INTERPRETING PHYSIOLOGICAL DATA FROM RIPARIAN VEGETATION: CAUTIONS AND COMPLICATIONS[1]

John G. Williams[2]

Abstract: Water potential and stomata] conductance are important indicators of the response of vegetation to manipulations of riparian systems. However, interpretation of measurements of these variables is not always straightforward. An extensive monitoring program along the Carmel River in central California, carried out by the Monterey Peninsula Water Management District, provides examples of the complications that can arise in practice.

The Monterey Peninsula Water Management District (MPWMD) has monitored riparian vegetation along the Carmel River since 1981. A large data set has been developed, and been presented and analyzed in various reports (DMA Consulting Engineers 1985; McNeish 1986; Williams and Matthews in press; Williams and others submitted; Woodhouse 1983, 1984). This paper describes the history of this effort, and reviews some of the complications encountered in interpreting the data, particularly from the point of view of environmental management. A possible subtitle would be: "Problems in Proving the Obvious."

Study Area

The Carmel River is a small coastal stream in central California, draining 660 km^2 with an average annual discharge of 3.1 m^{3}s^{-1}. In the lower 25 km, the stream flows over alluvial deposits that make up Carmel Valley.

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The undisturbed riparian forest along the lower Carmel River is dominated by Black Cottonwood (*Populus trichocarpa*), together with abundant Arroyo Willow (*Salix laseolepis*) and Red Willow (*S. laevigata*); White Alders (*Alnus rhombifolia*), Bay (*Myrica californica*), and Sycamore (*Plantanus racemosa*) and minor constituents. Large areas of riparian forest were cleared for agricultural and suburban development, but a nearly continuous stretch of forest existed along the lower river until recent decades (fig. 1).

Figure 1 – Relatively undisturbed riparian forest along the Carmel River; trees to the left in the picture grow over a layer of clay that buffers the effect of groundwater extractions.

Coastal California enjoys a Mediterranean climate. Within and between year variances in the precipitation and stream flow are large, with average annual precipitation varying over the drainage basin from 350 to 1050 mm, almost all falling as rain between November and April. In the summer demand for municipal supply for the adjacent Monterey Peninsula exceeds the supply available from the river and from two small reservoirs owned by the California-American Water Company (Cal-Am), and diversions for municipal use have made the river go dry in the summer for many years. Since the early 1960's, Cal-Am has relied increasingly on wells tapping the underflow of the river in the alluvial deposits.

Background

The effect of groundwater pumping on riparian vegetation and bank erosion along the Carmel River has been the subject of controversy for many years. Kondolf and Curry (1986), and Groeneveld and Griepentrog (1985) provide recent reviews. Local residents noticed the effects quickly, especially in the dry years of 1961

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[2] Senior Associate, Philip Williams & Associates, San Francisco, California.

and 1966, when pumping increased sharply (Monterey Peninsula Herald, 1966). In 1971, local residents hired Paul Zinke of the Forestry Department at UC Berkeley, who wrote a brief report saying that the pumping appeared to be responsible for the death of vegetation near Cal-AM's wells (Zinke 1981).

Cal-Am hired Ed Stone, also of UC Berkeley, who wrote a report arguing that in the absence of floods and other disturbances, there would be natural ecological succession from cottonwoods and willows to more drought tolerant trees such as bays and oaks, so that even if the pumping were killing the willows and cottonwoods, it was only accelerating a natural process (Stone 1971).

This stand-off of expert opinion continued until 1977, when Cal-Am applied to Monterey County for permits to drill two more wells. Continuing local concern about the loss of riparian vegetation and associated bank erosion lead Monterey County to commission another study of the issue. Based primarily on a single field visit by a groundwater geologist and a remote sensing specialist, this study concluded that bank erosion was not related to the loss of vegetation (Carlson and Rozelle 1978).

However, the study recommended that some kind of riparian management system be developed, with all well owners contributing to the cost. Since there was at the time no feasible way to implement such a system, the county simply gave Cal-Am permits for the wells, although it did retain jurisdiction over the permits.

In 1979, Cal-Am applied for permits to drill four new wells farther down the valley, in an area previously unaffected by pumping. By this time, the Monterey Peninsula Water Management District (MPWMD) had been created, and as part of developing environmental mitigations to be required as conditions on the permits, the MPWMD had a physiological ecologist do a baseline study of the vegetation before the wells were installed.

Studies

In 1981, Woodhouse (1983) measured diurnal leaf water potential and stomatal conductance of Black Cottonwood and Arroyo Willow, along with environmental variables, at monthly intervals at the site of a planned well. He also measured dawn water potential (DWP) monthly at several other sites. One of these, near the mouth of the river where groundwater levels fluctuate only slightly, would serve as a control.

The 1981 data seemed unremarkable. Dawn water potentials were -0.1 to -0.3 MegaPascals (SI units of pressure - one MPa = 10 bars) as might be expected of trees tapping a water table, and the daily course of water potential and stomatal conductance also reflected environmental variables in expectable ways.

By 1984, Cal-Am was ready to put its new wells into production on a test basis, and a major monitoring effort was undertaken jointly by the MPWMD staff and a consulting engineer hired by Cal-Am. This effort emphasized measurements of depth to the water table, soil moisture, and DWP; unfortunately, stomatal conductance was not measured, and the necessary equipment was not acquired.

When the pumps were turned on, the effect of the pumping on nearby vegetation was rapid and obvious: leaves turned yellow and fell off (Williams 1986). However, the data collected were so confusing that the consulting engineer was able to conclude that "Based on all of the data collected and analyzed in this effort there is no indication that operation of the four Cal-Am wells in the Lower Carmel Valley have an adverse impact on the plant community along the Carmel River" (DMA Consulting Engineers 1985).

In response, the MPWMD undertook another summer of intensive work in 1985, which sorted out most of the confusion in the 1984 data, and firmly established that groundwater pumping did indeed severely stress riparian vegetation (McNeish 1986; Williams and others submitted).

Complications

Some of the problems in 1984 resulted from simple errors in judgement, such as monitoring trees that were irrigated by the overflow of a nearby well, or believing unrealistic data from soil moisture blocks. These had been installed in a slurry, which did not equilibrate with the soil until the profile was wetted the following winter.

Other complications were more interesting. These included incomplete nighttime stomatal closure in Black Cottonwood, spatial variation in substrate, differences between willow species, spatial variation in competition for soil moisture, historical effects, and "exogenous" water - water from sources other than the underflow of the river or directly infiltrated rainfall.

Incomplete Night-time Stomata) Closure in Cottonwoods

One striking aspect of the 1984 data was depressed DWP in late summer in cottonwoods in areas where the water table remained near the surface. In the most extreme case, DWP in a cottonwood was -1.0 MPa, while it was -0.2 MPa in a nearby willow, and -0.1 MPa in an alder (Woodhouse 1984).

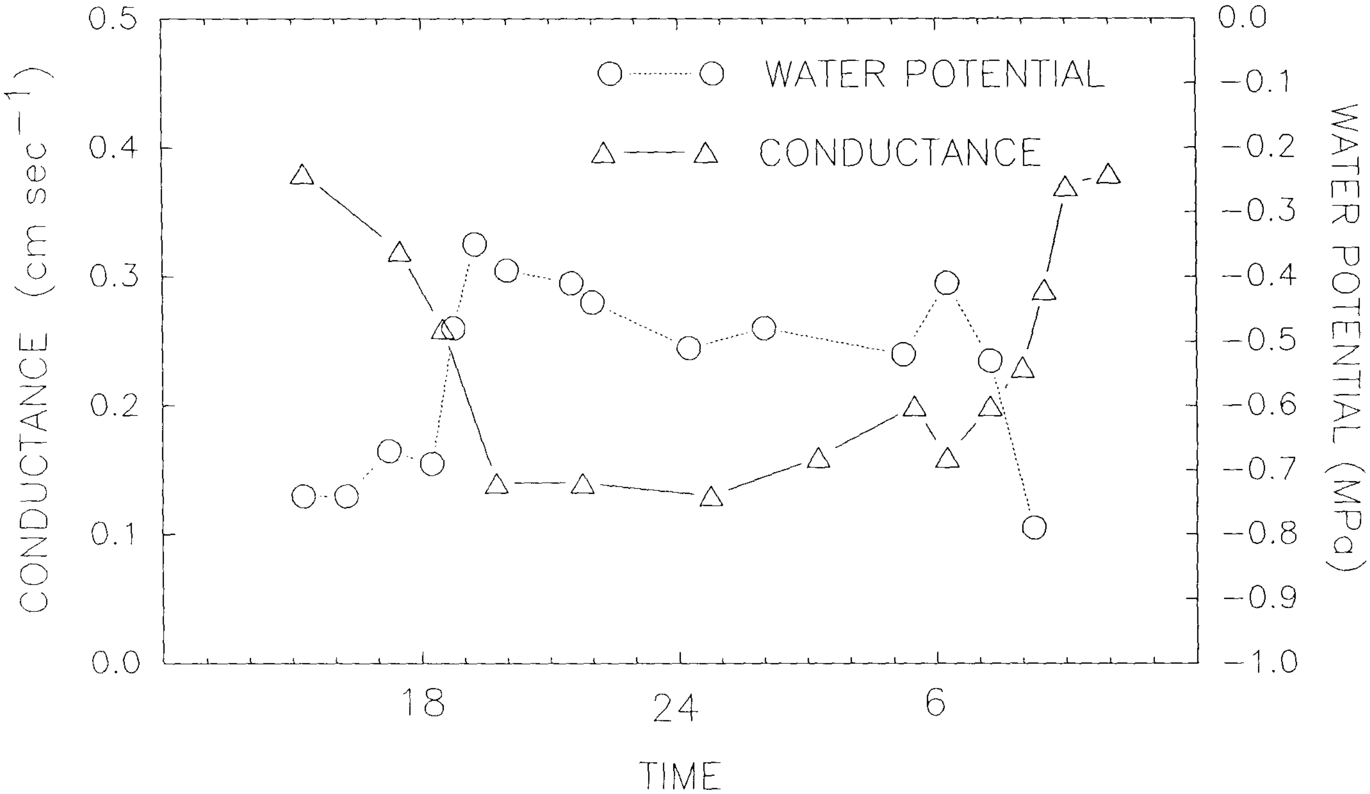

Figure 2– Stomatal conductance and water potential in an unstressed cottonwood, Sept., 1985, showing incomplete nighttime stomatal closure.

The more common situation was DWP in unstressed trees of -0.4 to -0.6 MPa, similar to values in stressed trees that had undergone significant defoliation. However, the depressed DWP was a sometimes thing; on some mornings DWP was -0.2 to -0.3 MPa, as observed in 1981. Together with data from trees receiving water from well overflow or other exogenous water, these resulted in a lack of a clear correlation between DWP and drawdown of the water table.

Based on a few mid-day measurements of water potential in 1984, incomplete nighttime stomatal closure seemed the likely reason. Mid-day water potential in the unstressed trees at the control site dropped to levels like those seen in 1981, around -1.5 MPa, indicating normal stomatal opening, while the water potential in the stressed trees remained above -1.0 MPa, indicating greater stomatal closure (Woodhouse, 1984). However, no porometer was available, so this was not confirmed until 1985.

Figure 2 shows stomatal conductance and water potential in a cottonwood on a September night at the control site, where the water table was within 2 meters of the surface. The stomates never fully closed, and the inverse patterns in conductance and water potential early in the morning show that the incomplete stomatal closure was keeping water potential down. Where trees were stressed, however, all night-time measurements found the stomates closed (McNeish 1986).

Presumably, Woodhouse missed this behavior in 1981 just by chance; his monthly samples were too sparse to provide a complete picture of baseline conditions. From the point of view of designing sampling programs within a reasonable budget, this is disheartening.

Spatial Variation in Substrate

Spatial variation in substrate, and perhaps in associated exogenous water, also complicated patterns in plant response to lowered groundwater levels. The stratigraphy in small valleys such as the Carmel can be quite complex, with landslide or mudflow deposits from the valley sides or side canyons interleaved with deposits laid down by the river itself. It appears that these fine grained deposits can act as conduits for lateral movement of groundwater from side canyons or sources such as septic tank drain fields, over-irrigated golf courses, etc.

The alluvial deposits are also heterogeneous. The lower Carmel Valley is moderately steep, with a channel gradient averaging 0.01, and the river tends to migrate discontinuously, with rapid changes during major floods, rather than by the more gradual migration of meander bends of the sort depicted in textbooks (Kondolf 1983). Consequently, the alluvial deposits consist largely of ribbons of course-grained channel deposits embedded in sheets of finer-grained overbank deposits, and even in the absence of exogenous water the difference in water holding capacity can be significant.

At the main monitoring site, near one of the new production wells, trees just around and to the east of the well were stressed much less than trees west of the well or across the river. Work in 1985 showed that there was a clay lens just beneath and to the east of the well, from which trees were able to extract at least 10 cm of water in September alone, at least around the neutron probe access tube (McNeish 1986).

Figure 3 shows the level of the water table and DWP in three cottonwoods: two to the west of the well (averaged) and one growing over the clay lens to the east. The water level shows clearly when the well was turned on, when it broke down, and when it was repaired. DWP in the cottonwoods west of the well followed the water table down, and then back up. However, when the well was returned to service and the depth to water increased again, DWP remained elevated, apparently because the trees were so far defoliated by that time that evaporative demand was much decreased. DWP did decline in adjacent willows that suffered less defoliation.

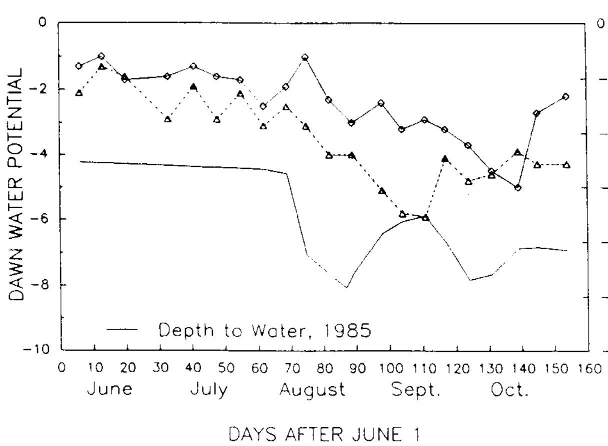

Figure 3 — Depth to water and dawn water potentials in one cottonwood growing over a fine-grained deposit (◊), and two nearby cottonwoods (Δ - averaged) growing away from it. DWP data are smoothed as described in McNeish (1986).

In the meantime, DWP in the cottonwood growing over the clay lens decreased slowly, and defoliation proceeded at about the same rate as at the control site until late October. If one first looked at the trees in mid-October, DWP would be identical, but trees west of the well would be prematurely defoliated, while the others were not.

Figure 4 shows the diurnal course of water potential and stomatal conductance in cottonwoods at the site in August of 1981 and 1985. The tree sampled in 1981 is west of the well, off the clay layer, as is one of the trees sampled in 1985. Mid-day stomatal conductance is higher and water potential is lower in 1981; the tree growing over the clay layer has intermediate values.

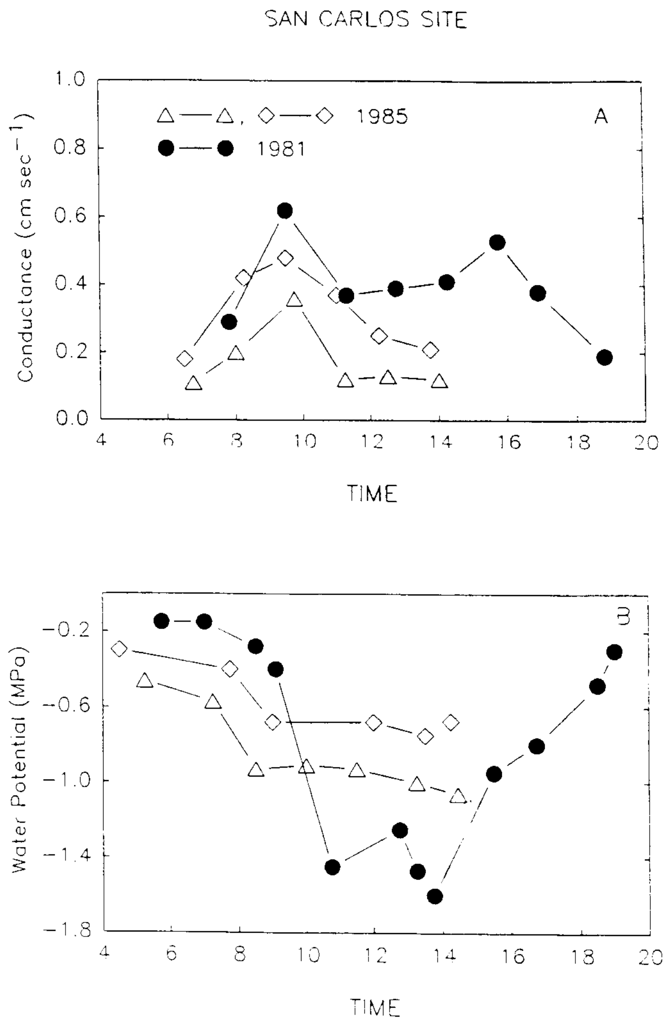

Figure 4 — A. Stomatal conductance in cottonwoods in August: 1981 (o); 1985, tree growing over (◊) and away from (Δ) a clay layer. B. Water potential: same symbols.

Besides the effects of variation in substrate, the figure shows that the mid-day depression of water potential is suppressed in stressed plants, as noted above. Evidently, cottonwoods and willows are like many crop plants, in that stomatal closure occurs at higher water potential if the plant has a history of water stress (Beggs and Turner 1976).

This effect may be exaggerated by the figure, however, as the 1985 data are mainly from shaded leaves. Based on several mid-day measurements, water potential was lower and stomatal conductance was higher in sunlit leaves of the tree growing over the clay lens; there was less difference with the more severely stressed tree.

In another example of the effect of previous water stress, one Arroyo Willow measured in 1985 had high water potential, -0.2 MPa, but very low stomatal conductance. This plant had been stressed and partially defoliated, and then irrigated by blow-off from the adjacent well a day previously. Apparently, the delayed stomatal opening is a response to abscisic acid levels. The acid levels are elevated by water stress, and stomates will not function normally after re-wetting until the acid levels decline (Bradford and Hsiao 1982).

Historical Effects

One group of trees monitored in 1985 are a stunted remnant of a closed canopy riparian forest that occupied the river terrace in this area until about 1970 (fig. 5). The cottonwoods here are probably root sprouts from larger trees that have died, fallen over, and decayed. A few large trees survive on this terrace around a well where they are watered by blow-off.

Figure 5 – Remnant, stunted trees in an area long affected by groundwater extraction.

The 1985 data shows that DWP in these stunted trees declined steadily after the river stopped running in June, and the trees also steadily lost leaves. There was nothing unusual about the few conductance data taken here, although leaves on these trees appear to be smaller and thicker than on trees in areas not subject to large drops in the water table. Smith (1984) noted similar changes in leaf morphology along dewatered Sierran streams.

The point here is simply that data from these remnant trees are not representative of what occurred when the adjacent wells were first installed, when competition for water in the unsaturated soil would have been much more intense, and, probably, the trees were less deeply rooted. What needs to be avoided is thinking along the lines of... The physiological data show that cottonwoods, while showing signs of water stress, can survive periods of lowered water tables. Therefore, the data show that earlier mortality was probably caused by other factors...

Differences Among Species

Differences among species can also be important. Arroyo Willow does not tolerate lowered water tables as well as Red Willow. Observations of water potential and stomatal conductance on paired trees indicate that Red Willow has more effective root systems (Williams and Matthews in press). Based on visual estimates of defoliation, the degree of differential response varies from place to place, and probably depends in part on substrate, being strongest where the roots of Red Willow can differentially exploit local variation in substrate or availability of exogenous water, and least where deposits in the root zone are relatively uniform.

Summary

Physiological measurements are often useful, and can be crucial for demonstrating the effects of human activities on riparian systems. In 1983, in a lawsuit involving bank erosion, "expert" witnesses for Cal-Am convinced a court that "...the condition of the vegetation was most probably the result of the unprecedented drought of 1976-77" (Agliano 1983). In light of the data collected in 1985, it is doubtful that the same verdict could be reached today.

However, it is hazardous to base conclusions on a few physiological measurements, especially on measurements of water potential alone. Conclusions can be based with much more confidence on diurnal measurements of both water potential and stomatal conductance, but even in this case results from one or a few sites may not be representative of the whole area of concern, and results from a few days may not be representative of the whole period of concern.

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