The Sonde Experiment

Back in September of 2008, Diana Engle (of Larry Walker Associates), and I decided to cooperate on the measurement of dissolved oxygen variations at a number of locations in the Ventura watershed. These measurements were to take place around the second week in September, at the time when Kristie Close was measuring algal densities at these same locations for the eventual UCSB algal report (a study financed by the Los Angles RWQCB as part of the nutrient TMDL process). My part was to get Santa Barbara Channelkeeper (SBCK) to appropriately schedule their monthly, volunteer based, measurements of pre-dawn and mid-afternoon dissolved oxygen, and Diana would deploy a number of rented sondes (automatic recording instruments placed in the river to measure parameters like DO, *p*H, temperature and conductivity at some specified time interval – every 15 minutes was the interval eventually selected).

I no longer remember all the details, but seem to recall that 5 sondes were used, one of which malfunctioned. The four sites for which good data were obtained were (1) the Ventura River just above the Canada Larga confluence, (2) Foster Park, (3) the Ventura just above the San Antonio confluence, and (4) Matilija Creek above the dam. Diana recorded measurements of DO over a period of approximately five days. One purpose of this effort was to evaluate the utility and accuracy of Channelkeeper measurements. As mentioned in a previous report, pre-dawn and mid-afternoon measurements do not actually measure DO concentrations at the daily minimum and maximum; instead they simply purport to be reasonable estimates of those limits.

Without going into details, pre-dawn and mid-afternoon measurements would be spot on if dissolved oxygen concentrations in a stream were solely governed by what algae were doing (they mark the points where total nighttime *consumption* or daytime *production* of oxygen by algae reach their maximum), but, of course, other factors are involved. Factors such as water temperature, the percent oxygen saturation, water depth and turbulence govern how much nighttime oxygen *enters* or daytime oxygen *leaves* the stream. Other biological activity, aside from algal production and respiration, may produce lesser, but still noticeable effects on oxygen concentrations (decay of organic material in stream sediments being the most obvious example – and since the intensity of biological activity is usually governed by temperature it too can produce slight diel variations in oxygen concentration).

But guessing at the appropriate times when oxygen should be measured during its daily cycle, while something of a crap-shoot, is not a totally useless effort. Algae, when abundant, are by far the most important factor, exerting the greatest influence on the timing of DO maxima and minima. And being close is often good enough when measuring the high and low points of a cycle, because the rate of change appreciably slows down in those areas – change moves much faster near the mid-point of transitions. Determining how close the SBCK estimates came to the true values was one purpose of the exercise; another was to evaluate the usefulness of the "delta-DO" parameter (delta-DO being the difference between the daily maximum and daily minimum concentrations, i.e., the magnitude of the daily variation) to determine how accurately it could be measured by SBCK, and how much it varied from day-to-day around the time of Kristie's algal density measurements. The reason being that delta-DO was to be used as one of the variables in a model predicting algal density.

Looking at the Results

O.K. Now to the data (after my usual long-winded introduction): Figure 1 shows Diana's data as colored lines; the colored circles (same color indicates the same location) represent point measurements made by SBCK volunteers on September 12. The additional measurements on September 14 were made by me. If I recall correctly, the afternoon of September 12 turned out to be highly overcast and I was concerned that it would prevent the algae from giving their best performance – resulting in lower than usual maximum values.

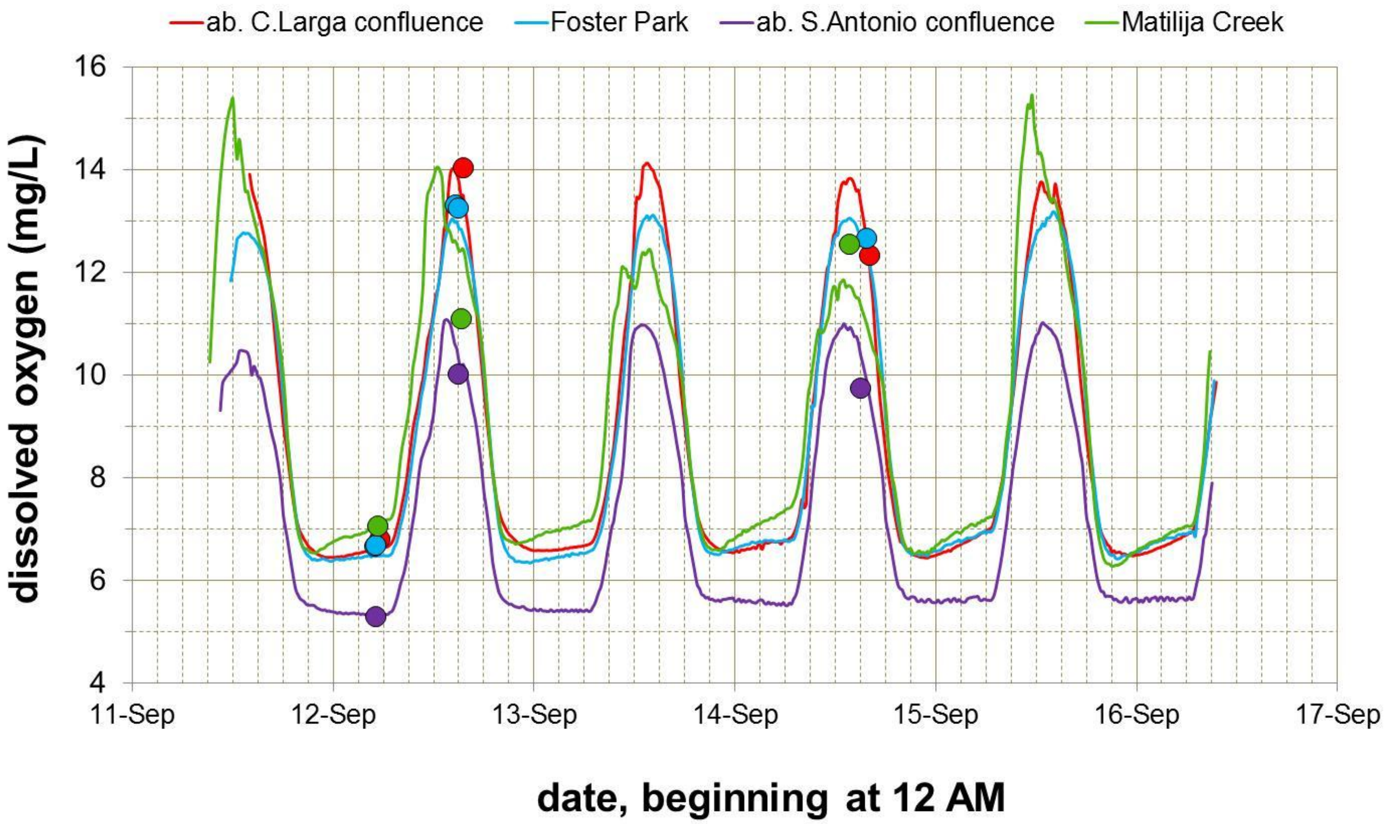


Figure 1. Sonde measurements of dissolved oxygen recorded at 15 minute intervals at four Ventura watershed locations (data provided by Diana Engle of LWA) during September 11-16, 2008. The circles (color coded to match the 15 minute data from each location) indicate point measurements made by SBCK volunteers during the same time period.

I went back two days later to check. As you can see from the data, and even better from Diana's results, I need not have worried. The Channelkeeper results are encouraging. First, they pretty accurately match the values recorded by sonde at the same locations and times. The major exception being afternoon measurements made on Matilija Creek: too low on September 12, too high on September 16. Of course, this is somewhat of a chicken and egg problem; there is no sure way of knowing which measurements were more accurate.

Sondes are usually calibrated before being emplaced, and checked after removal – with any necessary correction linearly distributed after the fact. The DO meters used by SBCK – these were older membrane meters which required manual entry of the estimated site elevation – would have been recalibrated at each site prior to making measurements. It's very unlikely that both of the afternoon manual meter readings were correct; at least one had to be in error to give values both above and below the sonde measurements. My best guess would be an error in the September 12 Matilija measurement (not solely because it was the one not made by me, but due to the magnitude of the difference).

Aside from that one measurement and that SBCK, as expected, missed the point of maximum DO, they got pretty close. The typical error was about 1 mg/L, an error of roughly 7-10 % (the largest difference was1.5 mg/L above the San Antonio confluence on the 14th). The effort to estimate the minimum concentration was even better: the *worst* result (on Matilija Creek) was off by only 0.5 mg/L, the others were almost spot on. Delta-DO was pretty consistent, with very little day-to-day variation except at Matilija Creek.

The wide variation in maximum DO (11.5 to 15.5) on the Matilija begs a question of "why?" Why, on the other hand, was minimum DO so consistent? Note that the evening DO trajectories were almost identical on the Matilija, at Foster Park, and above the Canada Large confluence, i.e., similar minima followed by slow increases throughout the remainder of the night. But why then were nighttime DO levels so different above the San Antonio confluence? Notice that the entire DO cycle at this location appears to be displaced downwards by about 1.5 mg/L. One possible explanation might be lower oxygen levels in the surfacing groundwater that supplies upstream flow to this location. As the dry-season progresses, the point where this

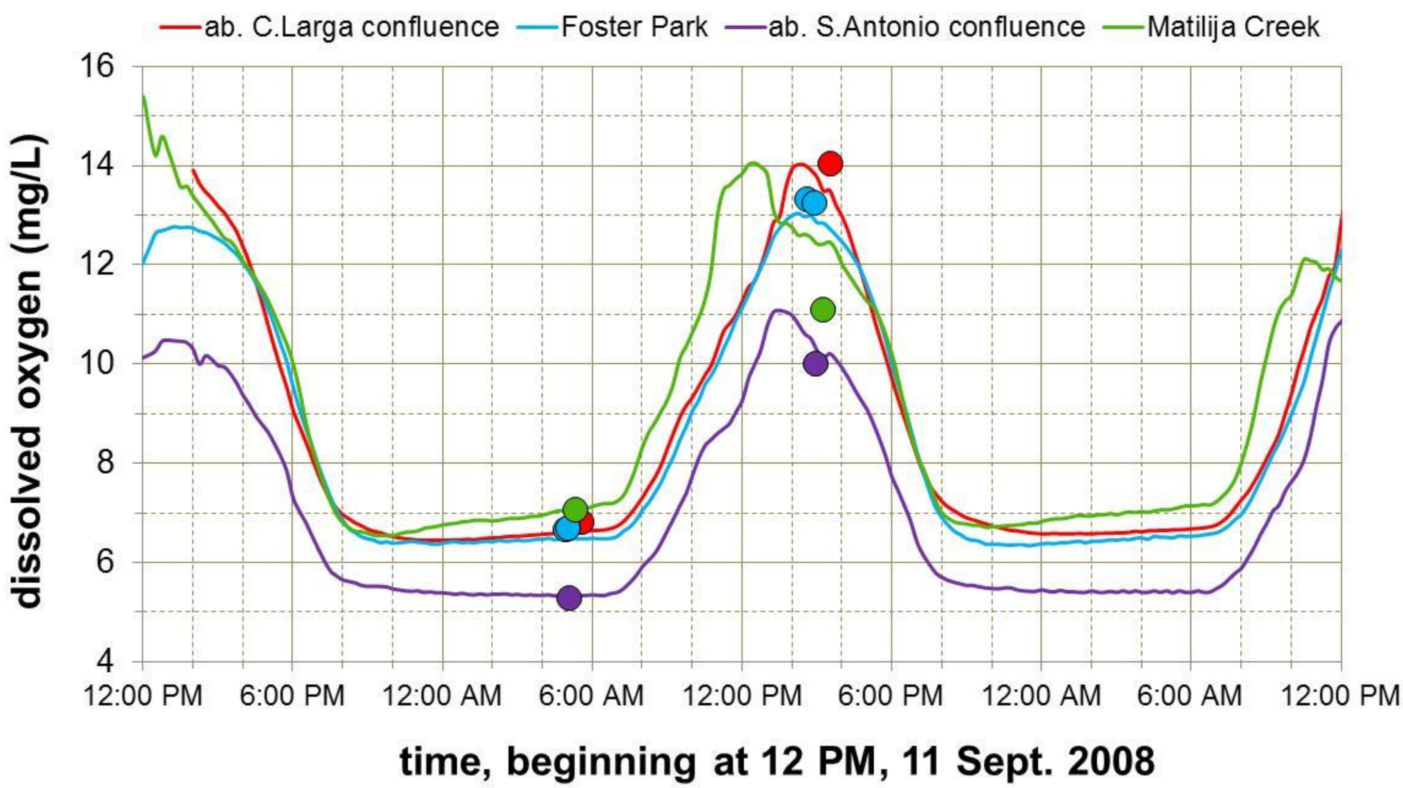


Figure 2. A close-up of Figure 1, focusing on September 12, 2008.

seepage begins draws closer and closer to the sampling location – by September it was only a few hundred yards upstream, a distance short enough to have appreciably reduced re-oxygenation.

On the other hand, some additional oxygen consuming process, working more-or-less around the clock – like organic decay – might have had simply exerted greater impact. Actually no; just kidding. Much less organic material accumulates here than further downstream where aquatic vegetation often chokes the river and effectively traps sediment and debris by late summer. (Perhaps I shouldn't be so dismissive. September 12, 2008, was the only time I calculated carbon dioxide concentrations for a SBCK sampling. Pre-dawn concentrations above the confluence were extraordinarily high: 3-times those seen lower down on the river; 5-times higher than on the Matilija. Carbon dioxide is a well-known byproduct of organic decay – but, on the other hand, groundwaters are also known to exhibit high concentrations. Incidentally, these carbon dioxide concentrations were high enough – 32 times the equilibrium concentration – to endanger fish in the confluence pool located just below the site.) The fact that we can easily come up with alternate solutions makes this problem interesting and worthy of further thought.

Figure 2 gives a better look at the times of occurrence of the various DO maxima and minima: Matilija Creek reached its maximum at 12:15 PM on September 12th (this varied between 11AM and 1PM over the week); the Ventura above the San Antonio confluence hit its maximum at 1PM (it varied between 12:45 and 2:00); Foster Park at 2:15 PM (between 1:15 and 2:15); and above the Canada Larga confluence at 2:15 PM (between 12:30 and 2:15). The times of minimum concentration on September 12th varied even more widely: 10 PM on the Matilija (it varied over the week between 9:15 and 10:15 PM); 5:15 AM above the San Antonio confluence (between 3:30 and 6:15 AM during the week); 10 PM at Foster Park (from 9:45 to 11: 30 PM); and 11:45 PM just above Canada Larga (11 PM to 1:45 AM).

An obvious question: why so early – hours before midnight – at three of the four locations? On Matilija Creek a reasonable answer is probably because of lower flows and shallower depths; also add in clearer skies and lower nighttime temperatures because of higher elevation. All these factors lend themselves to a rapid loss of whatever excessive oxygen remained in the stream after sunset – and an early minimum. And after the early minimum the transfer of oxygen from the atmosphere into the stream would have gradually increased as water temperatures declined even further, the oxygen gain more than keeping pace with continuing algal respiration; the increase in nighttime DO concentration following the minimum was also more appreciable on the Matilija than at any of the other sites.

Low flow was also the reason Matilija Creek exhibited the greatest daily DO variation (particularly on September 11 and the 15th) – it takes a tremendous amount of algae to effect great change in lots of water, but a surprisingly small amount can rapidly modify small flows. Although upper Matilija creek had undergone the most recent bloom, algal densities at the other locations were still much greater (Figure 4). Very low flows, a relatively narrow mountain canyon, an active bloom and variable cloud cover may have been responsible for greater variability in the daily cycle seen at this location.

Low flow and a higher elevation location also explain why *maximum* DO occurred so early in the day at Matilija. Just as decreasing water temperatures enhance the transfer of oxygen from the atmosphere into water (by decreasing oxygen saturation – colder water can hold more oxygen in solution than warmer) increasing temperatures rapidly increase percent saturation, speeding up oxygen loss. I don't know what the actual water temperature variation was during the sonde deployment, but temperature loggers were installed during the 2010 season. They showed that open reaches of the Matilija exhibited extreme variations in water temperature even into September – nearly twice those seen elsewhere in the watershed. For example, in September 2010 a daily variation of 12°C (from 66° to 88°F) was not uncommon nor was a rise of 6°C (11°F) between the hours of 8 AM and noon. These kinds of temperature increases increase oxygen saturation by 20 to 40%, speeding up oxygen loss from the creek and moving the point where the loss of oxygen matches and begins to exceed the gain from algal production to earlier in the day.

Figure 3. Photos of the four sonde locations taken on September 12, 2008: (top left) looking upstream from the Canada Larga confluence; (top right) looking upstream from the bridge at Foster Park; (bottom left) just above the San Antonio confluence; and (bottom right) Matilija Creek above the dam.

The problem, of course, is while all this explains what happened on upper Matilija Creek, why peak DO occurred so much earlier, and why it climbed to higher concentrations by dawn, it does nothing to explain why nighttime oxygen concentrations should have behaved so similarly around the time of minimum DO at three dissimilar locations (Figure 1): locations with different elevations, with different flows, different algal densities and even different conglomerations of algal species (not to mention different weather with regards to air temperature, morning fog, and whatever). Perhaps the answer lies in how the stars and planets were aligned or perhaps we simply don't know enough. It'd be nice to look at the water temperature and percent oxygen saturation data. Knowing the flow or, perhaps even better, the water depth at each location might help. These might shed light on why the decline in DO became very much the same between the hours of 5-6 and 10-11 PM at these very different places.

But perhaps it's just me being obsessive. The central facts remain: DO did decline; the SBCK measurements did capture minimum DO rather effectively, and did a reasonable job of measuring peak concentration.

Revisiting 2003

While contemplating the minor puzzle of similar declines — and plumbing the depths of my own ignorance – I was trolling through data collecting dust in my computer. Among the things rediscovered was a study done by Julie Simpson and myself back in 2003 – coincidentally, on almost the same date, September 11-12 – when we ran around between four lower Ventura River locations, from Main Street to Foster Park every 3 hours measuring, among other things, DO.

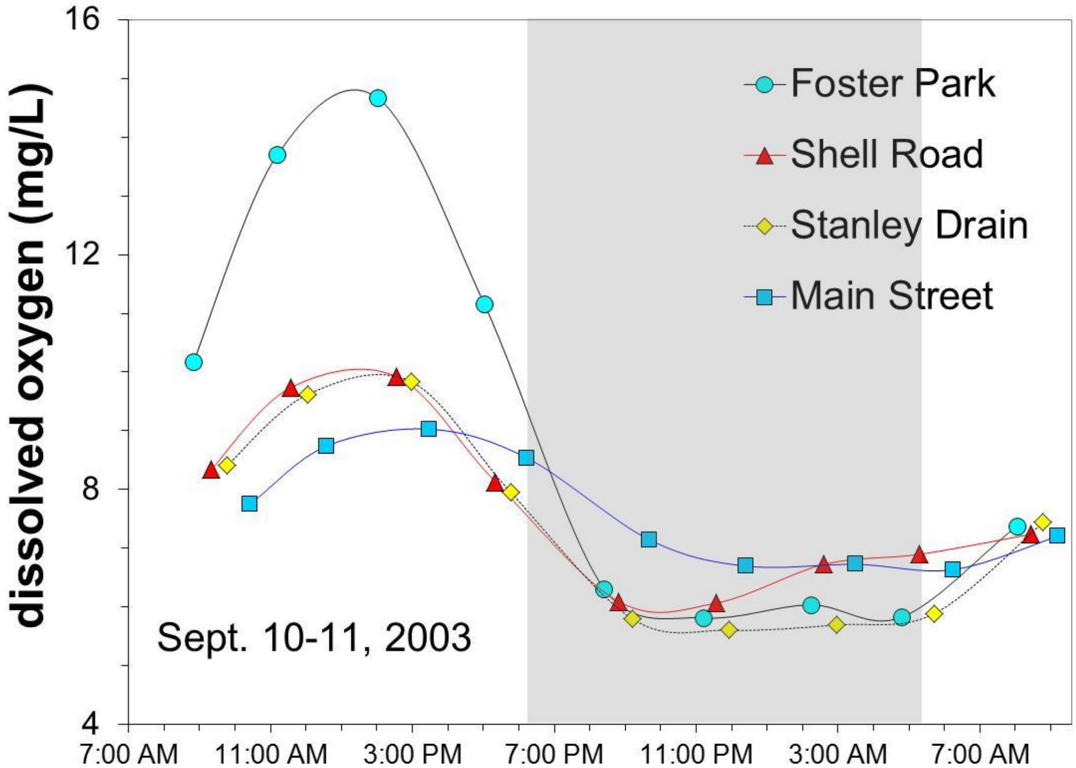


Figure 4. DO measurements made on the lower Ventura SBCK sampling sites from September 10 through the morning of September 11, 2003 – approximately every 3 hours. The four locations are listed on the chart: from Main Street (just above the tidal limit in 2003) to Foster Park (the furthest up the river). Only Foster Park was undergoing a late Cladophora algal bloom at this time; the lower locations were dominated by aquatic plants (Ludwigia).

Although “every 3 hours” is a rather course scale (aside from problems with staying awake for 24 hours, one of the sites required a considerable hike in the dark) the 2003 data do show some remarkable similarities with the 2008 measurements: (1) peak DO generally occurred around the same time (~ 2 PM, 3 PM at Main Street); (2) we observed the same early evening decrease to low DO, which occurred at nearly the same time (~ 10 PM); and there was a similar very slow recovery in DO concentrations throughout the remainder of the night.

There were also differences, mainly much smaller variations in DO below the wastewater treatment plant (Shell Road to Main Street). The river just above the Canada Larga confluence can be compared with Shell Road (approximately 2.5 km further down): the 2003 diel variation was 3.85 mg/L, it was 7.57 in 2008. At Foster Park it was 8.85 mg/L in 2003, 6.66 in 2008.

Figure 5. Photos of the four locations monitored for DO on September 11-12, 2003 (photos from September 6, 2003): (top left) looking upstream from the Main Street Bridge; (top right) the river nr. Stanley Drain; (bottom left) looking upstream from the Shell Road Bridge; and (bottom right) looking upstream from the Foster Park Bridge. The aquatic plant dominating the lower three river locations is Ludwigia. The vivid green color of Cladophora at Foster Park indicates an active bloom, and a sense of lower flow can be gotten by comparison with the same view in Figure 3.

The difference below the WWTP was due to dominance by algae in 2008 vs. dominance by aquatic plants in 2003 – aquatic plants usually have their photosynthesizing parts (i.e., leaves) sticking out of the water, thus are unable to influence oxygen concentrations *in* the water. At Foster Park greater diel variation in 2003 (8.85 mg/L vs. 7.57) and lower minimum DO (5.83 vs. 6.38 mg/L) was primarily due to lower flow (4.4 cfs in 2003 vs. 7.3 in 2008); both years saw active algal populations at this location into September (algal growth may also have been greater at Foster Park in 2003 due to a second, late season, algal bloom featuring Cladophora – something I've not seen at Foster Park, or elsewhere on the river since). These differences can be observed by comparing the scenes in Figure 5 with those in Figure 3.

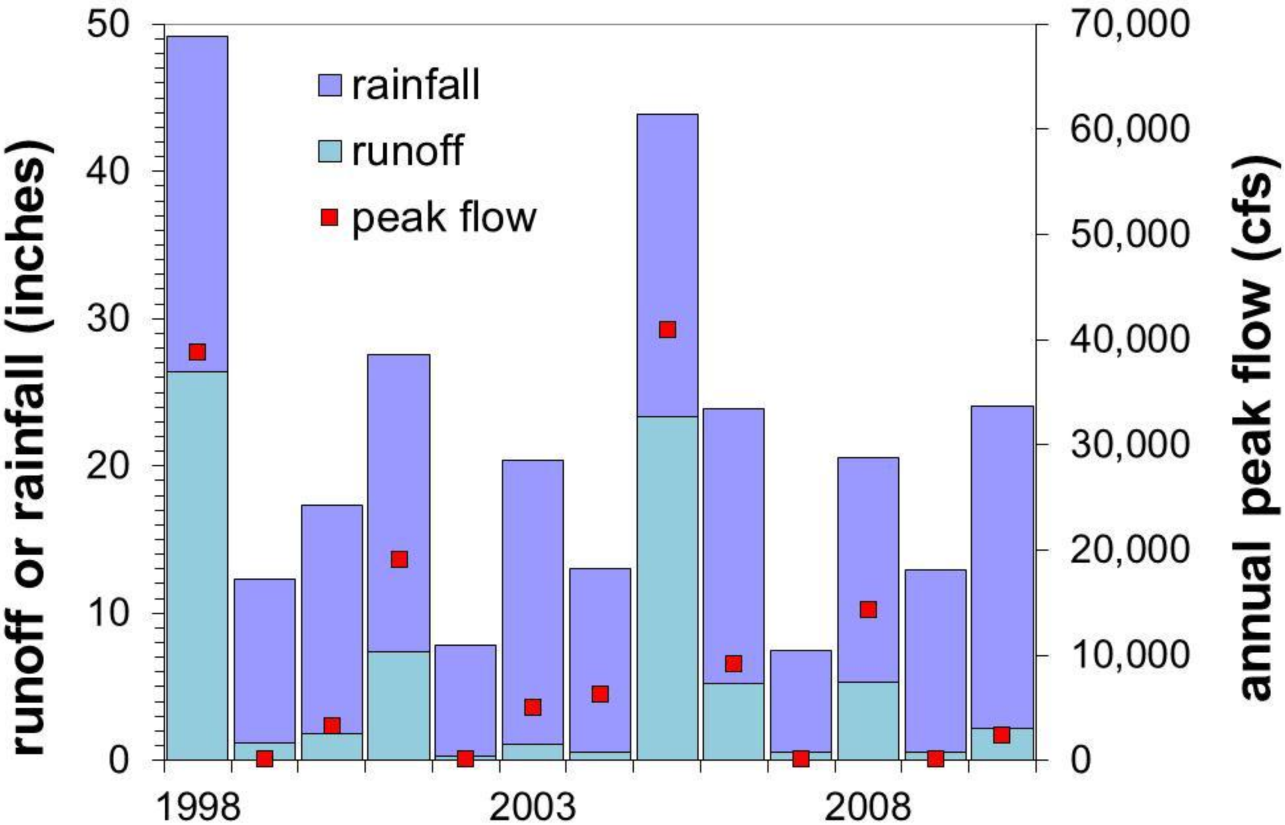


Figure 6. Annual (water year) rainfall (measured at Ojai), runoff (measured at Foster Park and expressed in inches of water spread over the entire watershed), and the magnitude of the peak flood flow during the year (also measured at Foster Park) for 1998 through 2010.

Why the Difference?

Figure 6, which shows annual rainfall, the amount of that rainfall that flowed down the river as runoff and the magnitude of the peak flood flow for each water-year since 1998 (the last big El Nino year) goes a long way towards explaining why September 2003 looked very much different from September 2008. Both years had the same rainfall (20.5 inches), but total runoff was appreciably lower in 2003 (summer runoff differences, with roughly 70 % less flow in 2003, were not as stark as the annual difference shown on the graph). The increased algal season runoff in 2008 was due to higher groundwater inflows. Although both

2003 and 2008 followed similarily severe drought years, the two earlier years prior to 2008 (2005-06) were far wetter than the corresponding period before 2003 (2000-01), i.e., groundwater levels were arguably higher at the start of 2008 than in 2003.

But the big difference between the two years lies in the size of the peak storm: 5,100 cfs in 2003 vs. 14,400 cfs in 2008. The 2008 flood flow, roughly 3-times as large, scoured more of the river channel and removed greater quantities of aquatic vegetation. In other words, a larger peak storm produced a greater flood which, in turn, created better algal habitat and more severely hammered extant aquatic plants and their root systems, thus delaying their re-appearance and eventual dominance of the lower river. Although aquatic plants (Ludwigia) were relatively pleantiful in the lower river by September 2008, they were nowhere near as overpowering as in 2003 – it took a subseqent dry year, 2009, to reproduce scenes like the ones shown in Figure 5.

Let's take a brief look at the nutrient situation during both Septembers: In 2008 the nitrate concentration just above the Canada Larga confluence was 1.60 mg/L; from there concentrations decreased downstream to 0.05 mg/L at Main Street. Just above the San Antonio confluence nitrate was 0.40 mg/L and had decreased to 0.05 by the time flow reached Foster Park. On the upper Matilija the concentration was only 0.002 mg/L, i.e., nitrate had almost disappeared. 2003 saw a concentration similar to that of 2008 at the Canada Larga confluence, 1.80 mg/L, but it had only decreased to 0.75 mg/L by the time flow reached Main Street. This was in spite of lower flow during September 2003 (the *amount* of nitrate removed is the product of the reduction in concentration multiplied by flow, i.e., similar amounts of nitrate removal would result in a *greater* reduction in concentration were flow decreased). The reason being that algae are more efficient utilizers of nitrogen than are aquatic plants – algae do a better job of cleaning the river. 2003 concentrations were more than double those of 2008 above the San Antonio confluence (0.90 mg/L), decreasing to 0.20 mg/L at Foster Park; nitrate was a higher, but still negligable 0.006 mg/L, on Matilija Creek.

Looking back at the photos in Figure 5 (2003) one can see that there were very little algae at locations with high nitrate (and although I haven't given the figures, higher nitrogen and phosphorus also), but lots of algae at the location with low nitrate (0.20 mg/L at Foster Park vs. 1.87 mg/L at Shell Road). Similarily, in 2008 there were lots of algae present at all four locations (Figure 3) along with near identical DO variations at three of the sites in spite of widely varying nutrient concentrations (particularly just below the WWTP with 1.60 mg/L nitrate compared with 0.05 mg/L at Foster Park; Matilija Creek is a special case since different algal species, species with a competitive advantage in low nutrient, slow-flow environments, were involved in that particular bloom). So what are we to make of this?

As I'm writing this, I received Lorraine Walter's notes from the Los Angles RWQCB's presentation to the May watershed council meeting (a rather heroic effort on Lorraine's part). I was struck by one set of statements: "*The (TMDL) framework relies upon relationships between nutrient concentrations and response indicators, which are parameters such as algal biomass, temperature, pH, and dissolved oxygen. The framework also recognizes the importance of cofactors, such as flow, shading, and light availability, as these factors have a strong impact on the growth of algae in response to nutrient loading*."

I see no problem there. Except that it doesn't go far enough. The recent past also matters. As may the not so recent past. What kind of winter proceeded the algal season? How much rain fell and how did the rains come? Was it one big storm or lots of minor storms? Did the rain arrive early or did it occur late in the season? (Late storms often provide less groundwater recharge and can sweep a developing algal bloom out to sea.) What was the year before like? And the year or two before that? Are aquatic plants and riparian vegetation well established and thus harder to remove (requiring greater and greater amounts of flood flow for similar amounts of removal as the years of plant growth accumulate)? What is the state of the groundwater? Is it old (little recent recharge and reduced nitrogen concentrations) or new?

When was the last *really* big winter? Big rainfall winters exert an influence that continues for years. 2001 was big algae year, but only because it occurred a few years after the great 1998 El Nino. By itself it had only slightly greater rainfall than 2010, but the river in 2001, three years after a big winter, was a very different place than in 2010, five years after the next big transformative winter: 2005. It looked different; in many places it had actually moved; trees and perennial plants had grown larger; more sediment had accumulated; it was different.

The past also matters because algae have enemies. Not just what we might call "passive" enemies: like riparian vegetation which deprive algae of needed sunlight; or aquatic vegetation which directly compete for light and space on the river bed; or accumulating sediment which eliminate habitat for algae requiring a rock or cobble substrate for an adequate holdfast (like the cladophora that typically defines most of the watershed's algal problem). Algae also have active enemies: things that eat algae. Besides fish (yep, steelhead and trout eat algae), lots of critters prey on algae. Predators are nature's response to an aquatic world suddenly full of lots of something to eat. This remains a great unknown, but I suspect that one reason we have almost never had *two* big algal years in a row is that by the second year the predator population might have caught up with the algal bonanza. But by then the algal population are facing such an array of obstacles that there is no way to separate out the effect of just one more enemy.

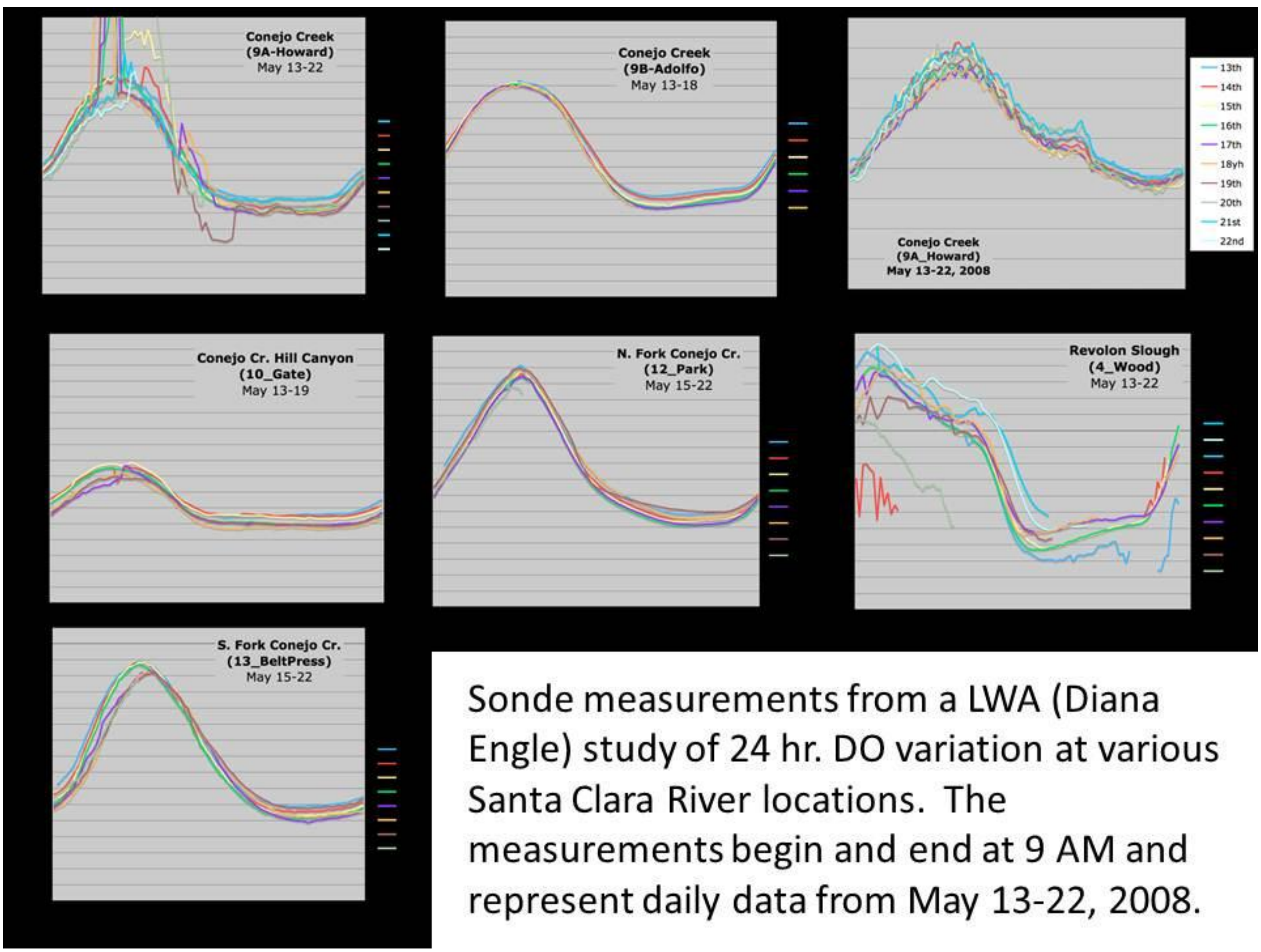
The real problem with an algal TMDL is that algae are not the real problem. They are a symptom of the problem. The real problem is excessive nutrients – in particular, on the Ventura, nitrogen. Aquatic plants are another symptom (perhaps I should say "*response indicator"*). Exuberant growth of riparian plants and trees another. Reduced biodiversity another, but not as easily seen. And that's algae's problem: it's easy to see. Aquatic plants are easy to see too, but they don't strike as much of a dissonant cord: plants, natural; algae, ugh! Algae *can* be a problem. Certain species exude poisons that can affect fish and marine mammals, but these are almost exclusively found in marine or brackish waters – *none* have ever been documented in the Ventura. Algae can also directly affect dissolved oxygen – which is, after all, what this whole essay is about. But in over 5 years of looking at minimum oxygen values in the Ventura watershed we've seen only a few instances when the concentrations have fallen below the current limit of 5 mg/L.

Ironically, when algae are most visible is also the time when we are most unlikely to see oxygen levels below the minimum. *Simply because flow has a lot to do with it*. The biggest algal blooms occur after a real big rainfall winter, and they occur early in the dry-season (lots of water, lots of habitat, lots of nutrients). For algal respiration to appreciably lower the oxygen content of a large flow of water takes more than a lot of algae – it takes a hell of a lot of algae, more than we usually see. Ironically – there's a lot of irony in this algal TMDL business – it doesn't take very much algae to change the oxygen concentration of very small flows; sometimes the amount of algae it takes is hardly even noticed. Most of the examples of algal-caused low DO we've found over the years have been of this type: low flows in relatively stagnant conditions, having higher water temperatures, and probably being affected by appreciable organic sediment decay, in which a little algae make a big difference. I've written a long, conditional sentence because really low DO in the Ventura watershed usually requires more than a single, simple cause. This is why it has not been a common occurrence.

O.K. I'm done. Except perhaps for some final words from H. L. Mencken: "*For every complex problem, there is a solution that is simple, neat, and wrong*."

Sorry, I lied. I have one more thing. Just because we have some data showing the pattern oxygen variation took during one week in September, or even two, doesn't mean we know the pattern during every September or during any other month. A lot more work is required to further explore this critical issue. And oxygen is critical, for without adequate oxygen a river is simply a septic sewer. It's the second most critical problem faced by the Ventura or any other river. The most critical? Flow. Without flow there are no other problems.

To illustrate how much DO might vary I pasted below a photo of some more of Diana's data, also taken in 2008, but on the Santa Clara in May.



Sonde measurements from a LWA (Diana Engle) study of 24 hr. DO variation at various Santa Clara River locations. The measurements begin and end at 9 AM and represent daily data from May 13-22, 2008.