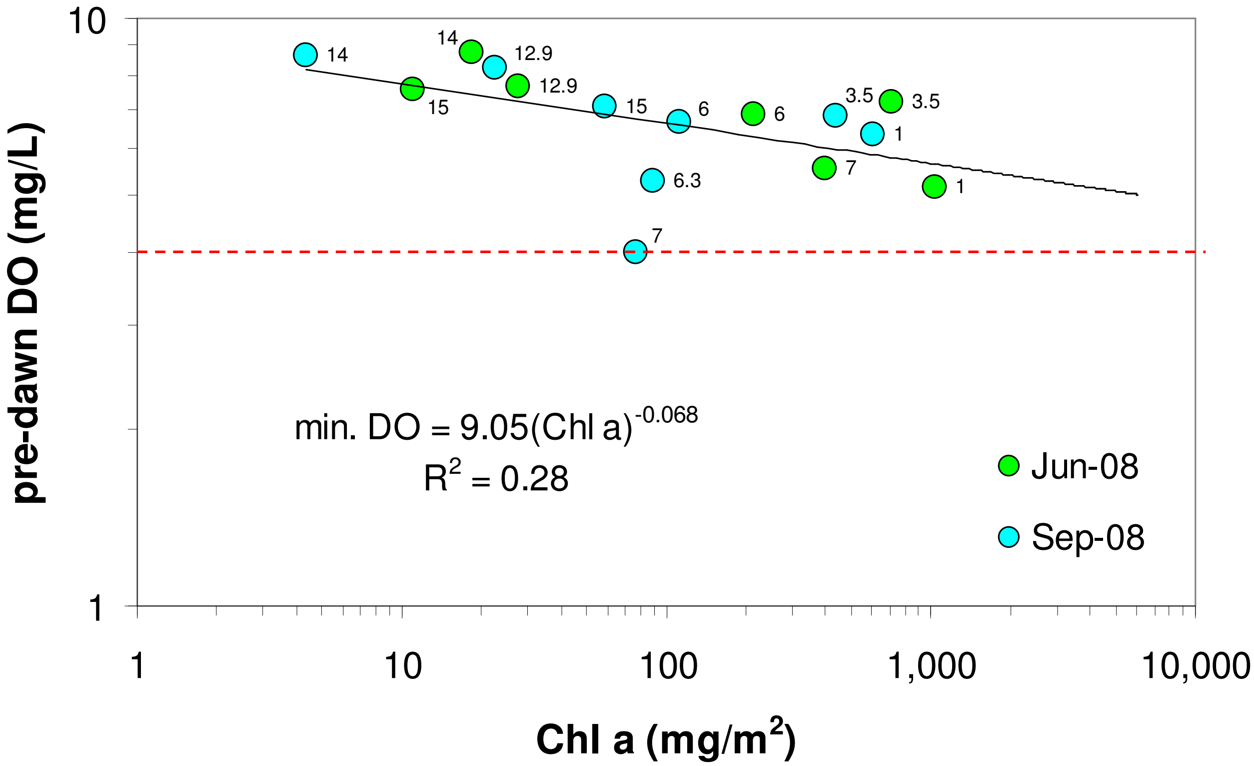
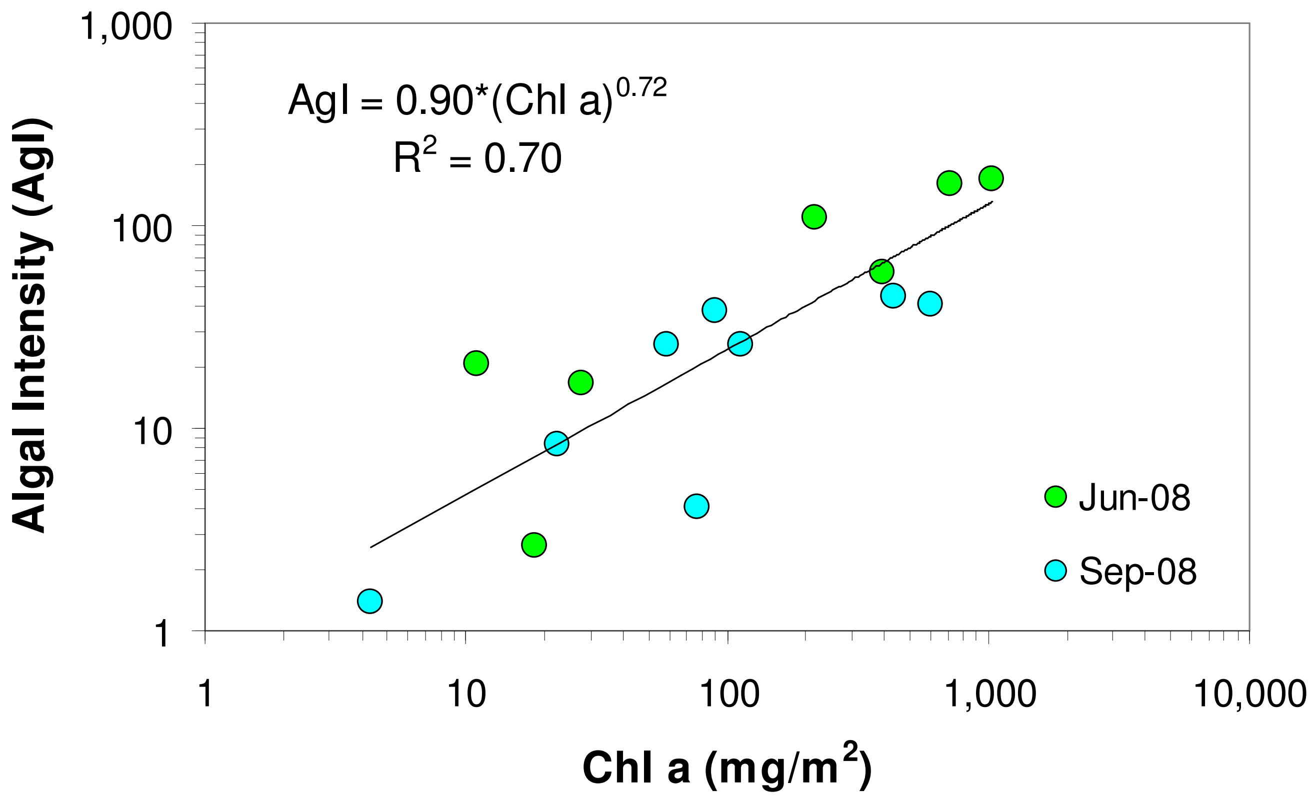


Scott, here you go. Off hand, I'd say it'd be a hard sell even though the regression is valid (just: p = 0.44; r-square = 0.22, so we can only expect it to explain about 20 % of the variation in minimum DO). The regression line shows you'd need a Chl a density of 163,000 mg/sq-meter to achieve a minimum DO of 4 mg/L. That sounds a little high even to me; I don't think the Regional Board would go along. I don't know why I'm having so hard a time convincing people that flow, *the quantity of water*, matters. If you have a fixed amount of algae the change in DO over a 24 hour period will vary based on the amount of flow: more water and algal modifications of dissolved oxygen will have less impact, less water produces a greater impact. Other things matter (as I've discussed elsewhere), but when flow is relatively high and algae are in the midst of a significant bloom – like what happened this spring – not so much.

[I'll repeat my main justification. Other processes depress oxygen (e.g. aerobic decay) or increase oxygen (e.g. physical re-aeration). My measure of Algal Intensity ignores all other factors, attributing changes in DO to algae alone. This is a reasonable assumption only as long as the magnitude of algal productivity dwarfs other processes. As the amount of algae increases, and as flow increases (reducing the relative amount of oxygen gain or loss per unit flow via physical processes), this becomes increasingly true. As algal biomass and/or flow decrease, other factors become increasingly important and the utility of AgI as a measure decreases.]

So let's take this a step or two further. Let's use Chl a to predict, not minimum DO, but "Algal Intensity" (AgI, the product of the diel DO variation and flow).



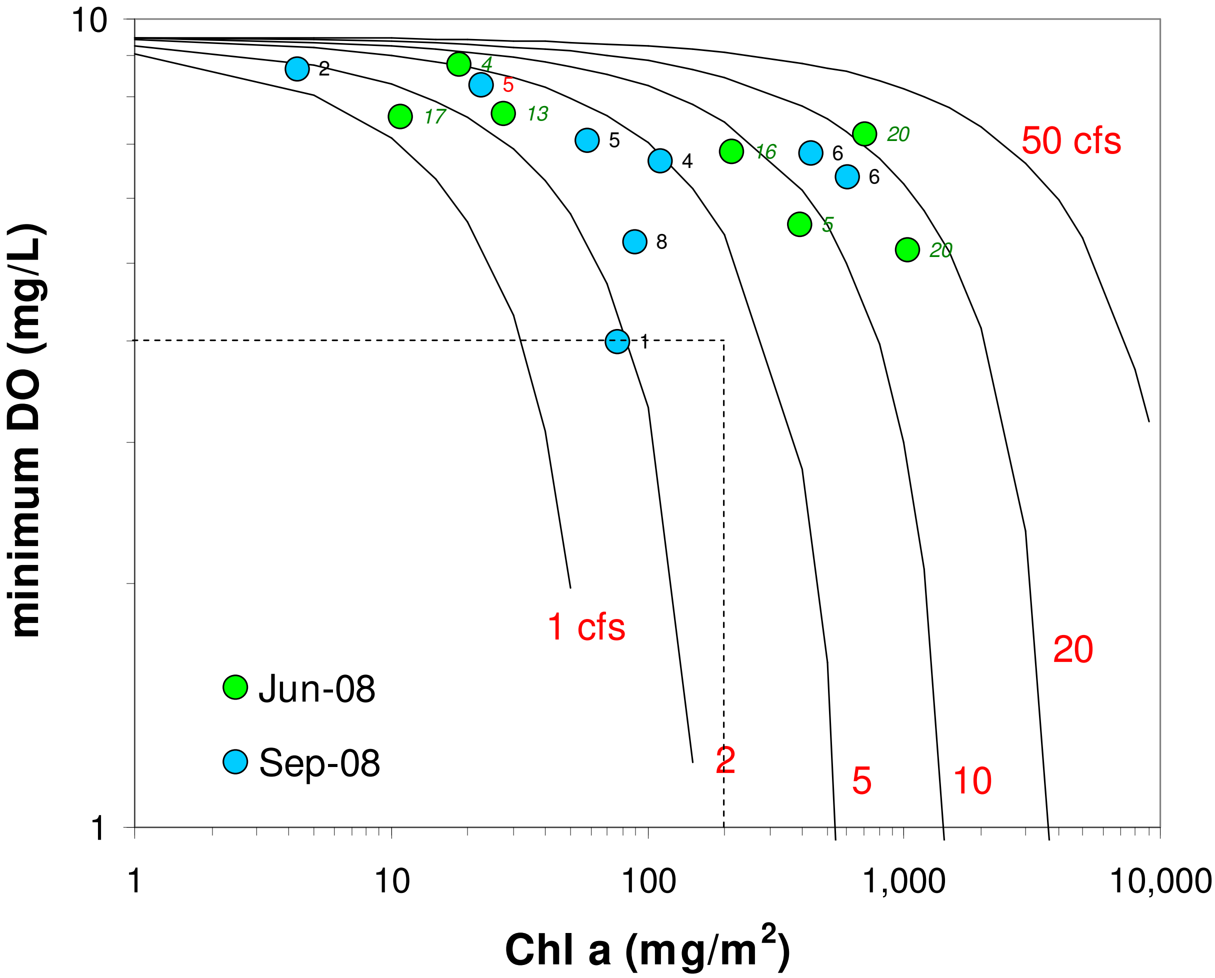
OK. Here's a plot of Algal Intensity against Chl a. I think it's a kinda nice relationship, but I'm probably biased. All we need to do now is deconstruct AgI into its two components: the diel variation and flow, i.e. AgI = delta-DO * flow or expressed another way (maximum DO – minimum DO) * flow. And since we are not interested in maximum DO we can re-write it as: AgI = 2 * (mean diel DO – minimum DO) * flow. In other words we can assume that the diel variation occurs around some mean value. From the diel measurements made this past dry-season the mean (halfway) concentration was 9.49 ± 0.14 mg/L (± SE of the mean); or if we look at the overall Ventura mean DO concentration (DO is measured around 9:30 to noon, which generally puts us about halfway) we get 9.68 ± 0.08 mg/L. I'm going to simply use 9.5 mg/L. So the relationship between AgI and minimum DO can be written as:

$$\text{minimum DO} = 9.5 - \text{AgI}/(2 * \text{flow})$$

Or substituting the Chl a equation from above for AgI:

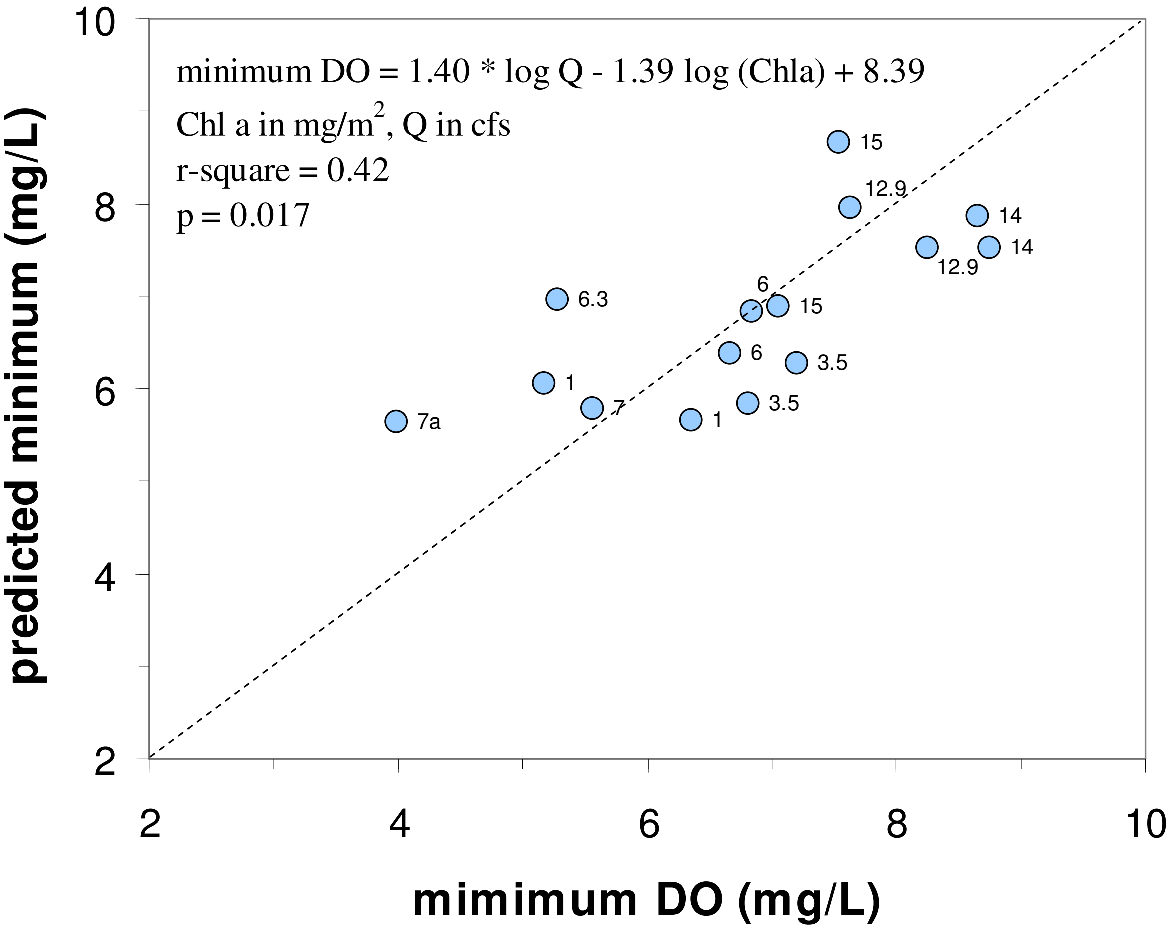
$$\text{minimum DO} = 9.5 - (0.45/\text{flow}) * (\text{Chl a})^{0.72}$$

From here I can construct a whole family of curves with which, *given Chl a and flow*, we can estimate minimum dissolved oxygen concentrations. In other words, the ecological impact of algal growth is not solely dependent on algal density (Chl a), *but is dependent on both density and flow*. The beauty of this, of course, is that when AgI is low (i.e. when factors other than algal growth play increasing roles in determining DO depression) the accurate calculation of AgI becomes unimportant – *because DO levels will not be at hazard*.



Here is the revised graph. This is exactly the same relationship as shown in the first graph, except that I've added a family of flow curves based on the AgI vs. Chl a relationship from the graph on page 2. I could be used by (1) entering a Chl a density value, (2) moving vertically to intersect the appropriate flow value, and (3) horizontally to determine the estimated minimum DO that will result from an algal density at that flow. The labels for each of the data points now show gauged flow at the time of DO measurement and not, as before, SBCK site numbers.

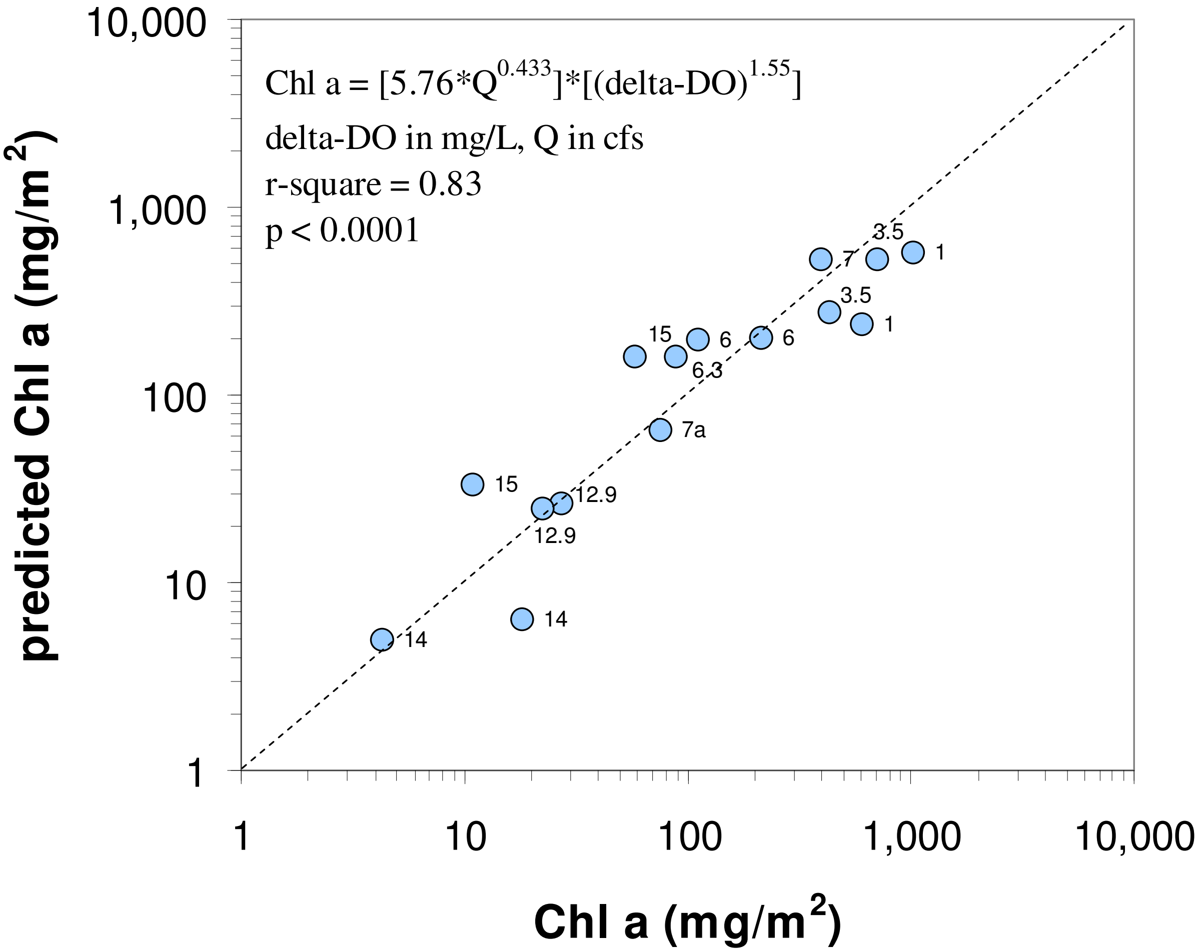
In my opinion the fit isn't bad at all, given all the assumptions that have had to be made. The one real problem point (flow of 17 cfs) is from Matilija Creek above the dam. I've shown two dashed lines on the graph, the first indicating 200 mg/sq-meter Chl a (an often-quoted figure for an algal boundary) and the second its intersection with your 4 mg/L DO limit. The interpretation would be that a 200 mg/sq-meter Chl a density would only depress DO below the minimum allowable if flow was under 5 cfs (or perhaps something a little greater if some sort of factor-of-safety were added.



Following up on Scott's suggestion, I tried a multiple regression relationship regressing minimum DO (i.e. pre-dawn DO measurements collected by SBCK, in mg/L) on flow (Q in cfs) and Chl a (Kristie's mean values, in mg/m2). In this, and the graphs that follow, I've plotted measured data on the x-axis and the corresponding values predicted by regression equations (shown, along with r-square and p-values, on the figure) on the y-axis. The data gives an acceptable regression (p = 0.017; r-square = 0.42, i.e. flow and Chl a can explain 42 % of the variation) but the spread is pretty wide. In other words, at some locations a minimum DO much higher than actually measured is predicted (at sites 6.3, 01 in June and 07), while in others the opposite occurs (sites 3.5 and 01 in September were predicted to be lower than actually measured). Of course the spread at the low end is where it matters most. A larger error (i.e. spread) at sites with little or no algae and high DO values would have little consequence. I derived two equations, one using all log transformed values and the other, shown here, using untransformed minimum DO measurements. The distribution of min. DO measurements was ~normal and not transforming those values gave slightly better results. The alternate equation, using log-transformed values was

$$\text{minimum DO} = 8.13 * Q^{0.113}/(\text{Chl a})^{0.090}\ ;\ p = 0.022;\ \text{r-square} = 0.38$$

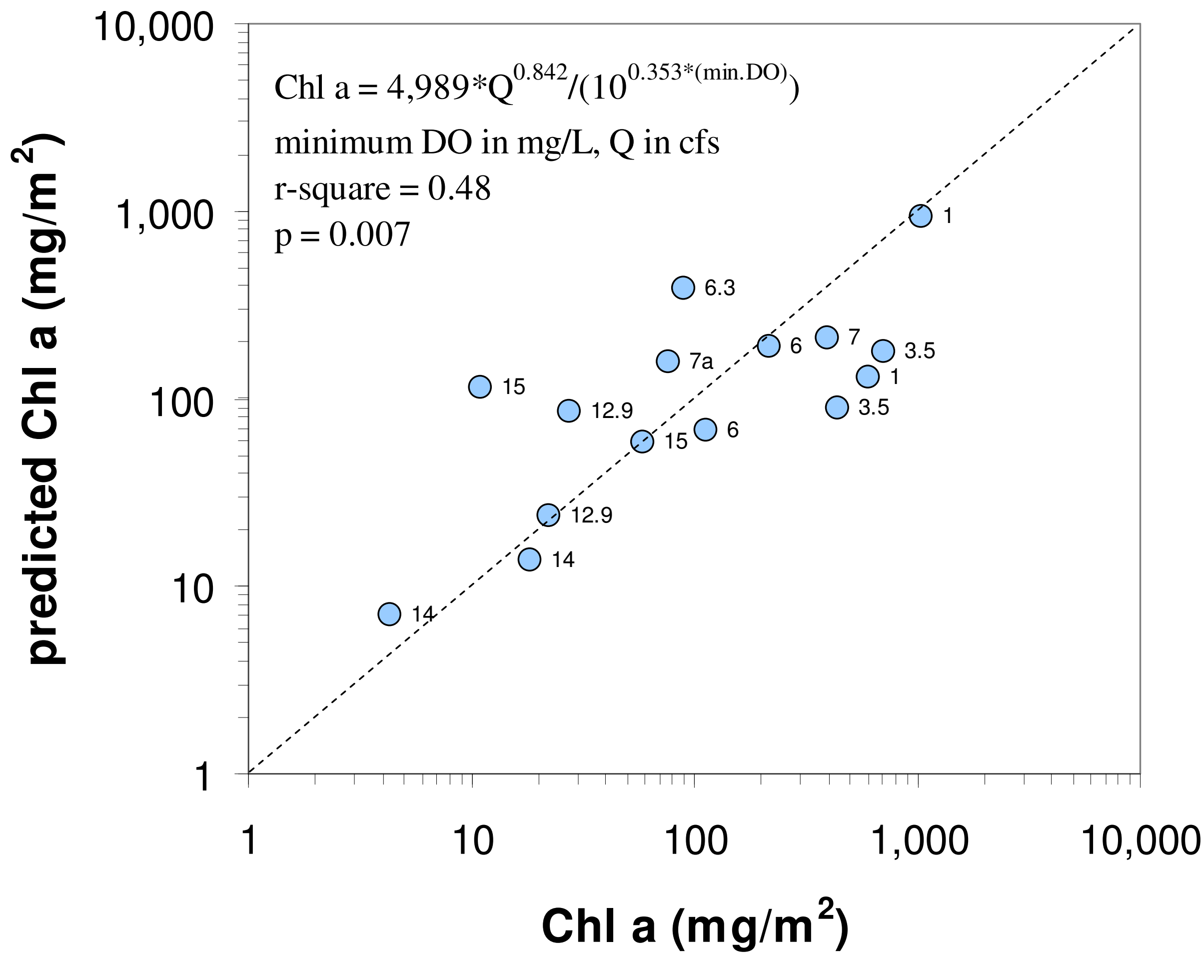
Besides being valid, both equations are reasonable: as Chl a increases, the minimum DO concentration decreases, whereas it increases with increases in flow, i.e. the affect of algal growth on reducing DO is directly proportional to the amount of algae and inversely proportional to flow.



For my next trick I decided to regress Chl a on both flow (Q) and delta-DO (the diel change, in mg/L, from minimum to maximum dissolved oxygen, i.e. pre-dawn to mid-afternoon). As might be expected, since the algal intensity parameter (AgI = flow * delta-DO) correlates well with Chl a, the multiple regression turned out to be pretty good, both factors explaining over 80 % of the DO variation.

The multiple regression equation correlates better with the Chl a data than did AgI (Chl a = 5.5 * (AgI)^0.93, r-square = 0.66). AgI gives equal weight to both flow and delta-DO while the regression equation increases the relative importance of delta-DO over flow.

I believe this relationship worthy of further exploration. It takes about 4-6 hours of direct on-site field time to conduct an algal survey, and many more hours of preparation, laboratory and office time, to derive a single mean Chl a value for one location at a single point in time. If simply measuring the diel oxygen variation and flow can estimate Chl a (if the results shown by these data verified) it would appear to be an effective alternative, saving both money and time. Measuring flow and diel DO variation every time an algal survey is conducted would rapidly accumulate enough data to explore this possibility (and at relatively little increased expense). And with validity established, allow increased, and more rapid, data collection at reduced cost.



The parameters used on page 4 can be easily rearranged and an equation, similar to the one on page 6, derived. Above is a plot of predicted and measured values of Chl a derived from a regression based on Q and minimum DO. Even though there is a wide spread in middle-of-the-range data, the regression is slightly better than the one for minimum DO based on Q and Chl a (page 4). Since the Basin Plan has set minimum DO at 4 mg/L, it would be an easy exercise to determine the Chl a concentrations required to bring DO down to this level by using this equation at any location with daily flow data.

Similarly, albeit with additional effort, we can use the previous equation, based on Q and delta-DO (page 5), to also estimate Chl a. All that's required to allow the use of this much better and tighter relationship is some logical procedure of estimating minimum DO from delta-DO. The procedure I've chosen assumes: (1) the diel DO variation is symmetrical around some mean value, (2) this mean value can be estimated as the 100 % saturation DO concentration based on site elevation and water temperature, and (3) this water temperature will be the average monthly temperature recorded by the SBCK sampling program. In truth, we really don't know any of this. Perhaps the diel variation is symmetrical (sonde data could test this assumption). But is the 100 % saturation value a good center point? I tried a number of alternatives based on % saturation (the range of DO values for the sampling locations used, calculated for each assumption using mean monthly temperatures are shown in parentheses): 100 % saturation (8.92-9.52);

90 % saturation (8.11-8.57); and using SBCK average saturation values for presumably non-algal influenced data (7.16-8.31). When compared with average DO concentrations seen in SBCK's 2008 diel measurements (9.49 ± 0.14, page 2), all these values are low. To be more precise the following table shows average April-Sept. mid-point DO values calculated for the given percent saturation assumptions along with actual SBCK measurements:

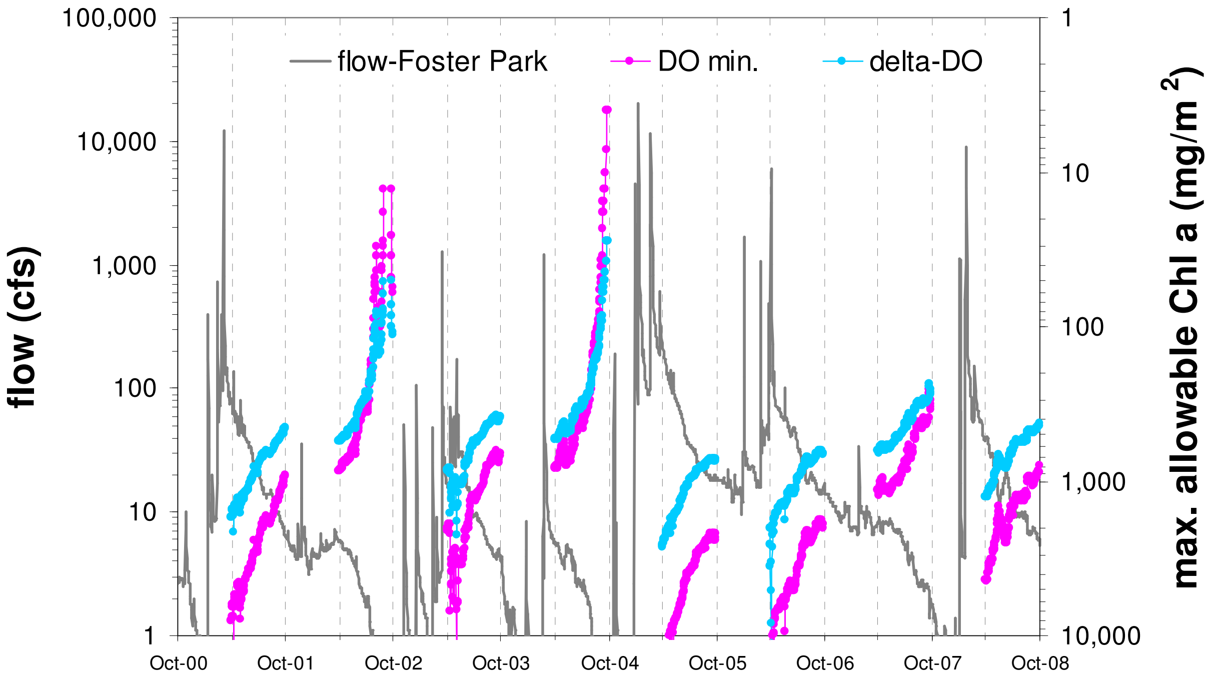
	VR01	VR06	VR07	VR14
100%	9.02	9.28	9.33	9.52
90%	8.11	8.35	8.40	8.57
avg.sat	7.16	8.70	8.34	8.31
SBCK	10.15	9.64	10.21	9.27

The four sites listed are the ones with flow data that I'll be using in this demonstration. The 100 % assumption values are, with the exception of N.F. Matilija Creek (VR14), noticeably lower than the actual measurements. Contrasting month-to-month 100 % saturation values with SBCK data (in red) show that this assumption is conservative and, as a result, the derived critical Chl a values will also be (i.e. lower than the true limiting value).

	09-Apr	15-May	17-Jun	25-Jul	12-Sep
Main Street (01)	11.70	10.59	9.34	9.46	9.66
	9.51	**9.32**	**8.95**	**8.83**	**8.79**
Foster Park (06)	10.59	8.95	9.34	9.31	9.99
	9.75	**9.53**	**9.28**	**9.08**	**8.99**
lower San Antonio (07)	12.01	11.38	9.88	8.71	9.07
	10.02	**9.61**	**9.59**	**9.17**	**8.76**
N.F. Matilija (14)	10.47	9.25	8.96	8.65	9.04
	10.29	**10.00**	**9.41**	**9.09**	**9.22**

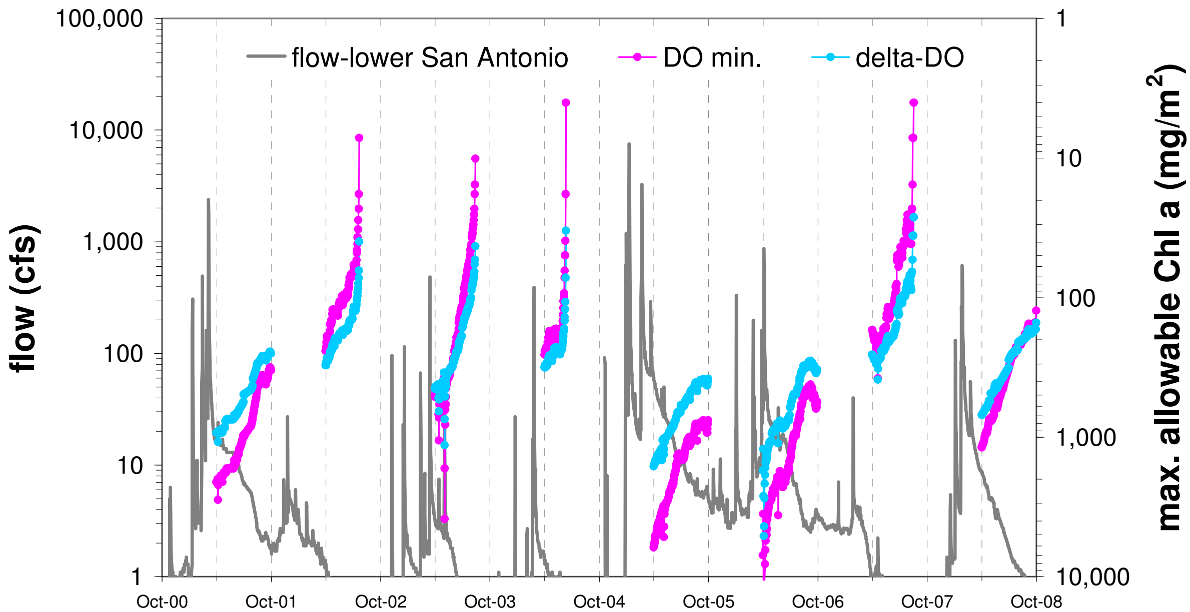
I think the answer as to why actual mid-point concentrations are so high lies with the diel temperature variation, which can be considerable. The SBCK data ranges from 1.5 to 8° C, which translates into changes in DO saturation DO from 1 to over 15 %. As water temperatures decrease from late afternoon till early morning, stream flows more easily hold on to dissolved oxygen than during the daytime temperature rise, i.e. increased nighttime retention vs. greater daytime losses. The net result would be, if you will, an upward displacement of the oxygen relationship with time, giving a higher than otherwise expected centroid mean – the implication of the second table is that actual mean DO value were above 100 % saturation. (This assumes that the average temperatures used to estimate saturation DO concentrations were appropriate. In general, 2008 Ventura stream temperatures were either right at the long-term average, or slightly higher. The average temperatures used to calculate sat. DO were in almost all cases lower than mean temperatures for the SBCK diel data – on average 1 ° C lower which would imply that the assumptions are even more conservative than shown. On average, measured mid-point DO conc. at sites 01, 06 and 07 were at 110 % of saturation; conceivably, I could improve the model by assuming this percentage of saturation as the mid-point of delta-DO.) The one exception, the N.F. Matilija, had lower mid-point DO than the assumed 100 % sat. values due to wide temperature fluctuations and minimal DO variation (delta-DO < 1.0) which led, in one case, to mid-afternoon DO lower than pre-dawn (average N.F. mid-point DO concentrations were at 98 % of saturation).

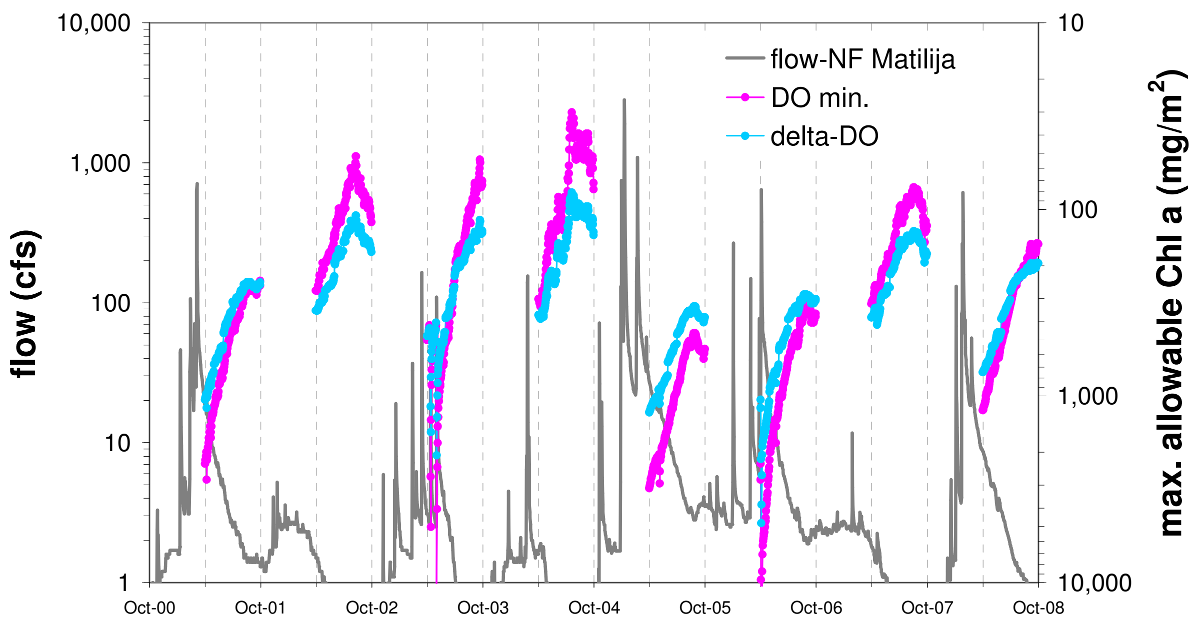
Given the mid-point of the diel variation (delta-DO) derived from the preceding assumptions, the maximum allowable delta-DO is calculated as 2 * (mid-point concentration – minimum allowable concentration), the minimum allowable being the previously mentioned Basin Plan level of 4 mg/L.



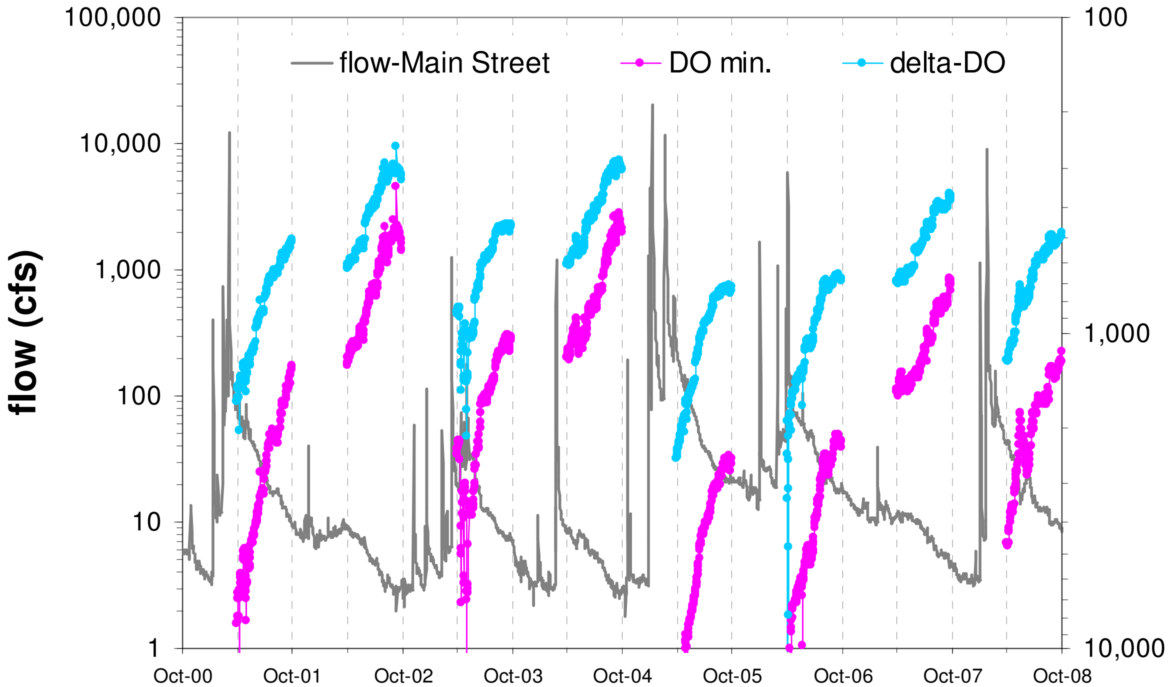
The above graph is an example of results. It shows maximum allowable Chl a (the highest concentration that will avoid lowering DO below 4 mg/L) for an 8-year flow record, beginning with water-year 2001, at Foster Park (VR06). I've shown allowable Chl a with the scale reversed since our main interest is in low, limiting, values. I've also eliminated results from October through March, when excessive algae is almost never a problem, thus avoiding the extremely high rainy-season Chl a numbers that can occur (recall that modeled Chl a is proportional to Q). Conversely, the very low Chl a densities shown for low drought-year flows (2002, 2004) should probably be ignored (low amounts of algae can produce extreme variations in trickling flows as streams are close to going dry – and low gauged flows are rarely accurately measured). Results for both equations are separately shown.

They differ – by quite a bit. The delta-DO values are highly conservative (i.e. underestimates, predicting too low a level of allowable Chl a), reflecting the conservative mid-point DO assumptions discussed previously. Both equations should be reasonably good for this location; the delta-DO model slightly overestimating, and min. DO slightly underestimating, the Chl a concentration required to reach min. DO (cf. page 5 and 6). The delta-DO model predicts ~ 4-times as much algae as Kristie recorded would have been needed to reduce DO to 4 mg/L, the other model, ~ 10-times (actual minimum DO never decreased below 6.5). Increasing mid-point DO values by revising assumptions and/or adding a factor-of-safety to the min. DO equation (e.g. raising the min. DO level to 4.5 ° C) would bring the two results reasonably close together, but that endeavor would be premature at this point. I would point out, however, that in any case a 200 mg/m2 Chl a standard would be far too conservative if the main goal were preventing DO < 4 mg/L at Foster Park.





Here are the results for lower San Antonio and the N.F. Matilija creeks. Results from the two equations are in more-or-less good agreement as both are reasonable predictors for these locations (cf. pages 5 and 6 – sites 7 and 14, the points generally fall close to the regression line, with the two separate data points for each of these sites falling on opposite sides, i.e. the equation splits the difference between actual data points). (Why the two San Antonio results should be closer together than those for Foster Park remains an open question.) I wouldn't say much, except to note that we never saw enough algae, or DO variation, at the N.F. to test these estimates. On San Antonio, SBCK measured a minimum DO concentration of 3.99 mg/L in September, in reasonable conjunction with a Chl a density of 76 mg/m2. This might indicate that the values shown might not be conservative enough.



Results for Main Street show the least agreement between the two equations. Looking at the predicted vs. actual data points on pages 5 and 6, both model would seem to underestimate Chl a at Main Street (thus predicting a lower than necessary allowable Chl a limit); the minimum DO relationship actually appearing to be slightly more conservative. (Main Street is site 1.) I'll need to explore further why the results are so disparate (that the same data, used in a log-log regression to predict delta-DO, greatly overestimates Main Street values might offer a clue as to what is going wrong). The combination of a conservative, under predicting, delta-DO equation and conservative mid-point DO estimates yields unrealistically low Chla values, values lower than Kristie's field data. To illustrate how conservative the estimated Chl a concentrations are (recall that these are concentrations needed to produce a min. DO of 4 mg/L) model estimates for Kristie's sampling dates were 791 and 515 mg/m2 on May 23 and Sept. 5, respectively; values lower than her measured concentrations of 1037 and 602. Needless to say, DO *did not* go below 4 mg/L. Minimum concentrations measured by SBCK circa the two dates were 5.17 and 6.35 mg/L, respectively. Comparable estimates from the min. DO model were 2219 and 1320 mg/m2 – probably still too low, but certainly more reasonable.

All that aside, these results show the impracticality (dare I say senselessness?) of applying any single Chl a TMDL criterion to the highly variable reaches of the Ventura watershed, if, and I probably should emphasize the *if*, reduced levels of dissolved oxygen are the primary biological concern. And if reduced levels of dissolved oxygen are not the primary concern, scientific evidence (and not simply hearsay) should be presented to document what other biological hazards excessive algal growth might engender.