Interdependence of Groundwater, Riparian Vegetation, and Streambank Stability: A Case Study[1]

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Abstract. Groundwater is closely coupled with streamflow to maintain water supply to riparian vegetation, particularly where precipitation is seasonal. A case study is presented where Mediterranean climate and groundwater extraction are linked with the decline of riparian vegetation and subsequent severe bank erosion on the Carmel River in Carmel Valley, California.

INTRODUCTION

By their nature, riparian systems require far greater amounts of water than other terrestrial ecosystems. Groundwater is often a critical source of supply to maintain the riparian zone, particularly in climatic regions with seasonal precipitation. The slow drainage by aquifers which intersect streamcourses serves to maintain channel flow during dry periods and to support the plant species which structure the productivity and character of the riparian ecosystem. This balance may be particularly sensitive to alteration. Removal of water from the system below a certain threshold equates to reduced productivity since water stress necessitates stomatal closure and loss of carbon fixation. This is especially so with riparian species since they are adapted to moist habitats and are, as a group, relatively intolerant to drought stress. Repeated or prolonged removal of water from the system, especially during dry periods may therefore induce severe impact to riparian vegetation.

Alluvial valley fill is generally an excellent source of groundwater to supply man's needs where high permeability, storage and rapid recharge from streambed infiltration exist. This is true of the Carmel Valley aquifer which is tapped for supply to regional development and the Monterey Peninsula in particular.

This study documents the link between the groundwater extraction from the Carmel Valley aquifer and the decline of riparian vegetation along a two mile section of the Carmel River. Subsequent severe bank erosion along the impacted stretch can be explained by loss of root stabilization.

Groundwater development, while necessary for man's activities, should be sensitive to potential impacts and be planned accordingly. The potential for degrading riparian areas and subsequent erosion is widespread in western North America. In addition to the Carmel River, groundwater pumping has been implicated in impacts to riparian systems along the Platte River drainage in Colorado[3], the Arkansas River in Kansas and Oklahoma[4], the Owens River drainage in California[5] and the Gila River drainage in Arizona (Judd, et al. 1971).

PHYSICAL CHARACTERISTICS

The Carmel River drains an area of 255 square miles in the northern Santa Lucia Mountains of California's Coast Range. The watershed extends from a divide elevation of over 5,000 feet to sea level where the river discharges into the Pacific Ocean just south of Monterey Bay.

Physical characteristics distinguish the Carmel River's upper and lower reaches. The upper river and its tributaries flow in steep, narrow, "V" shaped canyons cut into Pre-Tertiary igneous and metamorphic bedrock. In its lower 15 miles, the Carmel River flows through an alluvium-filled basin underlain by Miocene marine shales. The alluvial soils of the Carmel floodplain are typically poorly developed and coarse textured.

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[3]Glenn L. Crouch. 1982. Personal conversation. U.S. Forest Service, Rocky Mountain Forest and Range Exp. Sta., Fort Collins, Colorado.

[4]Lloyd E. Stullken. 1984. Personal conversation. United States Geological Survey, Garden City, Kansas.

[5]Groeneveld, D.P. and T.E. Griepentrog. 1982. Integrating environment with groundwater extraction. ASCE Preprint 82-026. Paper presented at the ASCE Annual Convention, April 26-30 at Las Vegas, Nevada.

The basin receives from 14 to 40 inches of annual precipitation mostly in the January-April period. Seventeen inches per year is the approximate regional average. The Carmel River discharge averages just under 100 c.f.s. on a long-term basis but measured flow has been as high as 8,620 c.f.s. in 1969 to zero flow during late summer of drier years.

DOMINANT VEGETATION

Low water retention of the floodplain soils restricts plants in the riparian zone to either xeric or phreatophytic habit due to the long summer dry period. The water loving species are maintained by shallow groundwater and surface water flows from the recharge received during winter and spring precipitation.

Trees dominate the mature riparian forest along the Carmel River. Although the composition of the riparian forest varies highly with location, within the more pristine stands it is composed of approximately 60 percent red willow (Salix laevigata), black cottonwood (Populus trichocarpa), 30 percent and 10 percent California sycamore (Platanus racemosa) and white alder (Alnus rhombifolia) combined.

Two distinct zones of riparian vegetation cover and health can be viewed along the lower twelve miles of the Carmel River. The lowermost four miles inland from the ocean is overgrown with nearly continuous red willow crowns where encroachment has narrowed the riparian forest to a strip lining the riverbank.

The next linear eight miles upstream have markedly reduced riparian cover (Fig. 1). The bank between clumps of the remaining riparian tree species is sparsely vegetated with weedy perennials, annual grasses and xeric shrub species. The denuded riverbanks here show conspicuous erosion. A 2.2 mile portion of this zone was chosen for detailed study of vegetation history.

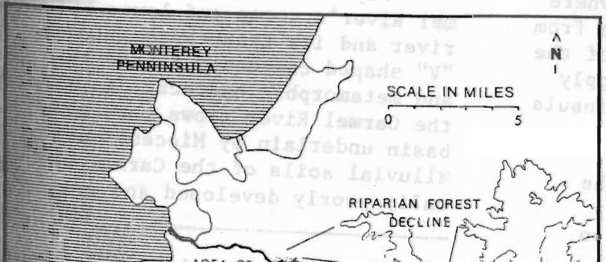

Figure 1.--The lower Carmel River Region. Contour intervals are 1,000 feet.

Riparian Forest Changes Through Time

The two zones of riparian cover observed during field survey is strikingly evident on recent (1980) air photographs. By contrast, an analysis of pre-1960 air photographs indicated that the river supported a continuous cover of riparian forest. A series of six photograph sets of suitable quality were assembled to document the change of riparian vegetation through time; black and white United States Soil Conservation Service (1956, 1966, 1971 and 1974), United States Forest Service color (1978) and color infrared obtained from a private source (1980).

Plant cover observed on the air photographs were mapped onto a base prepared from the U.S.G.S. Seaside 7.5 minute quadrangle enlarged to 1:6,000. A zoom transfer scope outfitted with optics for correcting distortion enabled keying the covertypes into correct position and scale by referring map features to the ground images on the air photographs.

Vegetation mapping categories were kept simple to accommodate the range in detail observable on the widely different scale, contrast and quality of each photo set. Three covertype categories were keyed to layers of vegetation greater and less than ten feet in height, and unvegetated river alluvium. Canopy height was inferred by cross-referencing eave height on one story houses adjacent to the floodplain using an eight power mirror stereoscope to accentuate three dimensional depth of field. The streambed was differentiated from the annual grass meadow cover by texture and tone on the black and white film and by color on the color infrared and color photo sets.

The mature riparian trees are all taller than ten feet. Therefore, within the floodplain, the map category for tree cover accurately represents the riparian forest. Field checking eliminated trees that were planted and maintained by man.

The time series of maps shown on Figure 2 documents the thinning of the riparian forest readily observable on the photographs. Loss of riparian forest cover over the 24 year period is visible initially in the upstream section toward the right of the 1966 map. Gradually the forest cover lessens in the remaining sections of the study area until, by 1978, the riparian forest cover is discontinuous with much of the remaining vegetation surviving at some distance from the channel margins. In 1980, the riparian cover is reduced even further and the river channel has widened dramatically, particularly in the downstream sections.

Following further analysis, tree pathogens, fire and encroachment by man were ruled out as possible causal agents for the decline of the riparian forest. The decrease of riparian trees coincides with the gradual development of the Monterey Peninsula and the wells to export groundwater to meet the increasing demand. The well field extracts water from the river alluvium within the zone of vegetation impact noted both in the field and on the air photographs. The operating wells in the vegetation study area are indicated on Figure 2 in the sequence of development and use.

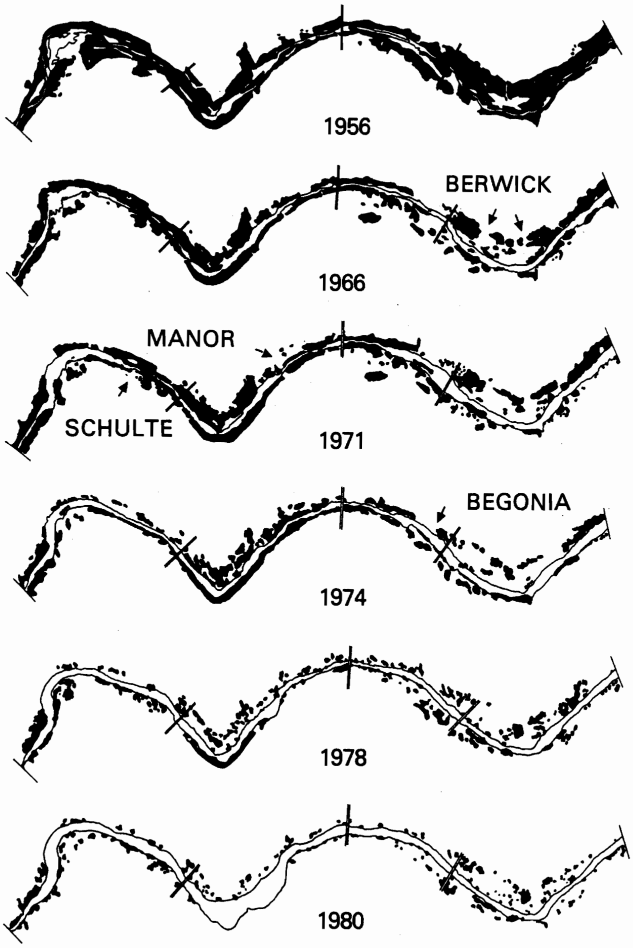

Figure 2.--Time series maps of the study area with the riparian forest indicated. The study area is divided into 4 sections according to the location of high capacity export wells.

GROUNDWATER HYDROLOGY AND PLANT RESPONSES

A water budget assessment of the study area was made for the study area which included quantifying gains and losses to the system. Recharge to the study area comes directly from precipitation on the valley floor, runoff from the bordering valley sides and tributaries, deep percolation from surface irrigation and septic systems, agriculture return flow, down-valley groundwater flow through the alluvium and in the river channel. Disposition occurs via evaporation, transpiration, consumptive domestic uses, outflow of the Carmel River, downgradient drainage through the alluvial aquifer and from pumping for export.

Based upon conservative estimates, the water budget indicated that local consumptive use as an annual total was only about eight percent of the aquifer capacity and was spread throughout the year. By contrast, pumping for export was seen to demand a large proportion of the aquifer capacity. The down valley groundwater flow and infiltration from the channel flow, when available, tend to recharge the basin at a rate slower than pump extractions. This recharge somewhat buffers the drawdown in the system so the drawdown from pumping tends to be greatest during late summer and fall. The five foot isocontour of groundwater drawdown from the spring high levels to an October low are plotted on Figure 3. These zones of influence encircle the export wells and correspond well with the zones of riparian vegetation decline on Figure 2.

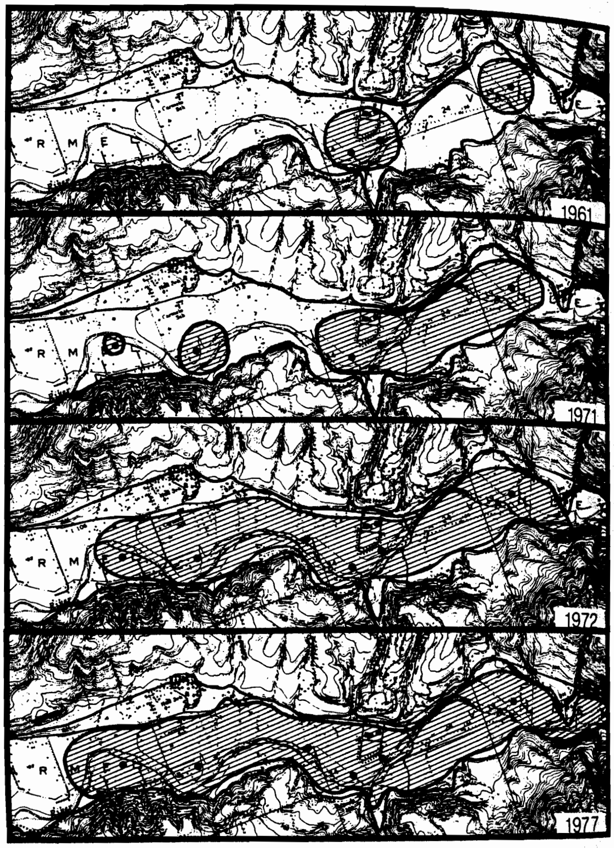

Figure 3.--Zones of influence in October for four select years. The 5 foot isocontour of drawdown from the spring high is the zone boundary. The limits of the valley fill are indicated.

Riparian Water Requirements

Young and Blaney (1942) measured water consumption by willow in Santa Ana, California to be about 56 inches during the period from June through September. It is reasonable to assume that willow and other riparian vegetation within the slightly more humid Carmel Valley would transpire at least 30 inches per year through the same period. The average June through September precipitation is less than one inch[6] confirming that willows and other riparian vegetation are groundwater dependent.

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[6]United States Weather Bureau Records. Carmel Valley, California.

Tree Roots and Declining Water Tables

An implied question is posed by the hydrologic analysis: can the roots of riparian phreatophytes follow a retreating water table? To answer this question, soil pits were dug around the base of red willow (S. laevigata) in the study area during late summer. The roots of the red willow were found only to a depth delimiting the bed elevation of the adjacent dry channel. These roots were quite fragile and spongy due to the presence of cortical air spaces.

Cortical air spaces called aerenchyma, are characteristic of many wetland species. The air spaces arise by lysis within parenchymal tissue and have been found to improve oxygenation to root tips. (Coutts and Armstrong, 1978), (Kawase and Whitmoyer, 1980). This morphologic adaptation, however, probably reduces the penetrating power of the root tips because the induced sponginess reduces both the axial rigidity and radial anchorage cited by Barley and Greacen (1967) as necessary for efficient soil penetration by roots.

Black cottonwood roots in the vicinity of the willow test pits were undercut and washed free from the bank. These roots showed the same pattern of truncation at about the elevation of the adjacent channel noted for the red willow.

The reason that the observed willow and cottonwood root systems had not adapted to follow the rapid water table retreat may be due to soils of the floodplain. The floodplain substrate is very coarse and retains only small amounts of water after drainage. This restricts contact of matrix water films after complete drainage from pumping. The gradient necessary for inducing deeper rooting is therefore probably broken during rapid water table decline. Poplars, of which the black cottonwood is a member, have been observed by Hoffman (1966, as cited by Kramer and Kozlowski, 1979) to achieve five centimeters per day growth rates. Such rates are, of course, moderated by soil impedance and the timing required for redifferentiating root buds from aerenchymatous tissue to roots more suited for exploring the soil.

Sequence of Events

Each of the covertype maps shown in Fig. 2 was fitted with a clear template delimiting a riparian corridor along the river. The study area was divided into sections conforming to the location of high capacity wells designated from down to upstream; Schulte, Manor, Berwick and Begonia. A dot planimeter was used to obtain three replications of the area of the riparian forest and unvegetated river alluvium covertypes. These values were averaged to yield data documenting the temporal relationship of riparian vegetation decline, increased channel erosion and pumping[7] plotted on Figure 4.

[7] Pump production records obtained from the California-American Water Company.

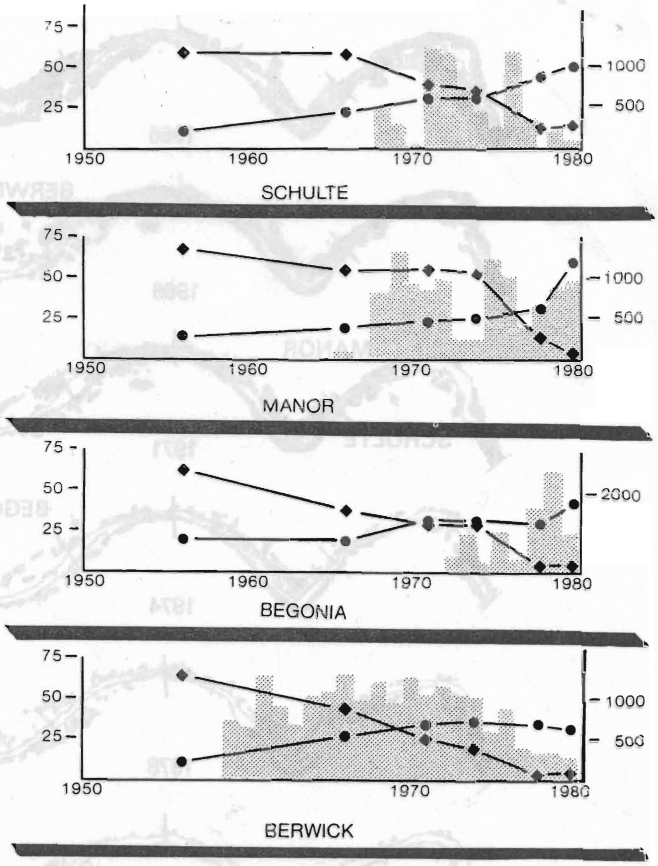

Figure 4.--Percent cover by riparian forest (diamonds) and unvegetated river channel (circles) versus pumping in acre feet from wells in each section.

PUMPING, VEGETATION DECLINE AND CHANNEL EROSION

Kondolf (1983) analyzed the geomorphology of the Carmel River system to determine the cause and effect relationship for the massive streambank erosion by measuring such parameters as river sinuosity, bed load, gradient and channel configuration in relation to influencing factors such as historic fires in the catchment basin, streambed minimg, construction of dams upstream and the timing and rate of river flows. Kondolf concluded that although "some bank erosion is natural in most fluvial systems ... natural, random process is inadequate to explain the massive bank erosion experienced along the Carmel River in 1978. This erosion must be regarded as out of the ordinary in that it occurred during years unremarkable for high flows." After lengthy examination of the physical system, Kondolf concluded that the bank erosion was coupled with groundwater pumping through dieoff of riparian vegetation.

Streambank stabilization by vegetation results from the reinforcing nature of the plant roots. This mechanism is documented in the literature and though limited discussion will be made here, the reader is urged to see Smith (1976), Seibert (1968), Ziemer (1981) and Gray and Leiser (1982) for more background. In summary, streambank stabilization by roots results from increased tensile and shear strength of the bank soil mass and through armoring provided by roots as they wash free from the substrate. These mechanisms were obviously lacking for the readily erodable bank material within the impact area.

The most severe erosion of streambanks on the Carmel River occurred within the study area. A time series of photographs taken from the Schulte Road Bridge looking upstream document the process of bank erosion following loss of stabilizing plant growth (Figures 5, 6 and 7). The photo point can be located on the maps of Figure 2 as the double line between the Schulte and Manor sections of the river. The 1976 photograph was taken in late fall 1976 and shows dead cottonwoods and willows lining the approximately 60 foot wide channel. The 1978 photograph captures the same scene following spring high water flows which equate to a ten year recurrence interval (Kondolf, 1983). Note that the toe of the bank has been eroded back about 30 feet from the channel margin position visible in 1976. According to photogrammetry of the 1978 air photograph set, the erosion due to this flow resulted in an ultimate channel width of about 150 feet within the field of view of the photograph. A photograph following spring high water flows in 1982 illustrates the same scene but with aggradation of the margins to form a channel over 400 feet wide. This erosion occurred following two five year recurrence interval flows in the intervening four year period.

Figures 5, 6 and 7.--1976[8], 1978[8] and 1982 photographs of the Carmel River Channel. The arrow indicates a reference point.

[8]Ed Lee. 1982. Photographs of the Carmel River. Board of Directors, Monterey Peninsula Water Management District.

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