Minimum and Maximum (Pre-dawn and Mid-afternoon) Dissolved Oxygen concentrations in the Ventura River Watershed: 2008 through 2011

Santa Barbara Channelkeeper (SBCK) has been monitoring minimum and maximum (more precisely, pre-dawn and mid-afternoon) dissolved oxygen (DO) concentrations in the Ventura River watershed over the last four algal seasons: April through September from 2008 through 2011. Measurements were typically taken once a month, but not all of SBCK's monitoring stations were sampled each time. Pre-dawn measurements were usually taken between 4:30 and 6:30 AM and mid-afternoon values collected between 2:00 and 4:00 PM. Figure 1 shows the minimum (pre-dawn) concentrations measured throughout the entire 4-year period.

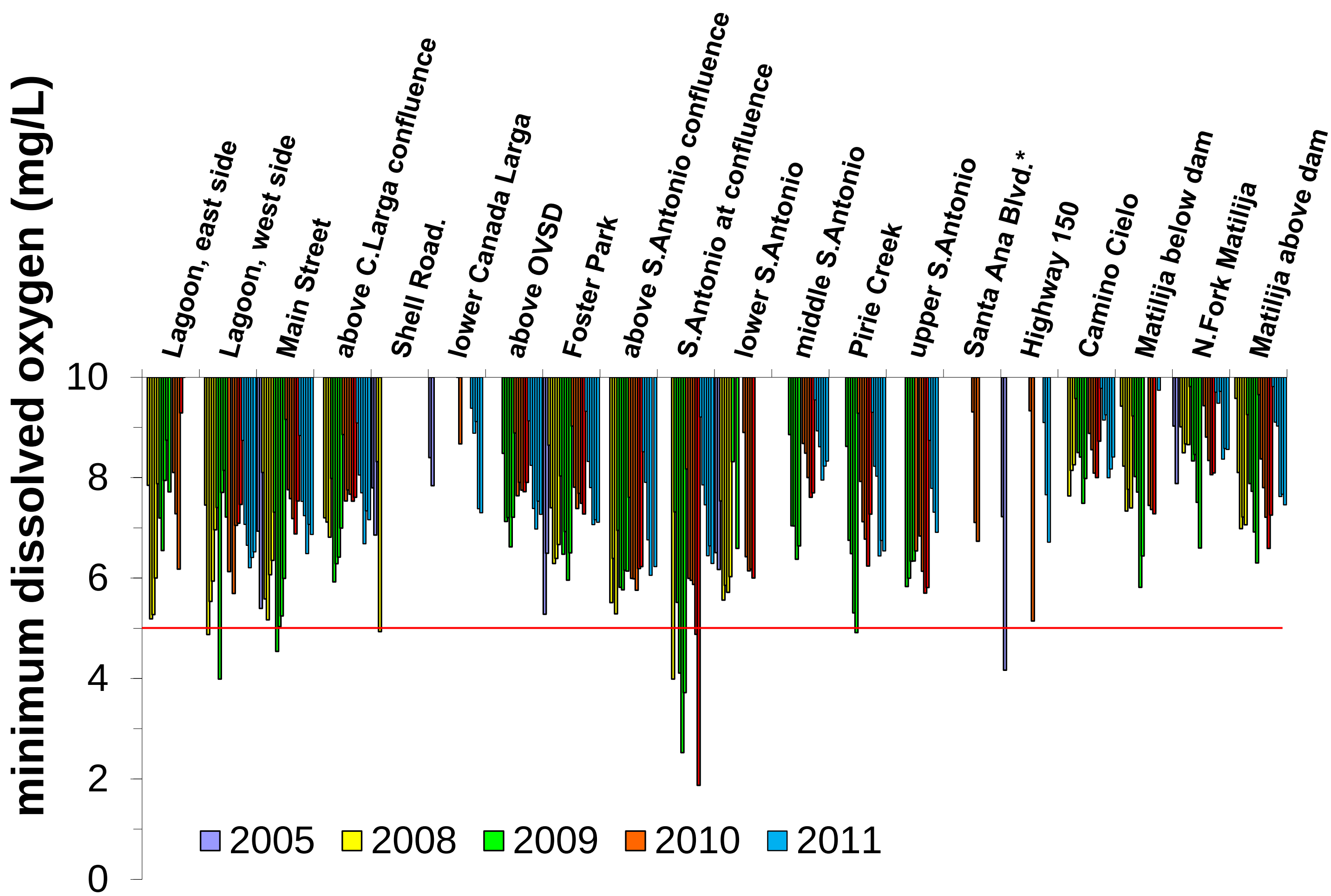

Figure 1. Minimum (pre-dawn) dissolved oxygen concentrations (in mg/L) for selected Ventura watershed locations from 2008 through 2011.

Data are shown in chronological order with each year identified by a different color. The red line at 5 mg/L is the allowable basin plan minimum. Any site with a value extending below the red line had a DO below the acceptable minimum (greater detail can be seen by zooming in on the graph). These are estimates of minimum DO at these locations and are not the true minimum; true values are almost certainly lower than those shown, but probably not by much. Minimum DO may not, indeed probably does not, occur just before dawn, unless algal respiration continually exceeds oxygen recharge during the night-time hours. While night-time algal respiration might be assumed to remain constant, oxygen recharge steadily increases (following the loss of lingering oversaturation during early evening hours) to a peak occurring near the time of minimum DO concentration (this varies considerably, but between 11PM and 3AM would be a reasonable estimate).

The principal cause of accelerating night-time oxygen recharge is the increased efficiency of oxygen transfer from the atmosphere as algal respiration and other oxygen utilizing processes decrease oxygen saturation in the water column. Declining water temperatures accelerate this gas transfer as the night wears on by increasing the oxygen holding capacity of the stream. Other factors, such as stream depth (gas transfer is mainly a function of surface area while water temperature and DO are more closely related to stream volume) play minor roles. In other words, as night-time dissolved oxygen concentrations decrease, the amount of oxygen entering the stream from the air above continually increases until DO reaches its minimum; from that point on DO gradually increases as oxygen recharge exceeds oxygen utilization.

In big algal years, like 2008, algal respiration is the predominant process causing minimum DO, so dominant that other factors can be ignored. However, in relatively low rainfall years, or near the end of the dry-season during moderate years, other processes play significant roles. As sediments accumulate during these times, oxygen-reducing streambed decay mechanisms becomes increasingly important and often supplant algal night-time respiration as the major cause of low DO. This becomes particularly true as aquatic plants begin to cover the river bottom and trap additional fine sediment; this happens most commonly below the wastewater treatment plant (WWTP) and in low flow situations elsewhere. Which process dominates, however, can be determined by looking at maximum DO concentrations: algae photosynthesize, producing oxygen *within* the water column during daylight hours; oxygen diminishing processes such as decay and the respiration of critters further up the food chain continue during this time (usually at a faster rate than during the night because of higher daytime water temperatures). (Aquatic plants also photosynthesize, but since the vast majority of their green parts are located above the water surface they add oxygen to the atmosphere and not the water column.) Simply put, only algae raise DO levels during the daytime and lower them at night.

Whether or not algae are the cause of excessively low DO concentrations can be easily determined by examining the *range* of oxygen variation over a 24-hour period (maximum DO – minimum DO: if low night-time DO is succeeded by excessive daytime concentrations algae are responsible. Figure 2 shows the range of daily DO variation for the sites monitored by SBCK over the 4-year, 2008-2011, period. Again, data are arranged chronologically with each year separately identified. Mid-afternoon concentrations are plotted as colored background bars and pre-dawn concentrations plotted as un-colored (white) bars placed in front. Since mid-afternoon values are estimates of peak DO and pre-dawn of minimum DO, the visible colored portion typically represents the range. But not always. In a few cases the corresponding mid-afternoon or pre-dawn measurement is missing (showing only a white bar in the first case, only a colored bar in the second); this is the usual exception for the lower Ventura River. However, on the upper Ventura or on its tributaries (Canada Larga, San Antonio) a missing colored bar usually indicates a mid-afternoon DO *lower* than the pre-dawn concentration. In the relative absence of algae, especially during times of low flow, higher daytime water temperatures often produce lower oxygen concentrations than are seen at night – the solubility of oxygen (and most other gases) in water increases as temperatures decrease. Obviously, this situation automatically indicates the absence of an algal problem (this is a common occurrence on the North Fork of the Matilija).

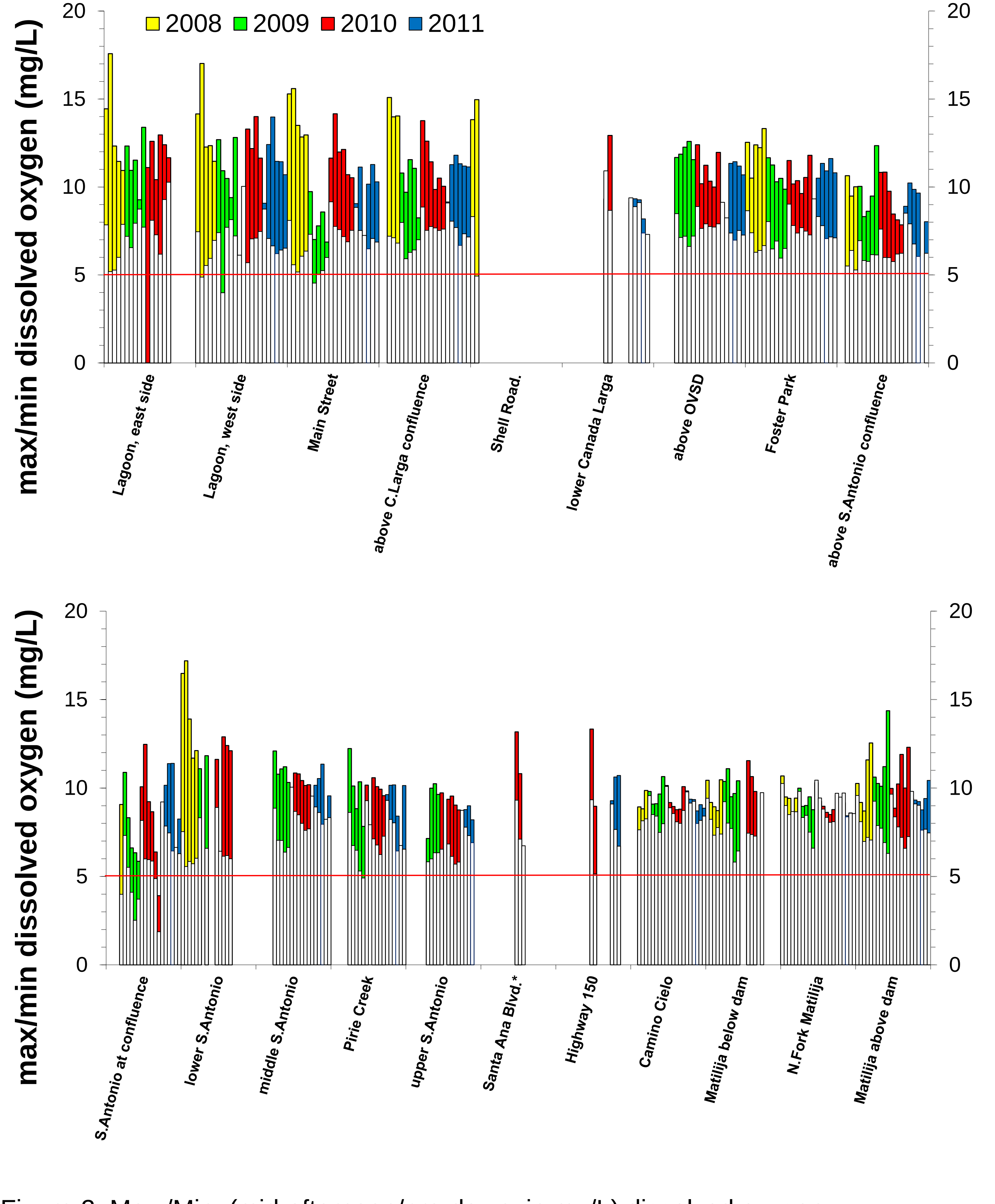

Figure 2. Max./Min. (mid-afternoon/pre-dawn, in mg/L) dissolved oxygen concentrations for selected Ventura watershed locations from 2008 through 2011.

To make the graph easier to read it's shown in two halves, the main stem from the San Antonio confluence to the Ventura Lagoon in the upper, San Antonio Creek and the upper Ventura River in the lower. A red line again indicates the basin plan 5 mg/L DO minimum. The same caveat expressed on the use of pre-dawn concentrations as estimates of minimum DO applies to mid-afternoon concentrations as estimates of maximum DO: mid-afternoon concentrations are an under-estimate, the maximum is always higher but again probably not by much.

(The rate of maximum DO change occurs in the middle of the transition from lowest to highest or vice versa. As you approach the maximum or minimum the change becomes more gradual – think of a sine-wave or climbing a rounded hill from the valley bottom. What limited data we have available shows that recovery from a night-time DO minimum is particularly slow and while changes near the DO peak are more rapid, mid-afternoon measurements are much closer to the time of maximum concentration.)

Instead of using DO concentrations in mg/L the data in figure 2 can be shown using DO expressed as percent saturation (% sat.). For any water at a given temperature, atmospheric pressure (basically defined by the elevation of the sampling location) and conductivity (the amount of dissolved ionic solids – usually a negligible factor for most freshwaters and only important for saline or brackish water) the *equilibrium* concentration of dissolved oxygen can be calculated; equilibrium meaning the water is in gas exchange balance with the overlying atmosphere and is neither gaining nor losing oxygen or, more precisely, is gaining oxygen at the same rate as it is losing it and maintaining a steady concentration. (This would be analogous to a glass of cold or hot water sitting on a table and gradually warming or cooling to room temperature, i.e., reaching equilibrium with the ambient temperature of its surroundings.) If water has a higher concentration of dissolved oxygen than its equilibrium value, it is said to be *super-saturated* and *must* be in the process of losing oxygen to the atmosphere; conversely, water containing less than the equilibrium concentration is *under-saturated* and the net transfer is from the atmosphere into the water.

The percent of DO saturation is simply the actual DO concentration divided by the equilibrium value with the result expressed as a percentage. For example: The Ventura River at Main Street (~ sea level) would have an equilibrium DO concentration of 8.77 mg/L at 20° C (68° F); if the measured DO was 14 mg/L the % sat. would be (100*14/8.77) or 160 % (this would not be an unusual day-time result during a good algal season). This super-saturated water would be in the process of continually losing oxygen to the overlying air. If the measured DO was 6 mg/L the % saturation would be 68 % (100*6/8.77), and in this under-saturated condition the river would be continually gaining oxygen from the air. The rapidity of the gain or loss, as mentioned earlier, is dependent on the extent of the oxygen deficit or excess and the opportunity provided for gas exchange by that particular stretch of the river (a slow process in deep, placid water, much faster in shallow cascading flows). Most modern DO meters calculate % saturation automatically by simultaneous measurement of DO, water temperature and atmospheric pressure (or by allowing manual entry of the sampling site elevation in lieu of pressure measurement).

Figure 3 plots the range of daily DO variation for the sites monitored by SBCK (2008-2011) in % DO saturation. As in figure 2, the actual maximum/minimum range is larger than that exhibited by the mid-afternoon/pre-dawn values used here as estimates. A red line is shown on the graphs at 120 % saturation. This is my personal rule-of-thumb indicating that a stream section is exhibiting an algal problem. I developed it over the past 12 years of stream sampling in the Ventura and Goleta Slough watersheds based on observations of algal conditions while measuring DO.

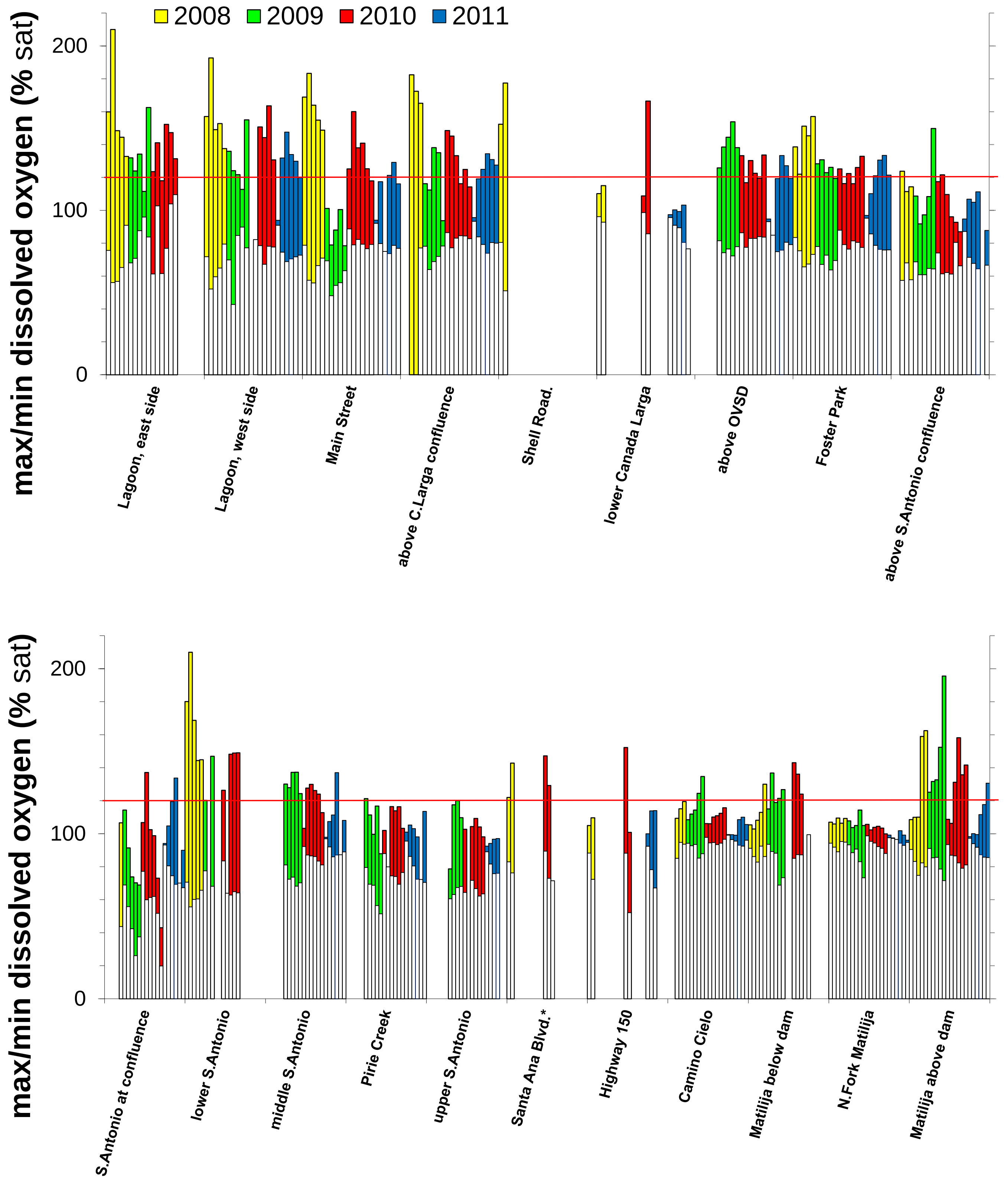

Figure 3. Max./Min. (mid-afternoon/pre-dawn in % saturation) dissolved oxygen concentrations for selected Ventura watershed locations from 2008 through 2011.

Since most of this hands-on experience occurred during morning hours (SBCK typically samples between 9 and 12 in Ventura, 10 and 12 in Goleta), hours before the peak values shown on the graph were measured, the 120 % rule may be a little too conservative when used in this context – but perhaps not, as I'll go into later.

Examining the Data

Let's turn to a brief look at the data. Looking at Figure 1, note how few DO measurements were below the 5 mg/L limit, and where and when they occurred. The worst sites (in descending order) have been San Antonio Creek just before its confluence, the Ventura lagoon, Main Street, and the middle Ventura at Hwy. 150. And the lowest values were not usually associated with the worst algal years, 2005 and 2008, years of extravagant algal growth. In other words, the majority of unacceptably low DO events do not coincide with excessive algae (except in the lagoon and on the middle Ventura, exceptions I'll discuss later).

The reason for this is simple: Big algal years invariably follow winters with above average rainfall, winters with at least one storm big enough to sweep aquatic plants and accumulated fine sediment out to sea; even better if that storm is large enough to also clean out riparian growth. These storms create near-perfect algal habitat by: (1) opening up the channel to increased sunlight (sunlight to power photosynthesis – even more sunlight if riparian vegetation is cut back or removed); (2) removing competitors (for sunlight, e.g., aquatic plants) and algal parasites; (3) scouring the stream or river bottom leaving only gravel or cobble (providing necessary holdfasts – anchoring points – for cladophora, the dominant alga during big blooms); and (4) increasing flow (expanding available habitat and providing for more rapid delivery of stream-borne nutrients to stationary algae). And behind it all, the increased rainfall of the preceding winter recharges water tables with high nitrate groundwater that continues to feed the stream with high-nutrient enhanced inflows throughout the subsequent dry-season (the high nitrate coming from agricultural, urban and suburban runoff, and – this will surprise some – multi-year accumulations of air pollution deposits on undeveloped and near-pristine areas in the watershed).

The higher than normal flows, coincident with the extravagant algal growth of these big years, are the principal reason oxygen concentrations remain relatively high. The amount algal respiration lowers DO is a function of the amount of algae *and* – this is the critical point – the amount of water (i.e., flow) the algae are acting upon: the higher the flow the more difficult it becomes to lower oxygen levels and the more algae it takes. Oxygen depression is directly proportional to the amount of algae, but inversely proportional to flow. The amount of algal growth is related to the available surface area of a stream (algae require sunlight and a heavy growth of algae on the surface prevents the growth of substantial amounts of algae deeper in the water column). Flow, on the other hand, is a measure of the volume and velocity of the water – and volume and velocity increase much more rapidly than surface area. As water moves faster (reducing the time available for algal respiration to lower DO) or increases in depth (increasing the volume of water algal respiration has to act upon) the less effect algae will have. Fast moving or deep water is ordinarily not the place to look for abnormally low DO, even if algal growth looks overwhelming. Instead, shallow, sluggish flows, even when the algal crop looks skimpy are the potential trouble spots.

This is why lower San Antonio Creek and the middle Ventura at Highway 150 (usually measured when this reach is going dry) have some of the lowest values, and why the lowest monthly values in Figure 1 usually occur a few months past the point of peak algal density, i.e., when algal growth has diminished but flows have decreased to a much greater degree. This is also the reason why sites like Foster Park, the Ventura just above the San Antonio confluence, or Matilija Creek above the dam often show the greatest amount of DO variation near the end of the dry-season, long after the algal peak has passed.

The Ventura Lagoon is a special case. Significant algal blooms, which cause the oxygen deficits shown in Figures 1-3, only occur under the following scenario: (1) an appreciable sand berm, durable enough to isolate the lagoon from the Santa Barbara Channel for a month or more, forms across the mouth of the lagoon during the Spring; (2) inflows from the river form what becomes essentially a freshwater, or slightly brackish, lake behind the berm; (3) nearly unlimited sunlight, warming temperatures, and the high nitrate concentrations of early dry-season river runoff do the rest – and a massive algal bloom results. Although the lagoon has a very large volume, which keeps growing as river inflows increase the depth, there is no flow and DO values in the shallower sections can drop below 4 mg/L (perhaps lower if we had been there to measure it). The bloom – and the low DO values it causes – ends when the expanding "lake" breaks through the berm. From that point on low nutrient ocean inflows, and the highly brackish conditions they cause, end the problem. Algae can still be found, but only at low densities.

The data show the worst site to be San Antonio Creek just before the Ventura River confluence. However, a close look at Figure 3 shows that maximum DO at this site is rarely above 120 % of saturation and episodes of very low DO always occur with maximum values below 100 % – usually below 70-80 %. This indicates that while algae are probably a contributing factor, the dominant cause of oxygen depression was organic decay in the sediments. (Aerobic decay – decay in the presence of oxygen – directly consumes oxygen while anaerobic decay – decay in the absence of oxygen – releases reduced compounds that are oxidized as they emerge from sediment into the water column. Anaerobic sediments are easily identified by their black color and the smells released – from gasses like hydrogen sulfide and methane – when disturbed.) The relative importance of decay in reducing DO is, like algae's impact, a "mass" problem: dependent on flow and the amount of decay taking place; it's directly proportional to the amount of fine sediment (and its organic content) available and inversely proportional to flow. Years of low flow, especially successive years of low flow, lead to organic material build-up on the streambed and very low DO concentrations during the low flow conditions that characterize those years. Algae, of course, may no longer be the principal culprit but still play a role in lowering concentrations even further (this can be observed at sites that still show a substantial 24-hr DO fluctuation).

The 2011 Problem

The hydrograph of average daily flow at Foster Park (http://waterdata.usgs.gov/ca/nwis/uv?site_no=11118500) for the four years covered by this data set is shown in Figure 4 (note the logarithmic vertical scale). Annual average daily flow over the four years varied greatly (as is typical): 73, 8, 27 and 71 cfs, for 2008-2011, respectively. For comparison, *median* annual daily flow is 17 cfs, (average annual daily flow is 69 cfs – that the median is far below the average indicates a highly skewed distribution – i.e., most years are below average and big water years are really big), so 2008 and 2011 were reasonably good years (a *really* good year, such as 1998 or 2005 has an annual average daily flow > 300 cfs), 2010 a little better than usual, and 2009 was a dry year with only about half the usual flow. Variations in peak annual flow, which indicates the size of the biggest storm and is a measure of the destructiveness of the largest annual flood, were even greater: 14,400 cfs in 2008, 136 cfs in 2009, and an estimated 2,500 cfs in 2010 (final numbers for the last two years are not yet available from the USGS; 2,500 cfs for 2010 was the highest hourly flow shown on their real-time data page). Given similar annual peak *daily* flows (circa 6,300 cfs) for 2008 and 2010, it's reasonable to assume the peak floods were of similar magnitude. Note that the peak flood flow in 2008 and 2011 was more than 100-times greater than in 2009, and about 6-times greater than that of 2010. The median average daily dry-season flow is shown on the Figure 4 for comparison.

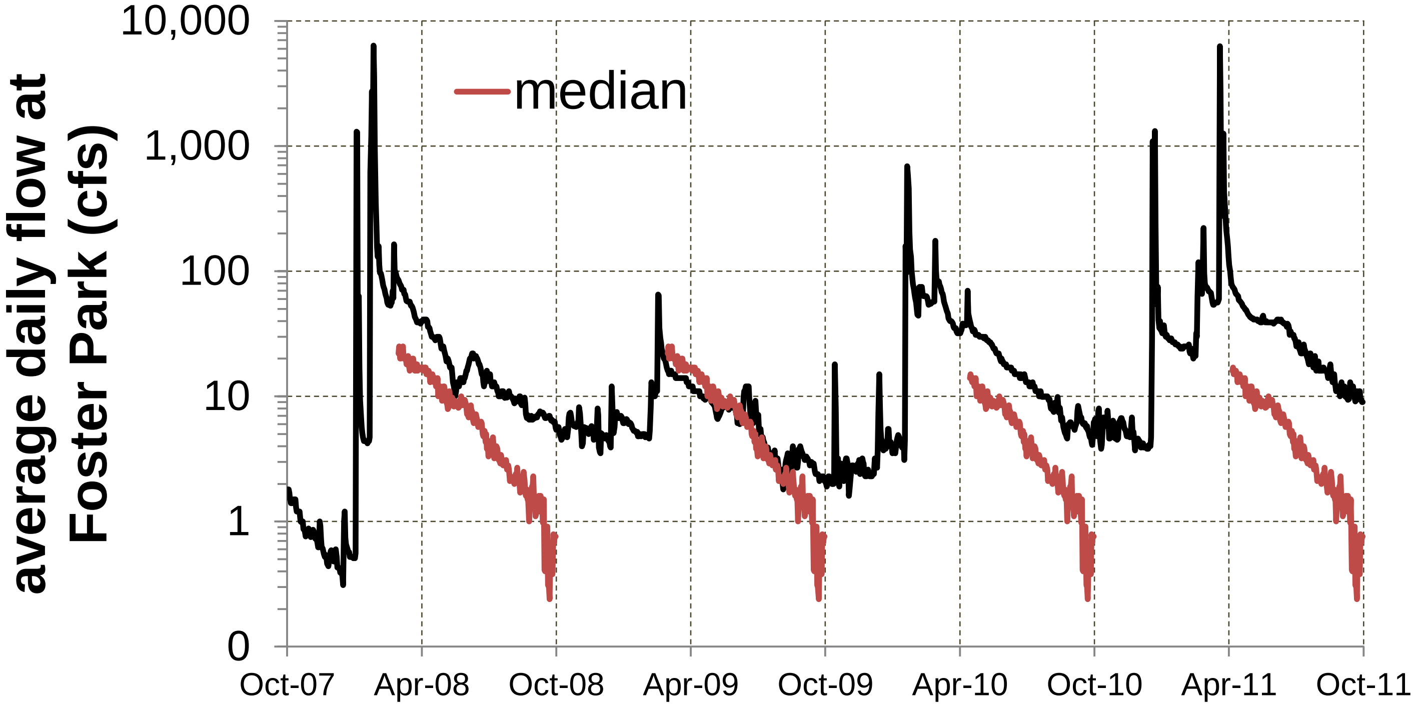

Figure 4. Average daily flow at Foster Park (in cfs) from 2008 through 2011.

The question concerning 2011 is: if 2008 and 2011 were very similar water-years, with similar average daily flows and similar sized peak flows and floods, why was the algal response so different, with 2008 a relatively big algal year (the year of the UCSB algae-nutrient study) and 2011 a year of limited algal growth. In terms of oxygen variation and deficits, Figures 1-3 show 2011 to have had even less problems than 2009 and 2010; it is noticeably the year with higher minimum oxygen levels and lower daily variations.

The main reason is that as successive years pass with without a substantial flood, a flood capable of clearing both the river bottom and adjacent riparian areas clear of vegetation such as happened in 1998 and 2005 (peak flood flows of 38,800 and 41,000 cfs respectively – almost 3-times greater than the flood of 2008), plants and trees become more deeply and strongly rooted, increasing the threshold size of a cleansing storm. The extreme flood of 2005 was followed by a moderate flood (9,250 cfs) in 2006, and the very dry year of 2007 (peak flow of 92 cfs). This sequence of big flood, moderate flood, no flood, allowed vegetation to become established, but not firmly established, by the end of 2007. The moderate flood of January 28, 2008 allowed most, but by no means all, of this vegetation to be swept away. Figure 5(a) shows what riparian vegetation remained above Main Street following the storm. The reddish roots exposed between the remaining riparian brush and the river's edge are Ludwigia, an aquatic plant that dominates the lower river below the wastewater treatment plant during drier years; the survival of this plant plays a big part in the relative absence of algae from these reaches in following 2008.

By early April 2008 the greenish under cast in the color of the water in Figure 5(b) indicates an early start to a substantial algal season (the last meaningful rainstorm occurred on February 24), but aquatic plants and riparian vegetation took advantage of the same early start. By March 2009, after a winter without a flood, this

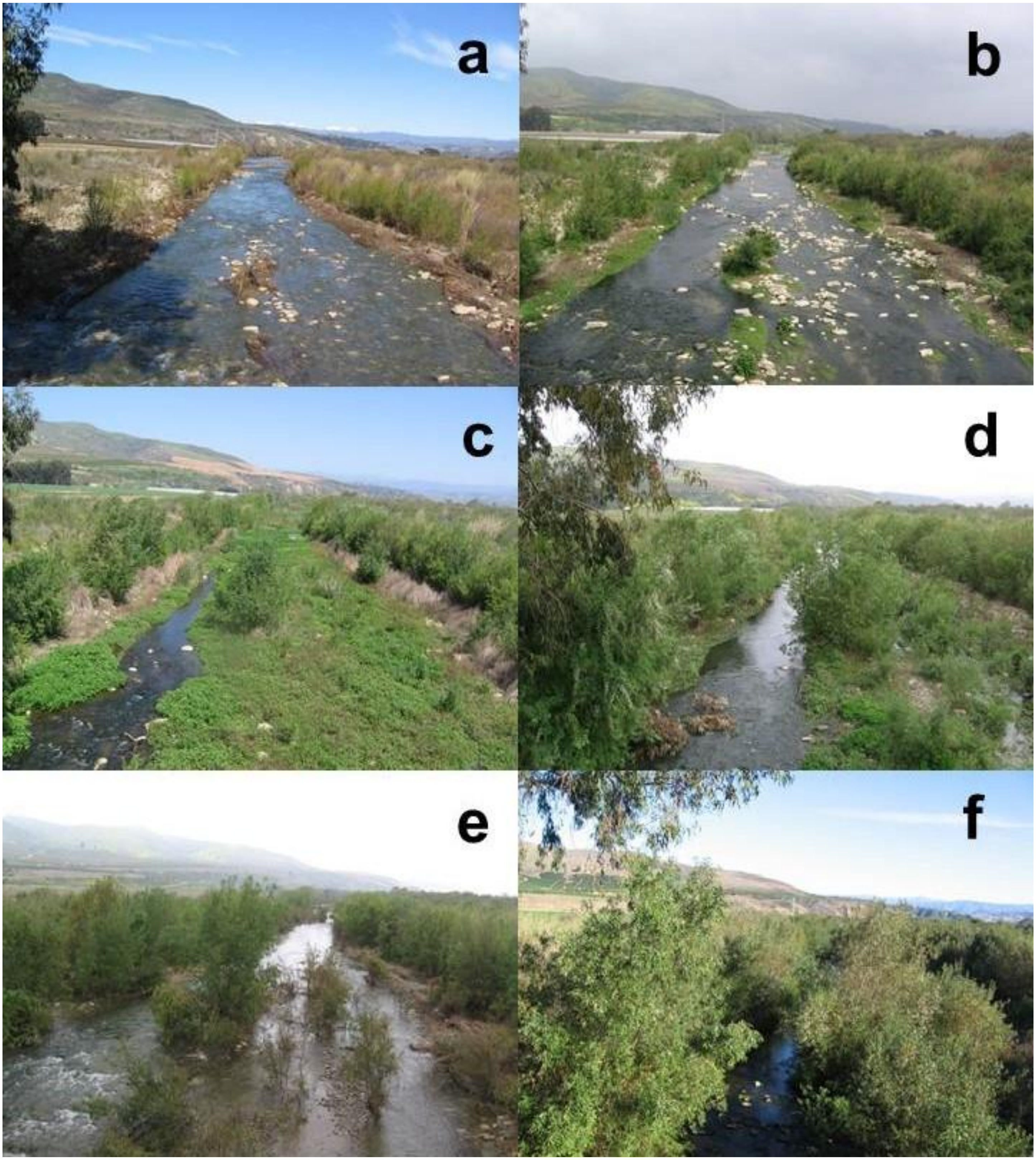

Figure 5. Looking upstream at the Ventura River from the Main Street Bridge: (a) 2 February 2008, (b) 5 April 2008, (c) 9 March 2009, (d) 10 April 2010, (e) 2 April 2011, and (f) 5 November 2011.

vegetative growth had advanced and become firmly established (Figure 5(c)); algae can be seen growing in the open water stretches but aquatic plants dominated most of the river (the green plants are mostly watercress, but the reddish roots of Ludwigia, which will come to replace it later in the season, can also be seen). Figure 5(d) indicates that the flood of 2010 did little to pare back this accumulating vegetation; only shallowly rooted aquatic plants like watercress were flushed out. The flood of 2011 was roughly the same size as that of 2008, but compare the scene in Figure 5(e) with that in (a). Both photos were taken within a few days of the biggest annual storm and during periods of similar flow (circa 100 cfs). Note the greater 2011 survival of plants and root systems within the river and the much greater dominance of riparian trees and brush. Even given high-nutrient water and plenty of sunlight, the rapid growth of riparian vegetation in what had only been three years continues to astound. It takes little imagination to visualize how much less ideal this reach will become for algal growth in the coming 2011 dry-season. Main Street is one of the most heavily impacted algal-dominated sites in the watershed – but only in big algal years, i.e., big water years, not in most years. Figure 5(e) shows that riparian vegetation and aquatic plants have almost completely converted by November 2011 what a few years before had been an ideal algal environment into one where algae can barely hang on.

Other factors play a role. Years without an intervening flood allow the expansion of various algal predator populations. The late start to the 2011 algal season, with the big flood coming at the end of March, gave plants a leg up in the annual competition (closer to the start of their growing season), in contrast with the very early (unusually early) start in 2008. Compounding this, flows were higher in 2011 than in 2008 (compare dry-season flows with median flows in Figure 4). Higher flows, along with a river more tightly constricted by expanding riparian vegetation, means higher water velocities which further delay the start of extensive algal growth (the dominant alga of the largest blooms being Cladophora which requires a velocity low enough to allow it to hold fast to cobbles on the river bottom). (Ojai rainfall in 2008 was 20.6 inches, a little below average in spite of it being a year with a pretty good flood; the year preceding, 2008 had only 7.4 inches. In contrast, 2010 had above average rainfall, 24 inches, and 2011 was an even wetter year with 29.3 inches. More rain means greater winter groundwater recharge means higher dry-season stream flows.)

These same higher flows, along with a 2011 flood large enough to sweep out sediment, also improved the oxygen situation on the upper river, along most of San Antonio Creek and on the Matilija. Low oxygen at these locations, as previously stated, is typically a product of low flows and organic decomposition aided, of course, by algae. The substantial rainfall and flood of 2011 removed much of the problem (Figure 4 shows that Foster Park flows at the end of the 2011 dry-season were substantially higher, usually more than twice as high, than in the other years; the same situation pertained to other reaches of the watershed).

Delta-DO

Delta-DO is the 24-hour (diel) difference between maximum and minimum dissolved oxygen concentrations. It can be considered a direct measure of the influence algal growth is having on the oxygen levels of a stream. Other factors, like temperature and flow, can cause oxygen to vary over the course of a day, but these changes are almost always minor; only algae cause a substantial variation. The SBCK delta-DO results are shown in Figure 6. Some of the locations show negative values on occasion. This indicates that algae were not a problem at the time of measurement; a negative result often occurs in a relatively pristine stream, especially in warmer weather when flows are low. Cooler night-time water can hold higher concentrations of oxygen in solution, concentrations often much higher than 100 % saturation in warmer daytime waters.

The red line on the graph at 2.5 mg/L marks my interpretation of a recently adopted guideline by the Central Coast RWQCB. The Central Coast board uses an oxygen deficit greater than 1.25 mg/L as a criterion, along with nitrate-nitrogen concentrations in excess of 1.0 mg/L, to designate water bodies as "impaired for aquatic life" (i.e., meeting the criteria for 303(d) listing). Figure 6 translates this 1.25 deficit into an equivalent delta-DO of 2.5 mg/L. The Central Coast's rational is presented in a report titled "*Interpreting Narrative Objectives for Biostimulatory Substances for California Central Coast Waters*" (Worcester, et al.) that I wouldn't go into other than highly recommending it to anyone interested in delving further into this subject (http://www.swrcb.ca.gov/water_issues/programs/swamp/docs/reglrpts/rb3_biostimulation.pdf).

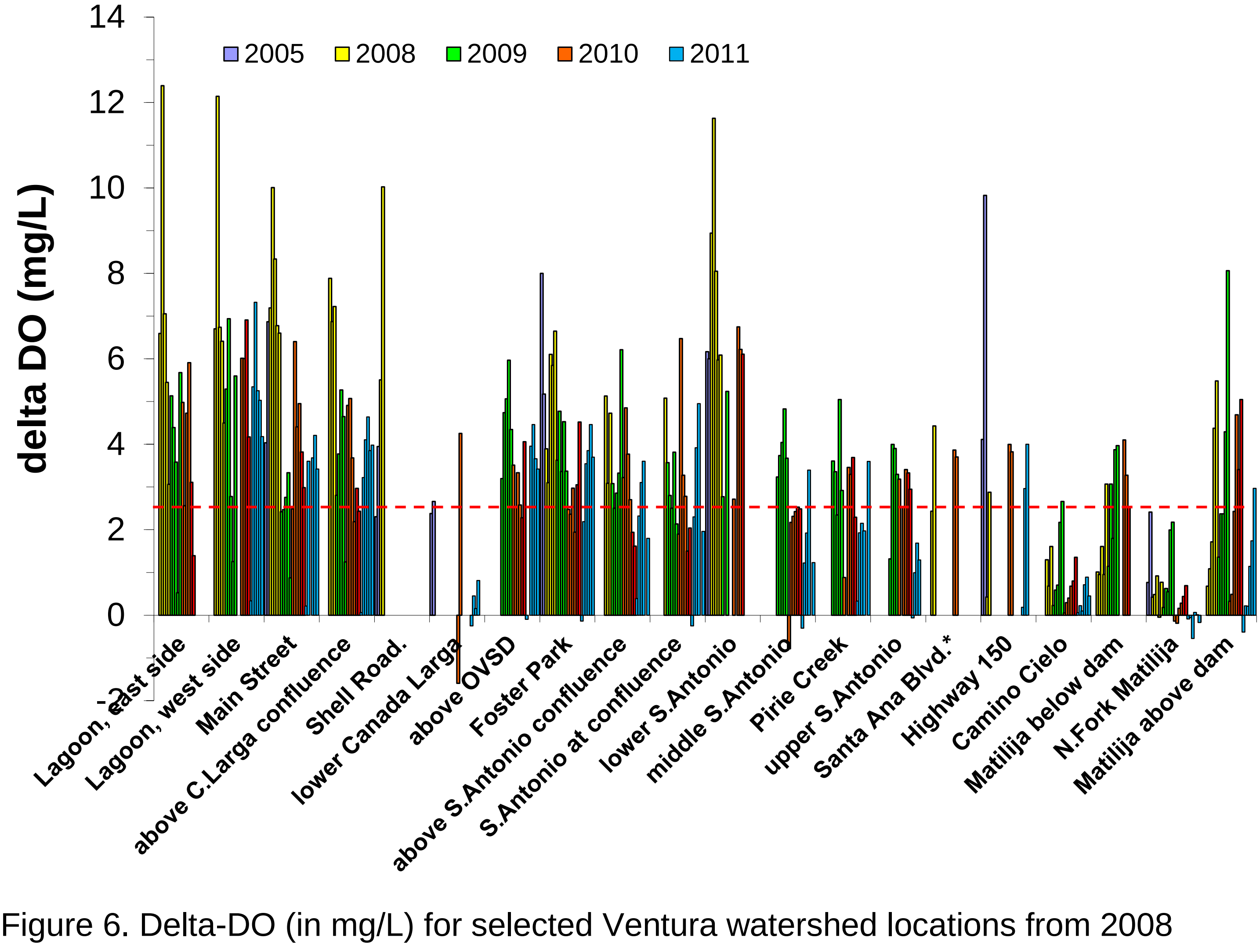

Figure 6. Delta-DO (in mg/L) for selected Ventura watershed locations from 2008 through 2011. Delta-DO is the difference between daily maximum and minimum (mid-afternoon minus pre-dawn) dissolved oxygen concentrations.

Note that of all the Ventura watershed sites monitored, only the North Fork of Matilija Creek continually met this standard. The report also sets out a criterion of 13 mg/L as a maximum DO level, noting that only 1.6 % of some 2400 grab samples taken at streams that met either the 5 mg/L warm-water DO objective or the 7 mg/L cold-water objective ever exceeded this level. The establishment of a *maximum* DO concentration is of great utility since almost all DO measurement normally takes place during daylight hours – the convenience of the sampler being usually regarded as of more importance than the usefulness of the measurement. A 13 mg/L maximum requirement in the Ventura watershed would result in an allowable % saturation limit higher than the 120 % shown on Figure 3. For Main Street it would yield, for the 2011 SBCK measurements, limits of 135 % in April to 156 % during the warmest part of the summer; for Matilija Creek above the dam the corresponding percentages would be 130 and 166. Whereas the 120 % marker might be considered too low (too conservative), 13 mg/L appears to be too high. On the other side of the argument the Central Coast report does mention that oxygen super-saturation alone may pose a direct danger to fish, causing “gas bubble trauma” (most often cited as a problem with nitrogen below dam outlets), and that the EPA has recommended an upper limit of 110 %.

Conclusion

I’ve said enough. Readers can draw their own conclusions. I will point out that measuring minimum, and maximum, DO concentrations is a useful activity and the watershed could certainly stand more of it. Dissolved oxygen concentrations are almost the easiest measurement that can be made, and are arguably the best instantaneous measure of stream health. Even better than having people stumbling around in the dark to record minimum levels would be a program of recording sondes, periodically moved from location to location to provide more complete coverage in the basin: in the lower sections during the early part of the dry-season, in the upper watershed and on San Antonio Creek during later months. This data, with measurements collected at 15 or 30 minute intervals, could also be used to estimate primary productivity (algal biomass) using currently available analysis techniques cited in the literature. And it would allow a check of the “pre-dawn equals minimum” and “mid-afternoon equals maximum” assumptions of the SBCK data collection. Sad to say, sonde measurements were made by Larry Walker Associates in conjunction with UCSB algal density measurements in the late summer of 2008, but were never freely circulated so that they could be used for this purpose.

Finally, I’d personally like to thank all the SBCK volunteers who collected the data shown here in 2005 and 2008-2011. They almost always got a free breakfast or pizza for afternoon volunteers, but that seems a small recompense for getting up around 3 or 4 AM to wade in a cold river before work, or sacrificing a Saturday or work-day afternoon. They should feel good about themselves for being willing to turn out and collect data, not when it was convenient but when it was meaningful.