along channel margins and in tributary mouths. This enhances their preservation potential by placing them out of reach of subsequent floods of lesser magnitude. Bedrock channels also provide stable cross sections for relatively accurate slope-area estimates of paleodischarge. The semiarid Chihuahuan Desert vegetation of the area limits bioturbation and provides a clear stratigraphic record of paleoflooding in the sediments.

Southwestern and central Texas are characterized by one of the most catastrophic rainfall-runoff regimes in the United States (*23*). The flood frequency plot for the lower Pecos River near Langtry illustrates the flashy character of streams in this area (Fig. 5). When conventional flood frequency techniques are used, there are tremendous difficulties in assessing recurrence intervals for the 1954 and 1974 flood outliers. Before 1954, annual maximum flows plotted along the lower trend (Fig. 5). Statistical analyses by conventional flood frequency methods failed to predict the 1954 discharge, which resulted from over 100 cm of rainfall in less than 48 hours when Hurricane Alice centered over the Pecos-Devils river divide in June (*24*). A similar storm produced the large flood in 1974. Contributing runoff for both events was limited to the lower 9500 km^2 of the Pecos River drainage. The gaging station at Sheffield, Texas, 200 km upstream from the river mouth, recorded negligible increases during the 1954 storm. Along the lower 100 km of the Pecos, flood stages averaged 25 to 30 m above normal. The dilemma faced by the user of conventional flood frequency methods is apparent. Simple extension of the data from Eq. 2 results in a recurrence interval of 81 years for the 1954 event. On the other hand, extrapolating the pre-1954 trend yields a recurrence interval of more than 10 million years.

Slack-water sediment paleohydrology. Twenty slack-water sequences from tributary mouths were studied along the lower Pecos River (Fig. 1). Each site was trenched with hand shovels. The stratigraphy at each site was described and samples were collected for textural, mineralogical, and radiocarbon analyses. Slack-water paleoflood sedimentation units of radiocarbon-dated tributary mouth sites were correlated (Fig. 6). The correlations are based on stratigraphy, sediment unit thickness, sedimentary structures, buried soil horizons, buried colluvial horizons and, most importantly, radiocarbon dates (Table 1) (*25*). Correlations based on stratigraphic and sediment data must be made more cautiously. In some instances we observed slack-water sediment sequences in tributary mouths that contained only ultramodern (post-1945) sediments (*26*), whereas sequences from neighboring canyons contained sediments more than 2000 years old. Destruction of slack-water sediments may occur when tributary basins experience major floods of local origin. Floods of 500 ± 50 years ago, 1954, and 1974 were particularly useful in establishing correlations (Fig. 6). In most sequences, the 1954 sediments are the thickest units and contain the highest frequency of medium-scale, up-canyon paleocurrent indicators such as cross-bedding and climbing ripples. Mean grain size of slack-water deposits varies directly with paleoflood magnitude. Abrupt demarcations on vertical plots of grain size aid in separating the individual events. In addition, reversals of upward fining or coarsening trends sometimes occur at sedimentation unit boundaries. Variations of sediment induration result from incipient calcification of silt into sand-sized aggregates. Marked contrasts in induration occur between 1954 sediments and sediments from the underlying event of about 500 years ago. These changes are even more pronounced between the 500-year-old flood sediment and underlying sediments.

Patton and Dibble (*13*) described a sequence of interstratified cultural debris and flood sediment from the Pecos River and Rio Grande based on interpretations of archeological data obtained from excavations of Arenosa Shelter (*27*). This radiocarbon-dated sequence provides additional paleoflood information for the lower Pecos River (Fig. 7 and Table 2) (*28*). Recurrence intervals and paleodischarges were computed for 19 Pecos River floods recorded at this site (*13*).

A reliable paleoflood frequency analysis can be made for the lower Pecos River with the slack-water sediment data from tributary mouth sites (Fig. 6) and Arenosa Shelter (Fig. 7 and Table 2). Our analyses suggest that the recurrence interval for the 1974 flood is between 500 and 700 years. The events dated at 500 years ago and 800 to 1200 years ago also appear to have similar magnitude and frequency. The slack-water sediment record indicates that the 1954 flood has a minimum flood recurrence interval of 2000 years (*29*).

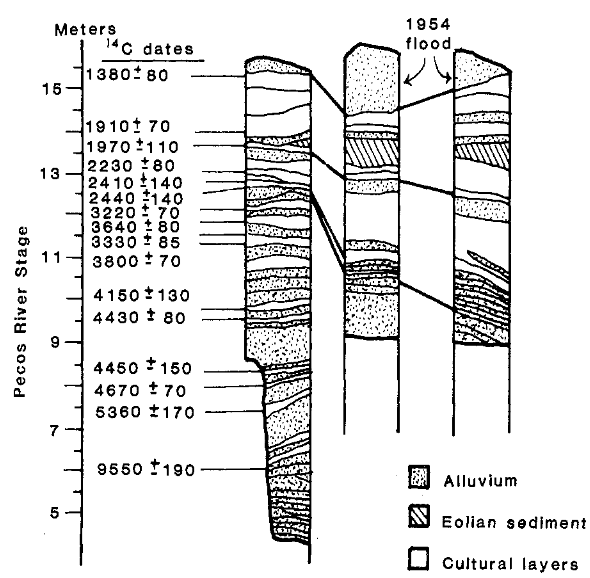

Fig. 7. Stratigraphy and radiocarbon dates at Arenosa Shelter (*28*). Flood recurrence intervals (Table 2) were calculated from Eq. 2 (*13*).

Applications of Slack-Water Sediments

Modern hydrology has many alternative methods for estimating the frequency recurrence intervals of large floods. Examples of the more commonly used approaches, applied to the lower Pecos River historical flood record, are shown in Fig. 8 (curves 1 through 7) and Table 3. Curves 1, 2, and 3 (Fig. 8) are recurrence intervals calculated by Eq. 2 from extensions of the 1900 to 1954 flood frequency relation. Curve 1 is a simple extension of the data to include the 1954 flood. Curve 2 is a similar extension, but ungaged historical data were also used. Curve 3 represents an extension of the pre-1954 relation to the 1954 discharge. Note the wide range of values indicated for the recurrence interval of the 1954 (discharge = 27,400 m^3/sec) and 1974 (discharge = 16,000 m^3/sec) floods. Curves 4 and 5 were calculated with the log Pearson type III method adopted by the U.S. Water Resources Council (*30*). For curve 4, the 1954 and 1974 outliers and the skew coefficient calculated from the sample data were used; curve 5 was derived from the outliers and a regionalized skew coefficient of −0.4 (*30*). Curves 6 and 7 were calculated with multiple regression equations developed on the basis of drainage basin morphometry in southwestern Texas (*31*).

Data are also included from our studies of slack-water sediments (Fig. 8, curves 8 and 9). Curve 8 is the flood frequency curve calculated solely from tributary mouth slack-water sediments and the Arenosa sequence. Curve 9 was developed by substituting slack-water sediment data into log Pearson calculations as historical outliers. Therefore, curve 9 incorporates historical measured data and geomorphic evidence of paleoflooding.

For recurrence intervals of less than 20 years, the agreement between various

Table 3. Comparison of different methods of calculating flood frequency on the lower Pecos River, Texas, at various recurrence intervals.

Method	Flood discharge (m^3/sec) at recurrence interval (years) of						1954 recurrence interval (years)
	2	5	10	25	50	100	
Equation 2 [(*n* + 1)/*m*]							
With outliers	560	1,817	2,515	3,075	3,250	35,000	10,000,000+
Without outliers	560	1,817	2,515	3,075	3,250	5,480	80
With historical data	560	1,817	2,515	3,075	3,250	27,000	150
Regressions based on basin morphometry (*31*)	450*	1,400	3,800	5,200	7,900	12,000	450
	115†	325	570	1,100	1,600	2,300	10,000,000+
Log Pearson type III							
With regional skew and outliers	600	1,730	3,065	5,745	8,724	12,811	400
Calculated skew and outliers	575	1,702	3,142	6,289	10,092	15,715	300
Slack-water deposits							
Deposits only						5,000	2,000
Modified log Pearson type III‡	586	1,458	2,309	3,733	5,965	6,647	11,000

*Calculated with entire Pecos River drainage. †Calculated with 1954 flood drainage only. Log Pearson data obtained from FREQFLO program of the Center for Water Resources Research at the University of Texas at Austin. ‡Modified by using slack-water floods as historical outliers.

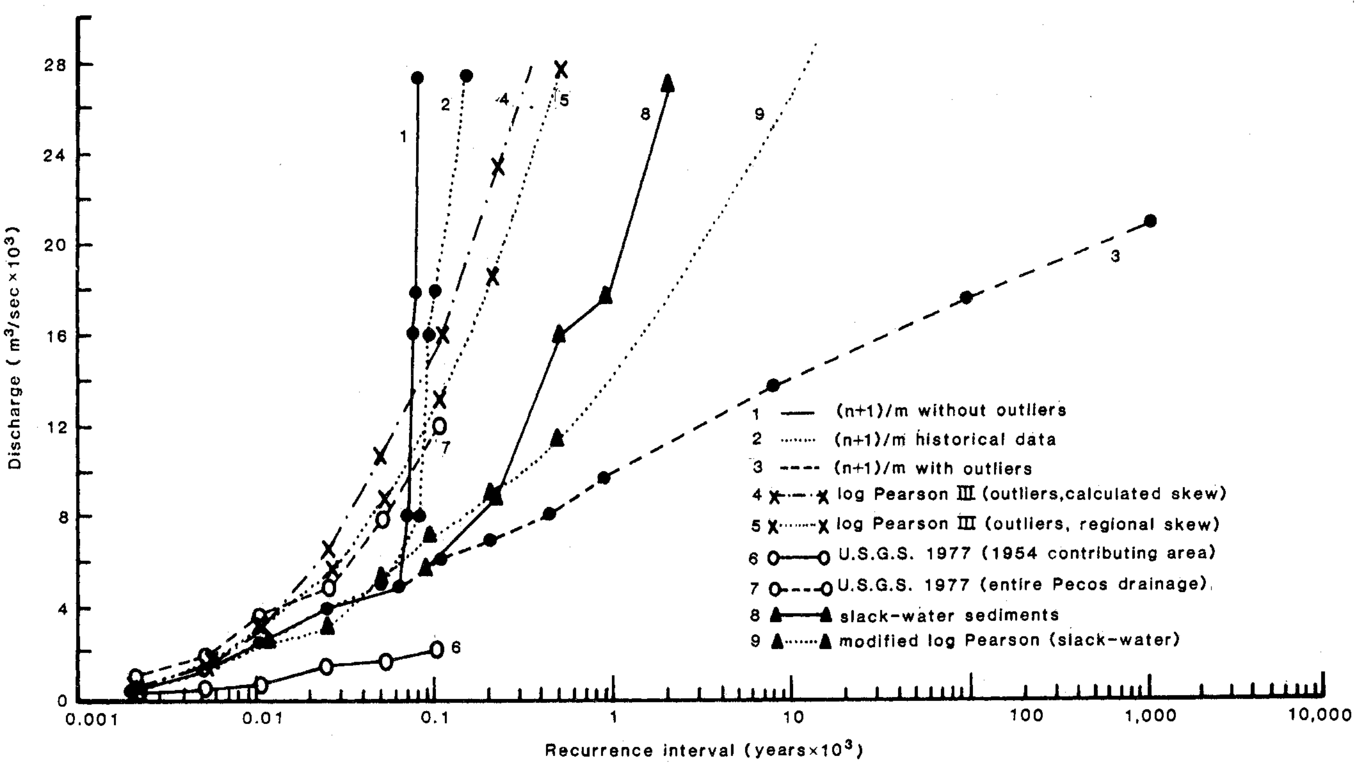

Fig. 8. Comparison of various techniques for estimating flood frequency in the lower Pecos River region near Langtry. Curves 1 to 7 illustrate techniques using historical data while curves 8 and 9 illustrate modifications using slack-water sediment data over the past 10,000 years. Data for these curves are summarized in Table 3.

flood frequency techniques is good (Fig. 8). As recurrence interval increases the disparity between the methods also increases. For the estimate of the recurrence interval of the 1954 flood, these differences exceed five orders of magnitude (Fig. 8, curves 1 and 3). When slack-water sediments are included, a more realistic estimate of 2000 years is suggested.

The problem of estimating return intervals of large floods is particularly acute in semiarid regions because of (i) the negatively skewed annual flood distributions, (ii) the large ratios of maximum discharge to mean discharge, and (iii) the short-term, widely dispersed nature of gaging records. Studies of flood sediments, especially slack-water deposits, can extend the record of flooding over 10,000 years. Records of this length are needed to establish reliable estimates of return intervals of floods whose frequency may be several times the duration of typical historical records. Because slack-water sequences preserve only a record of floods capable of overtopping their surfaces, it is likely that some large floods are neglected in this analysis. Our observations of flooding in southwestern Texas show that the 1954 and 1974 flood stages overtopped slack-water sites by more than 5 m. Thus, it is likely that few large floods were missed. In addition, we believe that flood frequency analyses should be based on all available information, particularly when historical data sets are short relative to the geomorphic record preserved in the floodplain.

Long, continuous paleohydrologic records such as the Pecos River data provide valuable information on climatic fluctuations, since they are recorded in the hydrologic response. Independent data on Holocene climates along the lower Pecos River are available from anthropological (*32*) and palynological (*33*) studies. In the Arenosa Shelter, arid phases are characterized by infrequent, large magnitude floods (*13*). In contrast, during more mesic intervals of the Holocene, there were more frequent Pecos River floods of lesser magnitude (*34*).

The application of slack-water sediment data to paleohydrologic studies in humid regions may be possible. Slack-water sediments were observed at nearly every stream junction in southeastern Pennsylvania during Hurricane Agnes (*14*). Slack-water sediments in central Virginia have been observed in association with debris avalanching and flooding brought on by Hurricane Camille (*35*). These studies suggest that slack-water deposits may be used in combination with floodplain stratigraphy and truncated landforms (such as alluvial fans) to extend flood frequency analyses throughout the Holocene in humid, temperate regions. The rapid recovery of floodplain vegetation and morphology in humid regions and greater bioturbation of sediments, in comparison with semiarid regions, underscore the importance of making these investigations as soon as possible after large floods. The technique of using slack-water deposits in paleohydrological analysis offers a relatively rapid and inexpensive way to determine the risk of catastrophic floods. This approach may be used to supplement short historical records or may be applied to regions where no data are available.

References and Notes

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17. Manning's *n* was first estimated from standard tables. These estimates were checked by solving for *n* by working the Manning equation backwards where discharges were known at the gaging station near Langtry, Texas.
18. In this case, slack-water sediments are insufficiently preserved to establish water surface slope. Therefore, channel bed slope was substituted. This provides somewhat conservative values for slope.
19. Rivers in southwestern Texas were selected because they are entrenched into resistant limestone bedrock. Significant errors in estimating paleodischarges could result in alluvial streams where large volumes of fill could be removed or could accumulate during major floods. Observations from aerial photographs indicate that during the largest flood of record on the Pecos in 1954, bedrock scour was minimal and very localized [R. C. Kochel, thesis, University of Texas, Austin (1980)]. Erosion in bedrock streams is typically greatest at meander bends and channel constrictions [M. G. Wolman and L. B. Leopold, *U.S. Geol. Surv. Prof. Pap. 282-C* (1957); R. C. Palmquist, *Geol. Soc. Am. Bull.* **86**, 1392 (1975); R. G. Shepherd and S. A. Schumm, *ibid.* **85**, 257 (1974)], or localized at discrete scour holes [P. C. Patton and V. R. Baker, in (*5*)]. The amount of bedrock scour during the time span (2000 years for tributary mouth sites) of our study is insignificant with regard to the errors inherent in slope-area estimates of paleodischarge. Geomorphic evidence indicates regional downcutting has been less than 1 m during the past 2000 years. This evidence is from observations of less than 1 m of tributary alluvium at the base of 2000-year-old slack-water sequences and from dated terrace sequences. This amount of degradation imparts insignificant errors in paleodischarge estimates because peak flood stages are commonly over 20 m.
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29. Generally, Pecos River slack-water sediment thickness is directly proportional to paleoflood magnitude at any slack-water site. However, considerable variations in sediment thickness occur in any flood unit between sites because of the geometry and cross section of the depositional site. We are attempting to further quantify the relation between sediment thickness and flood magnitude to determine if thickness can be used as an indicator of flood magnitude.
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34. No attempt was made to break up the Holocene flood record according to distinct phases of climatic fluctuation. Patton and Dibble (*13*) address this problem in the Arenosa Shelter slackwater record by performing discrete time-series analyses on floods occurring within the various climatic phases of the Texas Holocene. Our tributary mouth sites all fall within the same climatic interval, a xeric phase which extends back about 2300 years. Climatic fluctuations are significant only when the entire Holocene flood record is examined, such as at the Arenosa Shelter. We are investigating the effects of climatic fluctuations on paleoflood frequency.
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Autocidal Control of Screwworms in North America

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"Screwworm" is a name given to the larvae of several species of blowflies (Calliphoridae) which lay their eggs on or near open wounds of warm-blooded animals. Soon after they hatch, the first-instar larvae of the dipteran parasites enter the wound and feed on fluids from the living tissue, causing myiasis (*1*).

Summary. The larva of the blowfly *Cochliomyia hominivorax*, also known as the screwworm, eats the living flesh of cattle and sheep and other warm-blooded animals. A program to eradicate the screwworm in the United States was initiated in the 1950's. The program was very effective until 1968, but severe screwworm outbreaks occurred in 1972 to 1976 and in 1978. Although the program has again been effective since 1979, the possibility of outbreaks recurring in the future has highlighted the need for a broader understanding of the pest. Studies of screwworm populations in the United States and Mexico indicate that much of the genetic diversity of this insect is distributed among sympatric non-interbreeding populations. A new approach may be required to retain the effectiveness of the control program and to prevent a serious outbreak from threatening the economic viability of the U.S. livestock industry.

Mature, third-instar larvae drop from the wound and pupate in the soil. Adult female blowflies often lay their eggs on the navels of newborn livestock, pets, and wild game. The feeding larvae enlarge the wounds which thus attract more ovipositing females (*2*). Unchecked infestations cause death of even an adult host as a result of physical damage or secondary infections.

A program to eradicate screwworms [*Cochliomyia hominivorax* (*sensu latu*)] in the southern United States was initiated by the U.S. Department of Agriculture (USDA) in the 1950's. This program, which depended on an autocidal technique—the release of sterile blowflies—was completely successful in Florida, where eradication of the screwworm during 1958 and 1959 cost $10 million. In 1962 the program was expanded into Texas and the Southwest, with sterile flies being dropped from airplanes in a band two to several hundred kilometers wide along the U.S.–Mexico border (*3*, *4*). Suppression of screwworm populations was highly effective until 1968, and again in 1979 to the present. However, there were several severe outbreaks in the intervening years. Our studies of screwworms in the United States and Mexico have led us to believe that because of the genetic complexity of the screwworm populations the present approach to controlling the pest should be reexamined.

Background

Periodic outbreaks of screwworms did not become a serious problem in livestock (*5*) in the United States until the late 1800's, when there was a large increase in the number of cattle in the Southwest. New cattle trails and the construction of railroads and windmills (*6*) after the Civil War made markets and water more accessible and allowed Texas to become blanketed with cattle (*7*, *8*). The windmills were used to fill waterholes so that even in periods of drought water was usually available (*9*). A similar year-round water supply was achieved in areas of adequate seasonal rainfall by constructing earthen ponds.

The great increase in cattle led to increasing outbreaks of screwworms which, by the turn of the century, were becoming an annual curse on ranches in central Texas and along the Gulf Coast (*10*). It also led to severe overgrazing and fewer prairie fires (*11*) and, consequently, changes in the distribution of certain plants. For example, the chaparral in southwestern Texas and northeastern Mexico became a thorn forest of woody legumes, as did the central and southern Gulf Coast regions of Texas. Deer replaced the antelope as the dominant game animal, as cattle had replaced sheep (*12*). Since screwworm flies feed on the nectar of such legumes (*13*, *14*), and since, like cattle and deer, the flies are associated ecologically with watercourses, the flies, cattle, and deer were generally in close proximity and screwworm populations could rapidly expand.

According to Dobie (*8*), the importation of British cattle and the improved nutrition of the breeding stock also contributed to the increase in screwworms. Earlier, sparse winter grazing followed by spring growth of vegetation stimulat-

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