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EARTH SURFACE PROCESSES AND LANDFORMS, VOL. 11, 307–319 (1986)

CHANNEL EROSION ALONG THE CARMEL RIVER, MONTEREY COUNTY, CALIFORNIA

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Received 30 November 1984
Revised 5 March 1985

ABSTRACT

Historic maps, photographs, and channel cross-sections show that the channel of the Carmel River underwent massive bank erosion, channel migration, and aggradation in a major flood in 1911, then narrowed and incised by 1939. The channel was stable until 1978 and 1980, when bank erosion affected some reaches but not others. The narrowing and incision were in response to a lack of major floods after 1914 and construction in 1921 of a dam that cut off sediment supply from the most actively eroding half of the basin. Localized erosion in 1978 and 1980 occurred during low magnitude events along reaches whose bank strength had been reduced by devegetation. These events illustrate that the stability of a fluvial system can be disrupted either by application of a large erosive force in a high magnitude event (the 1911 flood) or in a low magnitude event, by reducing the resistance to erosion (bank devegetation).

The Carmel River is a potentially unstable system. Its discharge and slope characteristics place it near the threshold between meandering and braided. On the Lower Carmel, the presence of bank vegetation can make the difference between a narrow, stable meandering channel and a wide shifting channel with braided reaches.

KEY WORDS Channel instability Degradation below dams Groundwater withdrawal Riparian vegetation

INTRODUCTION

The role of vegetation in channel stability and as a determinant of stream width has been discussed by many authors, including Hadley (1961), Schumm and Lichty (1963), Turmanina (1963), Brice (1964), Zimmerman *et al.* (1967), Orme and Bailey (1970), Daniel (1971), Smith (1976), Graf (1978, 1981), and Charlton *et al.* (1978). Engineers have recognized the bank stabilizing properties of plants, especially willows, and have used them to control erosion and 'train' channels (Parsons, 1963; Seibert, 1968; Nevins, 1969). In general, one can observe that the relative importance of vegetation is greater for smaller streams, less for larger rivers (M. G. Wolman, personal communication, 1983).

The Lower Carmel River, Monterey County, California, is an example of a fluvial system in which loss of bank vegetation produced local widening at relatively low magnitude events in reaches that previously had responded mainly to high magnitude events. The potential instability of this system is illustrated by comparing its slope and discharge characteristics to those of other rivers. Using the event with a recurrence interval of 1·5 years (annual maxima) as bankfull, the Lower Carmel plots near the line separating braided from meandering channels on the plot of Leopold *et al.* (1964, p. 293) (Figure 4). Although this plot is generalized and must be applied with caution to a specific site, it suggests that the channel is metastable and is vulnerable to disruption if the balance between forces inducing and resisting erosion is upset.

0197–9337/86/030307–13$06.50

AIMS AND METHODS

Description of study area

The Carmel River rises in the rugged Santa Lucia and Sierra De Salinas Mountains in coastal Monterey County, California, and drains an area of about 660 km^2 (Figure 1). The upper 34 km of the river pass through steep canyons with only modest accumulations of alluvium; the lower 24 km traverse an alluvial valley (the 'Carmel Valley') before reaching the Pacific Ocean at Carmel. The alluvial fill is typically 15–20 m thick and consists of sands and gravels, with some silt and clay interbeds. The valley is generally up to a kilometre wide, but about 15 km from the mouth the valley narrows at a bedrock constriction (the 'Narrows') which divides the alluvial reach into the 'Middle' and 'Lower' Carmel River (Figure 2). In its upper reaches, the Carmel River is perennial, but in the alluvial valley, flow is intermittent, typically drying up in late summer.

The upper watershed is sparsely settled. Extensive commercial and residential development has occurred in the last three decades in the Carmel Valley, especially near the river mouth. Much of it is on lowland adjacent to the river and is clearly vulnerable to flooding.

The Carmel Basin has a Mediterranean climate typical of coastal central California, with moderate year-round temperatures. Virtually all precipitation (rain) falls between November and April, with 60 per cent falling between December to February. Rainfall decreases from an average annual total of 1040 mm in the high mountains of the southern part of the basin, to 360 mm near the valley mouth (R. Renard, U.S. Naval Postgraduate School, unpublished report to MPWMD).

Study objectives

Recent bank erosion along the Carmel River has caused property losses in excess of $1·5 million. Because of local concern, this study was undertaken to establish the causes of the erosion and to place this recent channel instability in the context of historic channel changes, natural and human-induced. Using data from a variety of sources, the history of floods, dam construction, and land use was developed and related to changes in

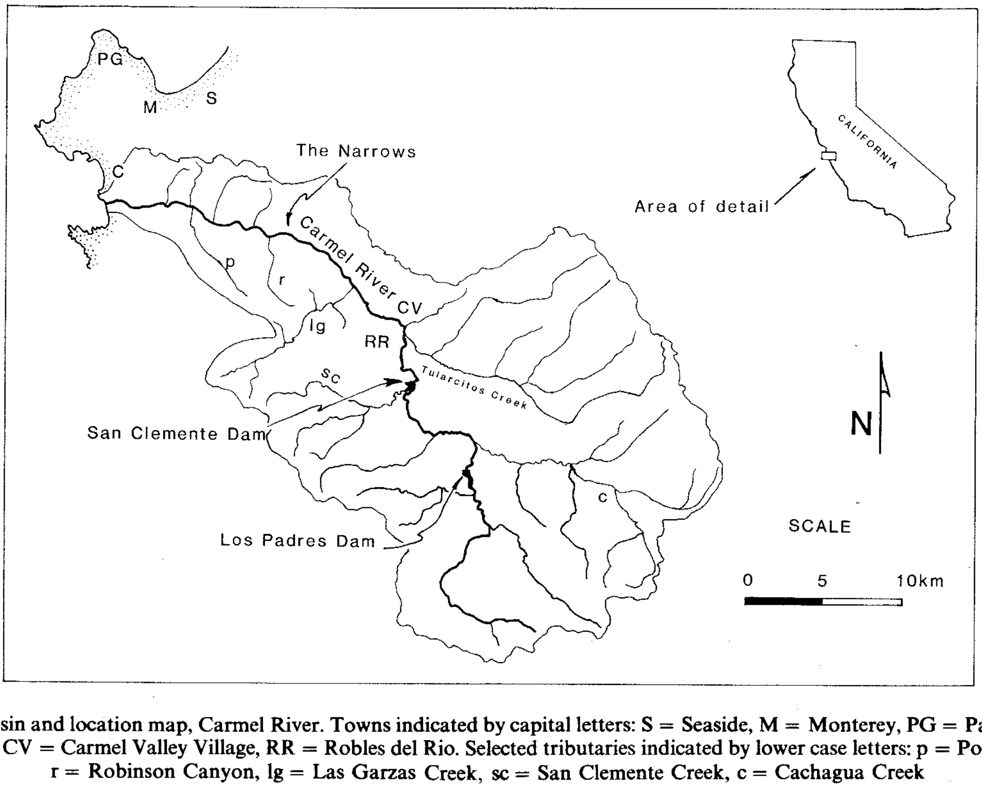

Figure 1. Basin and location map, Carmel River. Towns indicated by capital letters: S = Seaside, M = Monterey, PG = Pacific Grove, C = Carmel, CV = Carmel Valley Village, RR = Robles del Rio. Selected tributaries indicated by lower case letters: p = Potrero Creek, r = Robinson Canyon, lg = Las Garzas Creek, sc = San Clemente Creek, c = Cachagua Creek

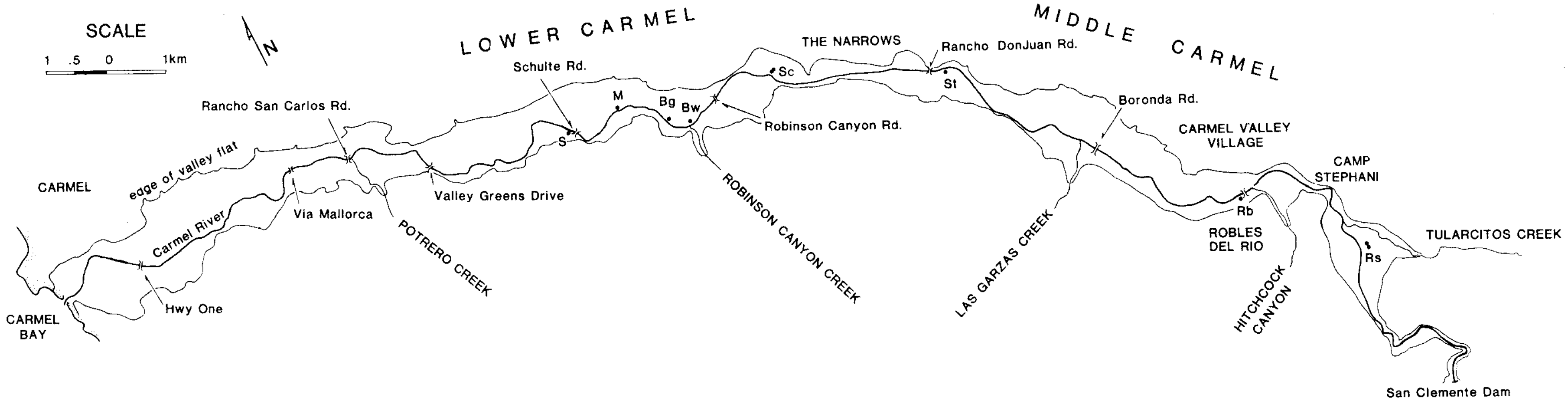

Figure 2. Location map, Middle and Lower Carmel River (Base from USGS Monterey, Seaside, and Carmel Valley 7·5′ quadrangles). Locations of Cal–Am producing wells: S = Schulte, M = Manor, Bg = Begonia, Bw = Berwick, Sc = Scarlett, St = Stanton, Rb = Robles

channel course, pattern, geometry and bed elevation. The results of these analyses were used to evaluate several hypothesized explanations for the recent bank erosion, including decreased bank resistance from loss of vegetation, degradation from closure of San Clemente Dam, and downstream variation in bank material size.

Sources of data and methods of analysis

Historic changes in channel course were plotted from boundary surveys conducted in 1858 and 1882 for Spanish land grants, and topographic maps (USGS Monterey 15′ sheet, 1913 edition; Monterey and Seaside 7·5′ sheets, 1947 and 1968 editions). Sequential aerial photographs taken in 1939, 1965, 1977, and 1980 from the collection of the Monterey County Food Control and Water Conservation District (MCFC) were studied to document changes in channel pattern and width. In addition, aerial photographs taken in other years (from the USGS, Fairchild Collection, and Map Collection at the University of California at Santa Cruz) were consulted at a reconnaissance level. Further documentation of old channel conditions was provided by ground photographs, *ca.* 1918 in the Slevin Collection, Bancroft Library, University of California, Berkeley, *ca.* the 1930s in the Pat Hathaway Collection, Pacific Grove, California, and *ca.* the 1960s in collections of Ed Lee, Carmel, Ca., and the *Carmel Pine Cone*. Other sources consulted included reports of testimony in court cases, newspaper accounts in *The Monterey Cypress*, and recollections of long-time residents (notably Roy Meadows, Meadows Lane, Carmel Valley).

Changes in channel geometry and bed elevation were documented by relocating 30 channel cross-sections surveyed in 1965 by the U.S. Army Corps of Engineers (unpublished data, U.S.A.C.A. San Francisco District). Relocation of cross-sections under bridges was straightforward and quite exact; however other cross-sections were not monumented and their relocation was not precise. Where the plotted changes were large, this imprecision was regarded as insignificant; where the plotted changes were small, the channel was regarded as essentially unchanged. At some bridges, the record could be extended back by using older cross-sections (unpublished data in files of Monterey County Surveyers and Monterey County Department of Public Works).

A flood chronology was developed from records of USGS gauges established in 1958 and 1963 (Nos. 11143200 and 11143250), and from a less reliable gauge maintained at San Clemente Dam by California–American Water Company (Cal–Am) since 1938. A pre-1938 flood history was developed from sources described above. Flood frequency plots and hydraulic geometry plots were developed from gauging station data. Drillers logs, observation well data, and pumping records were obtained from MCFC and Cal–Am. Bed and bank sediments, where exposed, were observed and sampled, and channel gradient was measured from topographic maps and field surveys. As the analysis proceeded, reaches of the river were classified as to slope, grainsize, and degree of stability in different time periods.

CHANNEL CHANGES TO 1965

Major floods occurred on the Carmel River in 1862, 1911, and possibly 1914. Little is recorded of the 1862 flood, but effects of the 1911 flood are documented. Newspaper accounts report that entire orchards were lost to bank erosion (*Monterey Cypress*, 11 March 1911), and old maps show that the course of the river shifted as much as 0·5 km during the flood (Kondolf, 1982). The peak discharge has been estimated at over 570 m^3s^{-1} at San Clemente Dam, on the order of a 100-year flood (U.S. Army Corps of Engineers, 1967). In 1914 another major flood occurred, but there is little evidence of its magnitude and none that it produced marked changes in course. It may have been much smaller than the 1911 event, or it may have caused less disruption simply because it flowed through a channel already enlarged by the 1911 flow. No major floods have occurred since.

In the decades that followed, the Lower Carmel and the Middle Carmel exhibited different changes. On the Lower Carmel, photographs taken in 1918 show a wide unvegetated channel, as yet unrecovered from the 1911 (and 1914) flooding (Slevin Collection, Bancroft Library, U.C. Berkeley). By 1939 (date of the first comprehensive aerial photography), the channel had narrowed, incised, and developed a dense riparian forest, and the channel bed from the 1911 flood stood 4 m above the incised stream as a fill terrace that can be clearly followed for 9 km (Figure 3). By 1965, the date of the first systematic channel surveys (U.S. Army

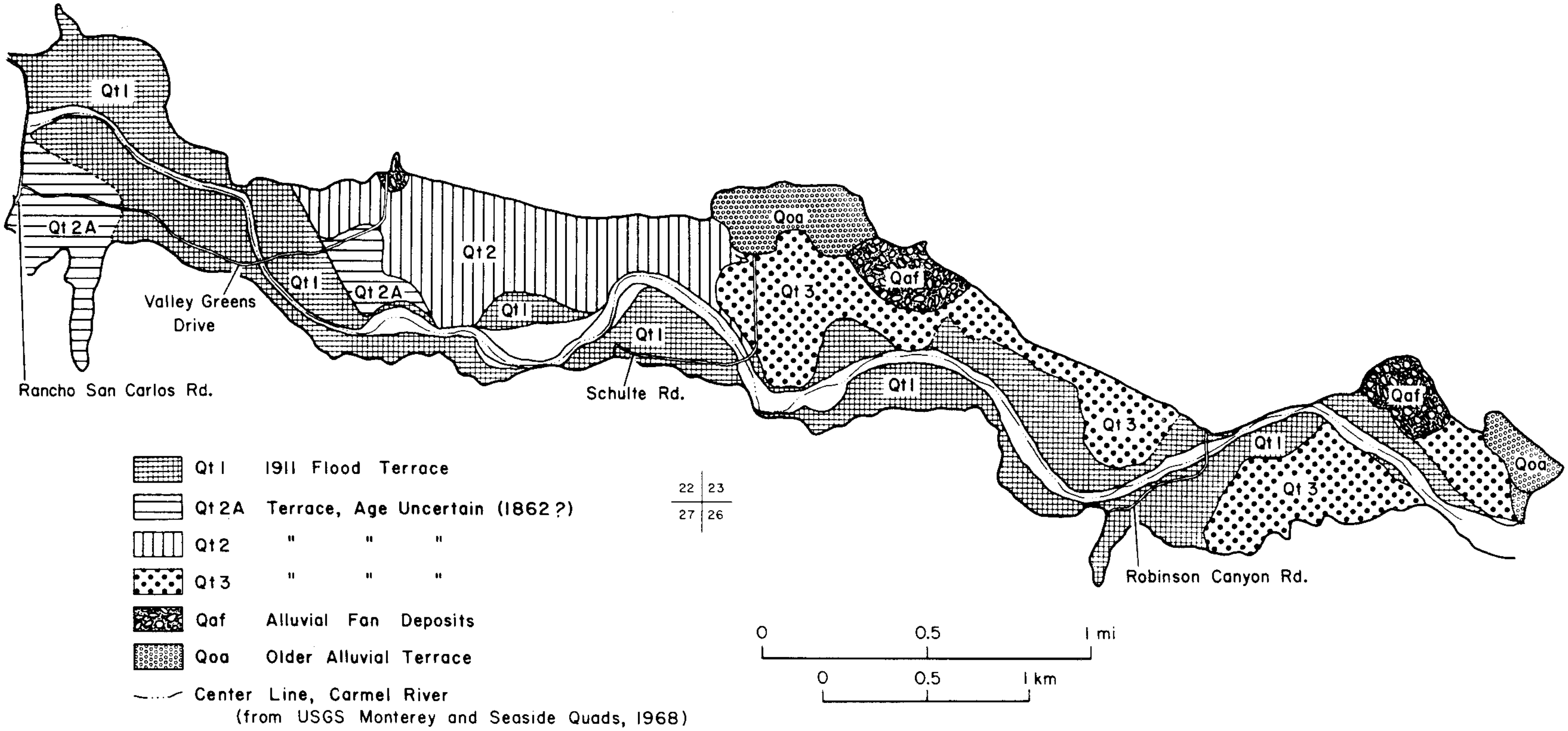

Figure 3. 1911 Flood Terrace and other Quaternary deposits of the Lower Carmel Valley, from the Narrows to San Carlos Road. Based on reconnaissance-level study of aerial photographs and field observations

Corps of Engineers, unpublished data), the channel incision and narrowing were complete. In fact, comparison of aerial photographs from 1939 with those of later years shows that the Lower Carmel changed little until the recent bank erosion.

In contrast, the Middle Carmel showed continued change from 1939 to 1965, and 1965 to the present. The channel became less braided from 1939 to 1965. From 1965 to 1982 the channel continued to incise and migrated laterally in many locations. Some specific causes contributing to the incision and lateral erosion can be identified (such as local straightening of the river for highway improvement) but much of the change may be due to the inherent instability of this steeper reach of the river. The overall gradient of the Middle Carmel is 0·005 compared to 0·003 for the Lower Carmel. The Middle Carmel plots in the braided portion of the graph defining channel pattern for streams on the slope vs. discharge plot of Leopold *et al.* (1964, p. 293; Figure 4).

Channel narrowing and incision are typically observed on rivers as they recover from major aggradational floods (Wolman and Gerson, 1978), so it is reasonable to regard the changes on the Carmel River as elements in recovery from the floods. However, the story is complicated by another event whose effects would be similar: dam construction.

In 1921, San Clemente Dam was constructed 29 km upstream from the mouth (Figure 1); in 1946 Los Padres Dam was constructed 11 km farther upsteam. Both reservoirs are small (2·65 million m^3 and 3·95 million m^3, respectively at closure) and have little effect on flood flows. However, the supply of bedload-sized sediment was cut off from the watershed upstream of San Clemente Dam. The basin upstream of the dam encompasses nearly 50 per cent of the total drainage and includes the areas of steepest relief and highest rainfall, so it was probably a major source of bedload to downstream reaches.

Sediment yields from the areas upstream of the dams, computed from reservoir sedimentation data, indicate minimum average sediment yields of about 160 tonnes/km^2/y for San Clemente Reservoir and 1050 tonnes/km^2/y for Los Padres Reservoir. The sediment yield value for San Clemente is low, in part, because sediment from half its drainage area has been trapped in Los Padres Reservoir for 39 of the last 64 years. The sediment yield for Los Padres is high because of the high erosion rates resulting from a major fire in the drainage basin in 1977 (Hecht, 1984). However, tree ring studies at a nearby site indicate natural fire frequencies from 1640–1907 averaged once per 21 years (Griffen and Talley, 1981), so fire-augmented, high sediment loads were probably typical for the Carmel in recent centuries before dam construction.

By reducing the supply of bedload to downstream reaches, dam construction on the Carmel River could be expected to induce channel narrowing, incision, and increase in sinuosity, changes that have been documented on many rivers following upstream dam construction (Williams and Wolman, 1984). Because recovery from a major aggradational flood and response to upstream dam construction induce similar responses, and because both occurred at about the same time on the Carmel River, it is difficult to separate their relative impacts in this case.

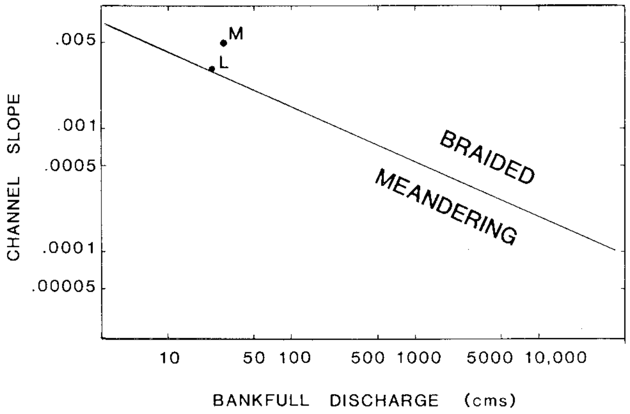

Figure 4. Channel patterns plotted by slope and bankfull discharge, with Middle (M) and Lower (L) Carmel plotted on graph. Original figure from Leopold *et al.* (1964, p. 293)

CHANNEL CHANGES SINCE 1965

Although the Middle Carmel was still undergoing adjustments from 1939 to 1978, the Lower Carmel was essentially stable over those four decades. Since 1978, however, the 15 km long Lower Carmel exhibited two distinctly different behaviour patterns: the downstream half remained stable, while the upstream half experienced extensive bank erosion. Bank erosion began in 1978 and increased in 1980. The most extensive bank erosion occurred in the reach upstream of Schulte Road bridge, where relocation of a U.S. Army Corps of Engineers cross-section site 30 m upstream of Schulte Bridge shows an increase in width from 25 to 65 m between 1965 and 1982 (Figure 5). The degradation apparent in this section occurred after 1980, and was subsequent to, not a cause of, bank erosion.

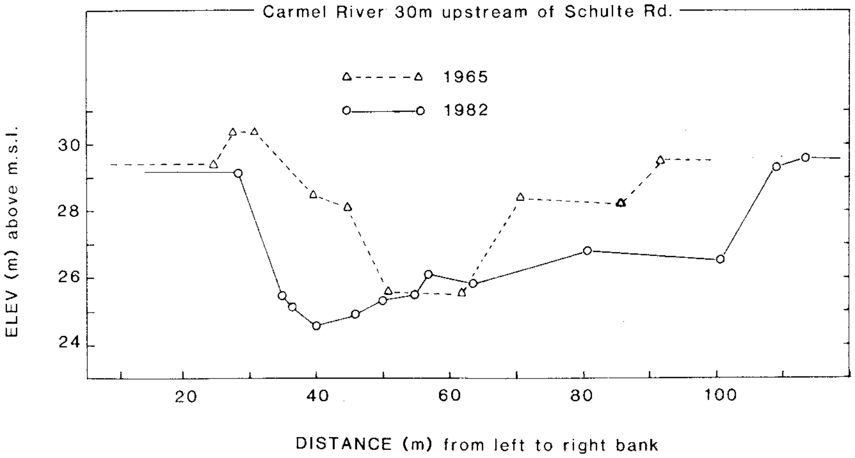

Figure 5. Sequential changes in channel cross-section of the Carmel River 30 m upstream of Schulte Road bridge. 1965 data from U.S. Army Corps of Engineers, San Francisco Office. 1965 section was not documented, so location may not be precise

The magnitude of this erosion is visible on sequential aerial photographs. Between 1977 and 1980, active channel width increased dramatically over a 0·6 km reach from Schulte Road to Manor Well (Figure 6C–D). The massive bank erosion resulted in aggradation in the eroding reach. Subsequent flows of 1982 were not as high and resulted in less bank erosion, but served to remove some of the aggraded sediment from the eroded reach, while high flows in 1983 produced further channel widening in the unstable reaches.

Altogether about 490,000 m^3 of bank material were eroded on the Lower and Middle Carmel in 1978,and 1980 (Fred Geiger, Monterey County Flood Control, personal communication, 1982), with an estimated 100,000 m^3 eroded from the 0·6 km reach from Schulte Road to the Manor Well. This sediment has, for the most part, been transported downstream to the lagoon and offshore canyon. Although residents report that some downstream pools have filled with sediment, sequential cross-sections at and near bridges show no significant changes in bed elevation. If the eroded material were evenly distributed over the channel bed downstream of Schulte Road, aggradation of about 1·9 m would be expected.

It is notable that the bank erosion occurred only upstream of Valley Greens Drive. Not only was the lowermost 8 km reach free of unusual bank erosion, but this narrow, vegetated channel remained stable despite passage of this increased load of sediment from the eroded reach. Some change in hydraulic parameters must have occurred for the downstream reach to accommodate its increased sediment load. Since no overall change in width and depth is evident, reduction of roughness through filling pools and burying riffles by finer sediment is likely.

The flows that produced the bank erosion were not unusual events. The peak flow of 1978, 208 m^3s^{-1}, was an eight year event (annual maxima), the peak flow of 1980, 166 m^3s^{-1}, a six year event. Any explanation for the bank erosion must account for its localized nature and its lack of precedent given the low magnitude of the events that produced it.

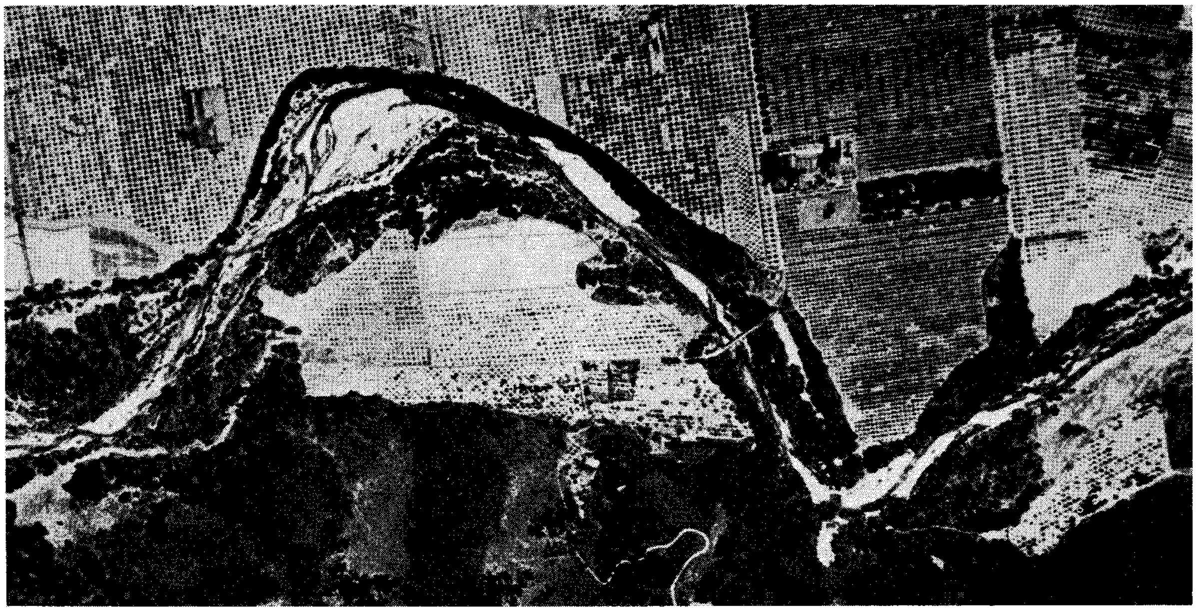

Figure 6A

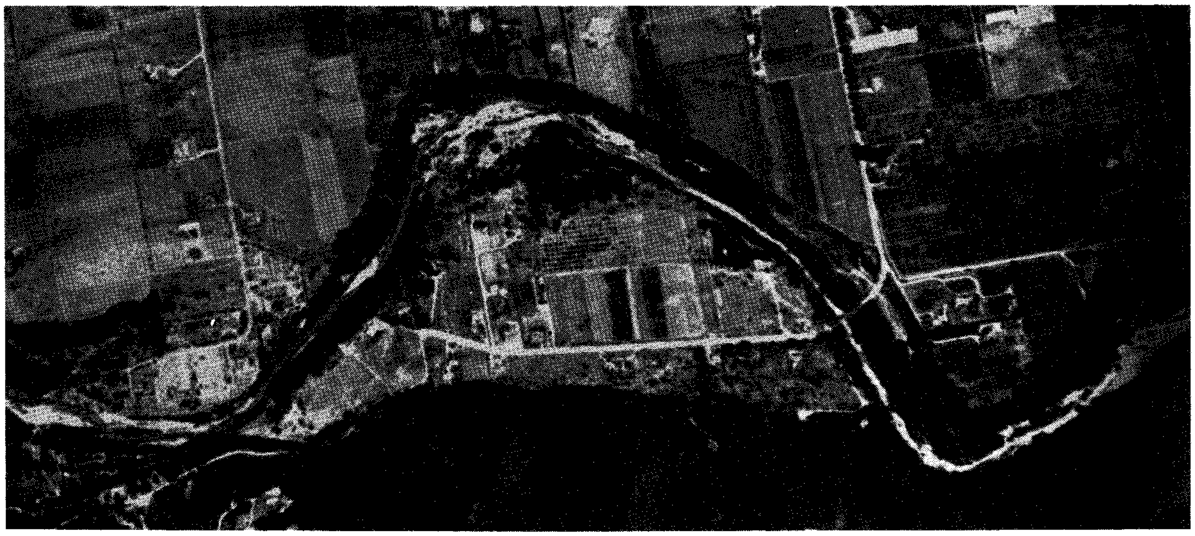

Figure 6B

BANK DEVEGETATION

The timing and distribution of bank erosion on the Carmel River are best explained by reference to bank devegetation caused by a lowered water table near municipal supply wells.

The Carmel River supplies most of the water for the Monterey Peninsula, and demand for water has increased as population has grown. The reservoirs were small when built, and sedimentation reduced their capacity further. Shrinking reservoir capacity and increasing demand over the past two decades led California–American Water Company (Cal–Am), a private utility, to draw increasingly upon water supply wells in the alluvium along the Lower and Middle Carmel. One of the first wells pumped heavily was the Berwick Well (Figure 2). By the late 1960s residents were complaining that trees were dying around the well

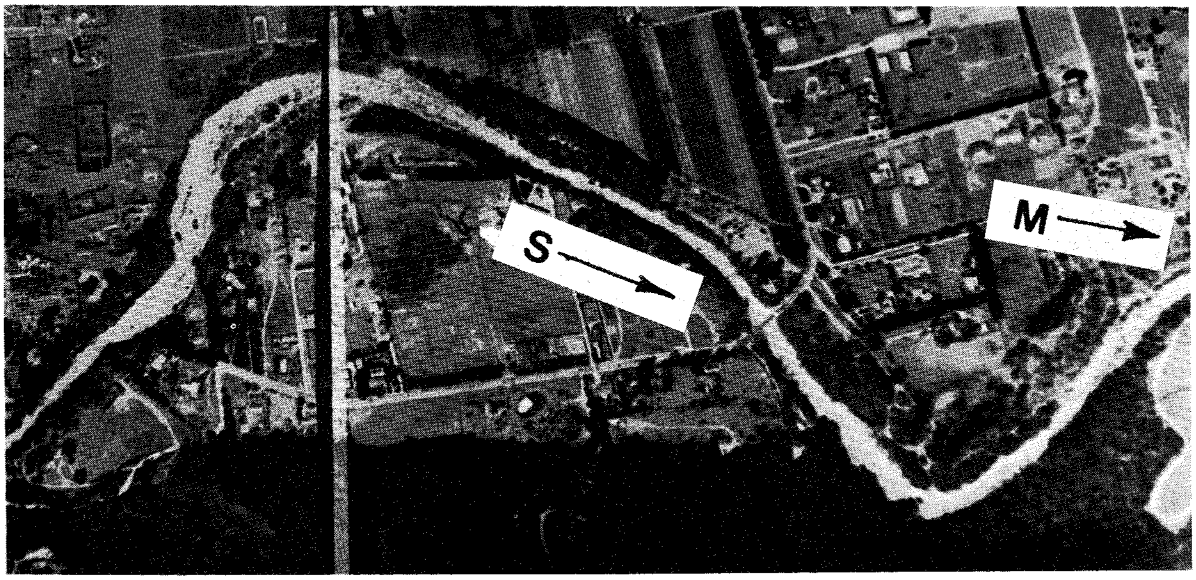

Figure 6C

Figure 6D

Figure 6. Aerial photographs, Schulte Road reach, 1939–1980. (A) 1939. A healthy but not uniformly dense riparian zone is visible. The channel had experienced a 20-year flood the previous year. (B) 1965. Riparian vegetation has grown more uniform, and encroached on formerly bare channel floor, narrowing active channel slightly. No major change apparent since 1939. (C) 1977. The riparian forest has visibly thinned. Clearing accounts for some of this thinning, but near the Manor Well, the once-live forest now consists of dead trees. Arrows point to locations of Manor Well (M) and Schulte Well (S). Some bank erosion has occurred, primarily on the outside of the large meander bed downstream of Schulte Road bridge (left side of photograph). (D) 1980. Massive bank erosion over most of reach, notably at bend upstream of Schulte Road bridge. Between Schulte Road bridge and Manor Well, approximately 100 m^3 of bank material was eroded in 1978 and 1980. Flow is from right to left. Source: Monterey County Flood Control and Water Conservation District air photo collection

(Lee, 1974), and a report by Zinke (1971) concluded that lowered water tables near the wells killed the vegetation.

As the demand for water increased, more wells were drilled and pumping increased, especially during the severe drought of 1976–1977 (Figure 7). Production from the wells reached a peak in 1976 and then decreased in 1977 because the aquifer (unconfined alluvium about 30 m thick and 0·5 km wide) was locally depleted.

Runoff in the Carmel basin is in response to rainfall and reflects the seasonal pattern of wet winters and dry

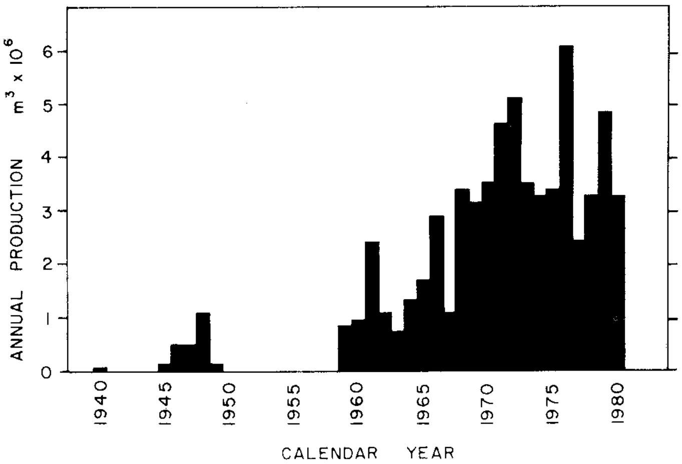

Figure 7. Annual production, Mid-Valley wells through 1980. Values are cumulative annual production for Scarlett, Berwick, Manor, Schulte, Dollar, Thacker, and Begonia wells. With exception of Dollar and Thacker, all wells located on Figure 1. Source: Cal–Am production records

summers. In normal years, the alluvium of the Carmel Valley undergoes a seasonal cycle of recharge by early winter flows, loss of water from bank storage in late spring, and drawdown of the unconfined alluvial aquifer by pumping. The pumping occurs year-round, but the drawdown is most pronounced in summer and early fall, when streamflow is not adequate to recharge the aquifer (Maloney, 1984).

During the two years of drought, the aquifer received almost none of its usual annual recharge from river flow. The lack of recharge combined with heavy pumping produced unprecedented drawdowns, exceeding 10 m over 4 km of the river. Downstream of the pumped reaches drawdown was minimal. Figure 8 compares autumn drawdown in a normal flow year (1980) and the extreme drawdown of the second drought year (1977) with the normal recharged level of the water table after a normal winter flow season (1978). The concentration of drawdown in the zone of most intense pumping supports the interpretation that the wells were primarily responsible for the depletion of the aquifer. Moreover, Kapple and Johnson (1980) report that drawdown in the pumped reach was so large that the hydraulic gradient was in the upvalley direction for much of the aquifer downstream of the Schulte Well.

Phreatophytes in the pumped reach were deprived of water for much of the two-year drought; as a result, many died. Although no one measured willow stress during the drought, Woodhouse (1983) has since found that willows are stressed near pumping wells in the Carmel Valley. Downstream of the pumped reach, phreatophytes remained healthy.

The reaches of the Carmel suffering severe drawdown and die-off of phreatophytes over the 1976–1977 drought were sites of bank erosion in 1978 and 1980. In Figure 8, the association of bank erosion (measured from cross-sections and aerial photographs) and drawdown is shown with bank erosion as measured on an arbitrary scale of *severe* (typically 30 m), *moderate* (locally variable; many reaches unaffected, many reaches with erosion, typically 10–20 m, but locally more or less), or *none* (typically no erosion, but local erosion of generally 10 m or less).

Sequential aerial photographs for the most severely eroded reach, upstream of Schulte Road, (Figure 6A–D) show the channel form essentially unchanged from 1939 to 1977. However, changes in the riparian vegetation are apparent: from 1939 to 1965, the riparian cover increased somewhat (Figure 6A–B); from 1965 to 1977 it had noticeably thinned around the Manor Well (Figure 6C). Following the flows of 1978 and 1980, active channel width had increased dramatically over the reach (Figure 6D), from 40 to 110 m at one section.

Most of the erosion occurred in 1980, despite a higher peak discharge in 1978. This is attributable to two factors: (1) The 1980 flow was of longer duration than the 1978 flow. The average daily discharge at Carmel exceeded 57 m^3s^{-1} for 6 days in 1980, but only two days in 1978. (These flows and durations were equalled or

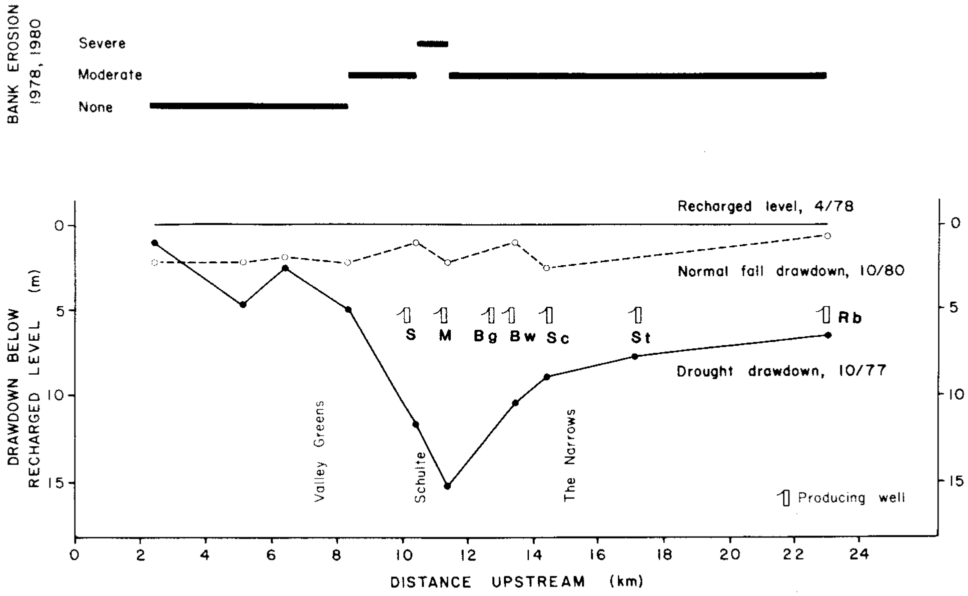

Figure 8. Water table drawdown and occurrence of bank erosion, Carmel Valley. See text for explanation. Sources of data: Monterey County Flood Control Records, Cal–Am, and field observations. Wells identified as in Figure 1

exceeded many times in the preceding decades with no comparable erosion.) (2) The roots of the willows killed in 1976–77 had decayed for another two years. Studies conducted on other species show that roots less than 17 mm in diameter are most effective in binding soil, and roots of this size generally decay within a few years after the death of the tree (Ziemer, 1981a, 1981b; O'Loughlin and Watson, 1979).

OTHER HYPOTHESES

Other hypotheses have been advanced to explain the bank erosion of 1978 and 1980. Carlson and Rozelle (1978) concluded that bed degradation, caused primarily by construction of the San Clemente Dam, was the 'underlying cause of enhanced bank erosion . . .' (p. 7.1). They also cited differences in bank material size as determinants of the distribution of bank erosion.

The historical record demonstrates that indeed the channel of the Lower Carmel incised after closure of San Clemente Dam, but the incision was essentially complete by 1939. This is consistent with published observations that degradation below dams proceeds rapidly at first, then slows as a new equilibrium profile is achieved, typically after a period of 20 years or less (Williams and Wolman, 1984; Leopold *et al.*, 1964, pp. 454–457). Given that channel incision preceded the bank erosion by four decades, it is unlikely that the one is cause of the other.

There is no evidence that the grain size of bank material differs between the unstable reach near Schulte Road and the stable reaches downstream. Drillers' logs show essentially the same heterogeneous mix of sand, gravel, and silt underlying both reaches (Cal–Am, unpublished data; MCFC, unpublished data). As shown in Figure 3, the Carmel is flanked by the same fill terrace from the 1911 flood at least from Rancho San Carlos Road to the Narrows. Where exposed in cut banks along the eroding reach, these deposits are seen to be non-cohesive interbedded sands, gravels, and silts, sediments that offer little resistance to erosion when exposed. Along the stable reaches, however, these bank sediments are not exposed. Instead, the channels are fringed by a dense wall of trees, and, most importantly, the toes of the banks are armoured with a mat of fine roots, which must be breached before the underlying bank materials are exposed to flow. Thus, even if differences existed in bank material size, the river would not be influenced by them until the stabilizing armour of vegetation had been pierced. Photographs of what is now the unstable reach show that it too had a mat of willow roots exposed along the bank toe before the effects of pumping were manifest.

CONCLUSIONS

The channel disruptions resulting from the 1911 flood and the bank destabilization of 1978 and 1980 provide a sharp contrast. The 1911 flood was a high magnitude event, with erosive forces vastly exceeding bank resistance. Massive channel widening resulted along the entire Lower and Middle Carmel. The 1978 and 1980 flows were low magnitude events, but channel widening occurred in local reaches where resistance of banks had been reduced by pumping, drawdown, and die-off of phreatophytes. For the severely eroded reach upstream of Schulte Road, the bank erosion of 1978 and 1980 was comparable to the channel widening effected by the 1911 flood. Downstream reaches, unaffected by pumping, maintained healthy bank vegetation, and experienced no major erosion. Clearly, the flows of 1978 and 1980 were not inherently more erosive than other low-magnitude events, but the banks were more erodible in a limited part of the river.

Channel stability in a system like the Carmel, so near the threshold between meandering and braided, is a precarious condition, subject to disruption by large flows or by local decreases in bank resistance. In banks composed of unconsolidated sands and gravels, willows are an important contributor to a bank's ability to resist erosion. Willows may be adversely affected by clearing of riparian forests for development, by phreatophyte elimination programmes, or by dropping the water table. It is encouraging that the well-vegetated narrow channel downstream of the unstable reaches remained stable, despite the enormous increase in bedload from the bank erosion. This implies that instability need not translate downstream, provided bank resistance is not otherwise affected.

ACKNOWLEDGEMENTS

This study was supported by a contract with the Monterey Peninsula Water Management District. For many helpful suggestions and criticisms, the authors are indebted to many, most notably John Williams, Luna Leopold, Barry Hecht, Gary Griggs, Bob Garrison and Gerry Weber. Mitch Swanson, Paul Boison, Graham Matthews, Larry Turner and others helped in the field and with ideas. Critical reviews of this manuscript by John Williams, John Cady, Robb Jacobson, Keith Richards, M. Gordon Wolman, and anonymous reviewers are gratefully acknowledged.

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