Use of Dissolved Oxygen and Water Temperature Data to Infer the Relative Importance of Components of a Stream Dissolved Oxygen Budget

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Abstract

Using hourly or more frequent paired measurements of water temperature and dissolved oxygen concentration, and plotting the latter against the former along with contour lines of constant dissolved oxygen percent saturation, it is possible to infer much about the dissolved oxygen budget of a stream. The degree of reaeration, the relative importance of photosynthesis and its source from periphyton or phytoplankton or macrophytes, the magnitude of oxygen demands from respiration or organic-matter decomposition, and important seasonal cycles all can be determined from this type of data plot.

In this analysis, five sites from the Pacific Northwest of the United States of America are used to illustrate widely different patterns in these oxygen/temperature plots, and knowledge of the characteristics of those streams is connected to patterns in the data. It is hypothesized that such plots might be used to determine certain aspects of a stream's characteristics and dissolved oxygen budget without any other information.

Introduction and Objective

The semi-continuous (hourly or more frequent) monitoring of stream water quality provides rich datasets to assess aquatic health, quantify water-quality variations that occur at several important time scales (daily, weekly, seasonally), assess trends, determine loads of important constituents, and better understand processes and factors that affect water quality. The deployment of continuous water-quality monitors has increased substantially in the last 20 years, from dozens to hundreds and even thousands of monitors today.

Even as these datasets are becoming more common, scientists are challenged to find ways to analyze the data to better understand the systems being monitored. For example, it can be important to understand the various factors and processes influencing a stream's dissolved oxygen budget, but it can be difficult to quantify the important processes affecting that budget. In this study, a simple plot of dissolved oxygen concentration versus water temperature with contour lines of constant percent oxygen saturation is used to illustrate how the relative importance of factors affecting a stream's dissolved oxygen budget can be quickly identified and their magnitude estimated.

Hourly or sub-hourly measurements from five sites in Oregon and south-central Washington State (fig. 1) were used to illustrate useful patterns in these oxygen/temperature plots. Data from these sites were collected year-round and span time periods of anywhere from 2 to 20 years. All such data were collected, processed, and approved in accordance with standard USGS protocols (Wagner and others, 2006).

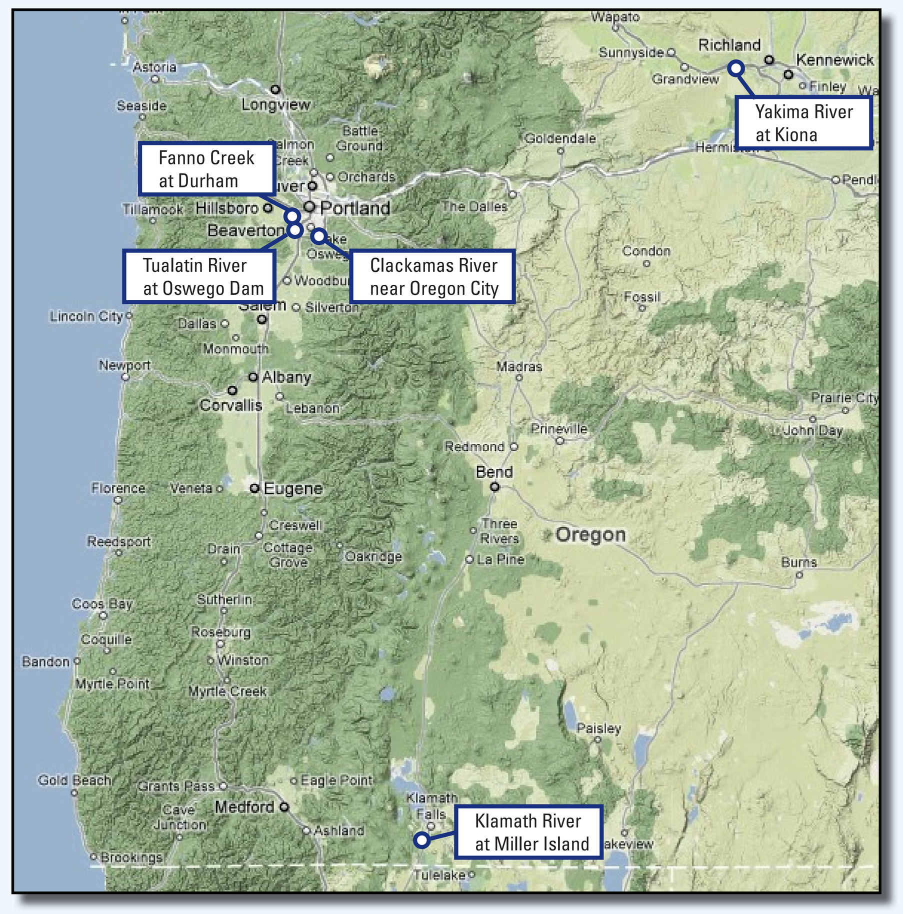


Figure 1. Map of Oregon and southern Washington State in the Pacific Northwest of the United States, showing locations of the five sites used in this study to illustrate different patterns of paired dissolved oxygen and water temperature measurements.

Making Oxygen/Temperature Graphs

Constructing plots of dissolved oxygen versus water temperature with contour lines representing constant values of oxygen percent saturation is not difficult as long as the equations for calculating oxygen solubility are known and can be programmed into a spreadsheet or graphics program. For the purpose of these graphs, the effects of variations in barometric pressure and salinity on oxygen solubility were neglected, and a constant pressure correction based on site elevation was applied. The equations developed by Benson and Krause (1980) were used to compute oxygen solubility in fresh water in milligrams per liter as a function of water temperature:

$$DO_o = \exp\left[-139.34411 + \frac{1.575701x10^5}{T} - \frac{6.642308x10^7}{T^2} + \frac{1.243800x10^{10}}{T^3} - \frac{8.621949x10^{11}}{T^4}\right]$$

where T is water temperature in Kelvin (degrees Celsius + 273.15). The pressure correction factor F was derived from the method of Duke and Masch (1973) as stated by Bowie and others (1985):

$$F = \left(1.0 - 6.97x10^{-6}\ H\right)^{5.167}$$

where H is the site elevation in feet above sea level.

The graphs used in this analysis were constructed using the *Specialized XY Plots* feature of the USGS Data Grapher system (see http://or.water.usgs.gov/grapher/). The Data Grapher allows users to create customized graphs and tables from hourly or more frequent continuous monitor data. When dissolved oxygen and water temperature are selected in the *Specialized XY Plots* program, the user is given the option of plotting contour lines of constant oxygen percent saturation. Graphs can be modified and saved in a variety of formats. The user also has an option to highlight subsets of the data, such as plotting data from different months in different colors (for example, fig. 3), which allows the user to explore the data in more detail.

References Cited

Benson, B.B., and Daniel Krause, Jr, 1980, The concentration and isotopic fractionation of gases dissolved in freshwater in equilibrium with the atmosphere. 1. Oxygen: Limnology and Oceanography, vol. 25, no. 4, p. 662-671. (Also available at http://www.jstor.org/stable/pdfplus/2835754.pdf.)

Bowie, G.L., Mills, W.B., Porcella, D.B., Campbell, C.L., Pagenkopf, J.R., Rupp, G.L., Johnson, K.M., Chan, P.W.H., Gherini, S.A., and Chamberlin, C.E., 1985, Rates, constants, and kinetics formulations in surface water quality modeling: U.S. Environmental Protection Agency, EPA/600/3-85/040, p. 91.

Wagner, R.J., Boulger, R.W., Jr., Oblinger, C.J., and Smith, B.A., 2006, Guidelines and standard procedures for continuous water-quality monitors--Station operation, record computation, and data reporting: U.S. Geological Survey Techniques and Methods 1-D3, 51 p. + 8 attachments. (Also available at http://pubs.usgs.gov/tm/2006/tm1D3/.)

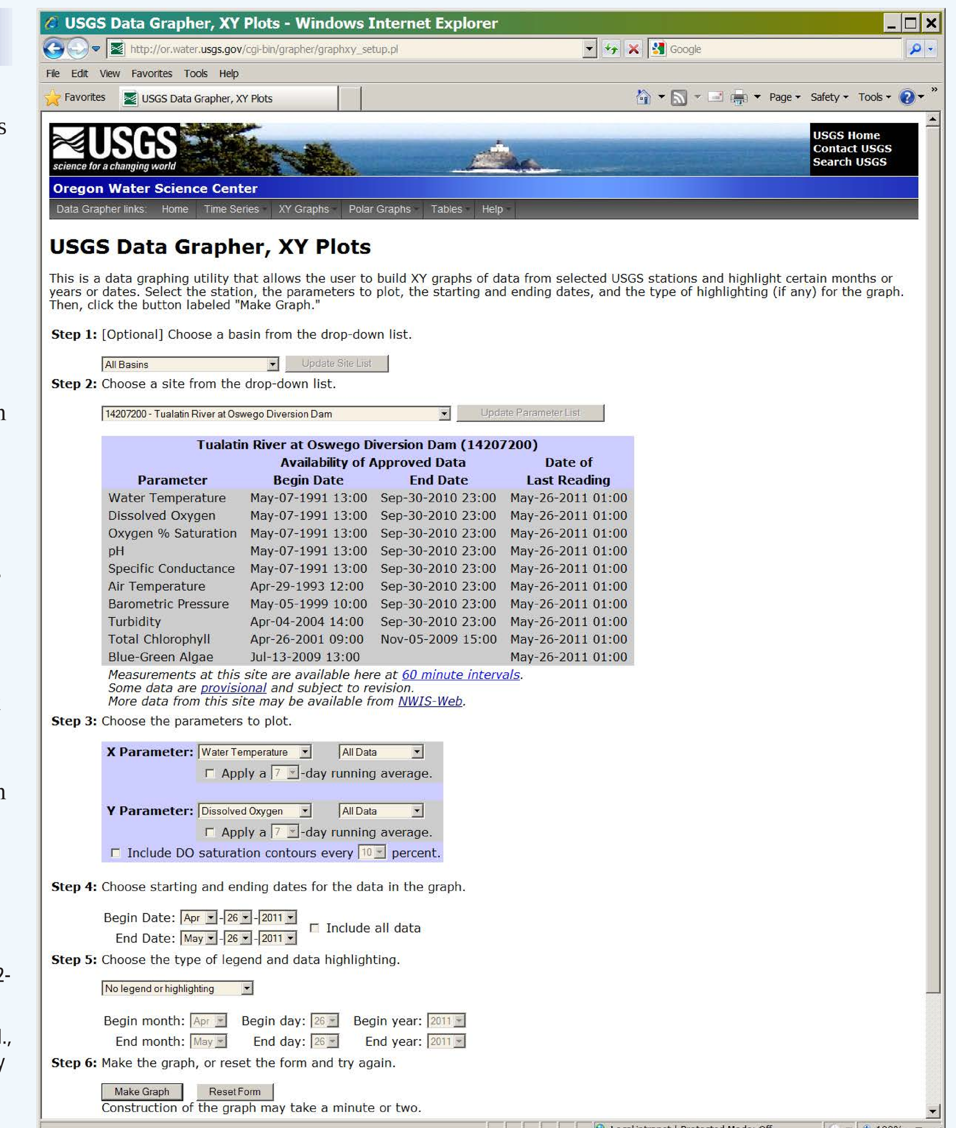


Figure 2. Screen shot of the Data Grapher interface for specialized XY plots. To visit the site, go to http://or.water.usgs.gov/grapher/.

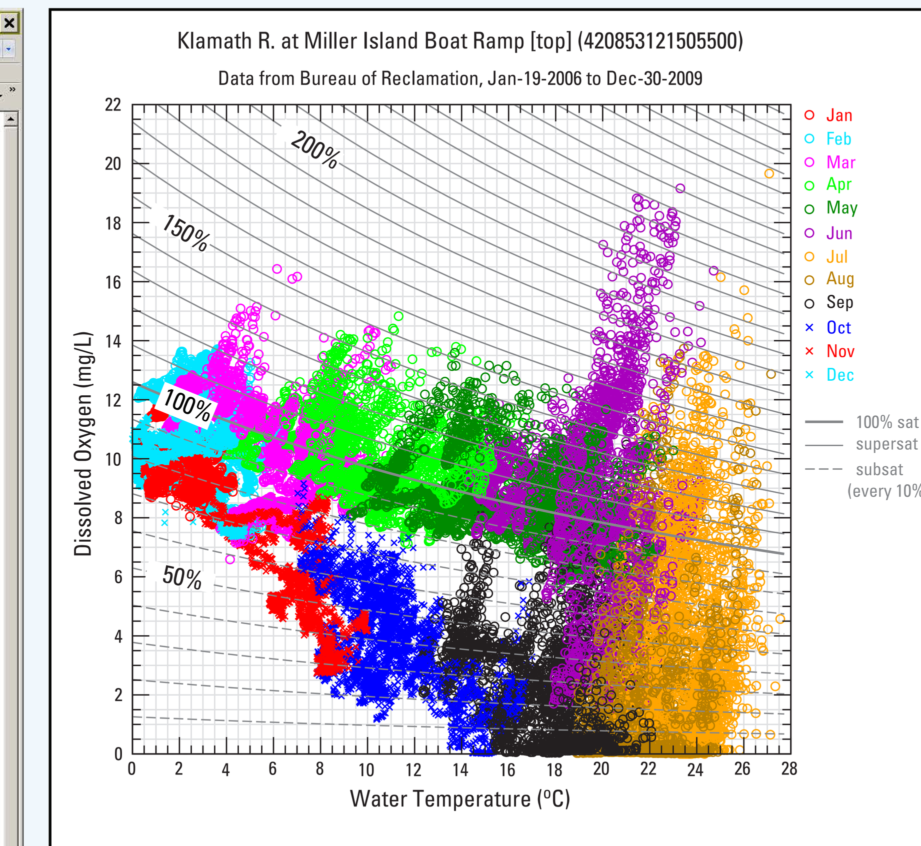


Figure 3. Graph of dissolved oxygen concentration versus water temperature for the Klamath River at Miller Island Boat Ramp [top] site, showing how the data vary as a function of the month of year. This plot is the same as the one below except for the color highlighting.

Conclusions

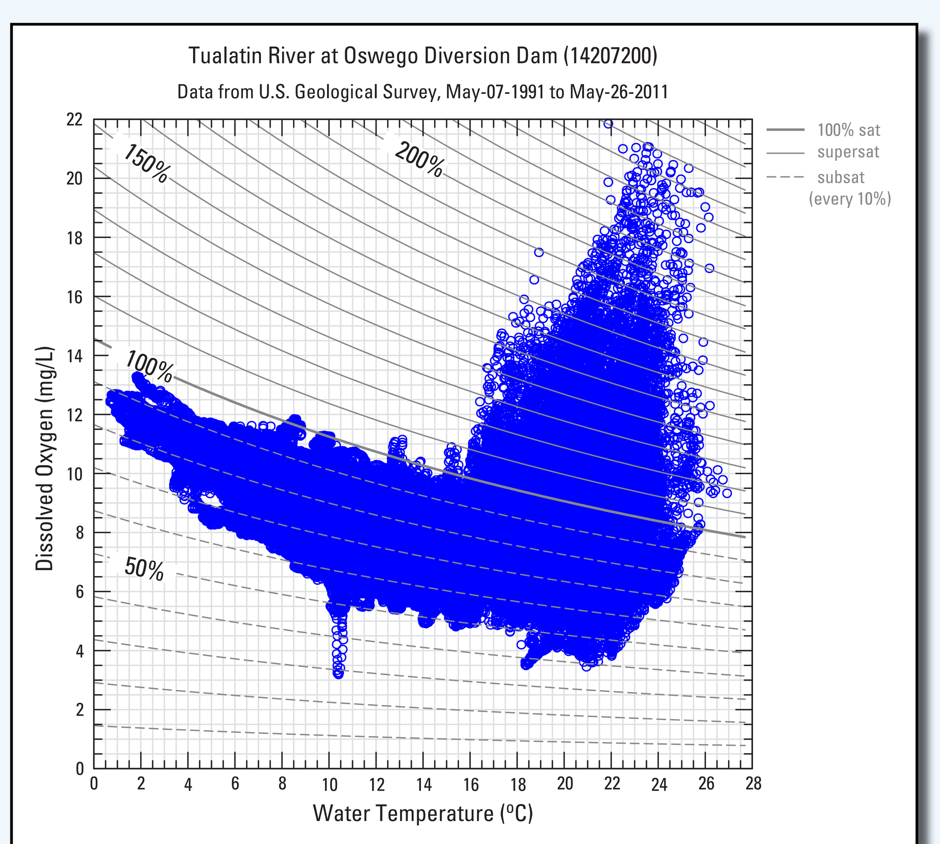
Assessing the components of a stream's dissolved oxygen budget is facilitated through the use of plots of dissolved oxygen concentration versus water temperature when those plots include contour lines of constant oxygen percent saturation. The patterns in the data are indicative of the relative importance of processes such as reaeration, photosynthesis, respiration, and decomposition, as well as the type of algae or macrophyte present.

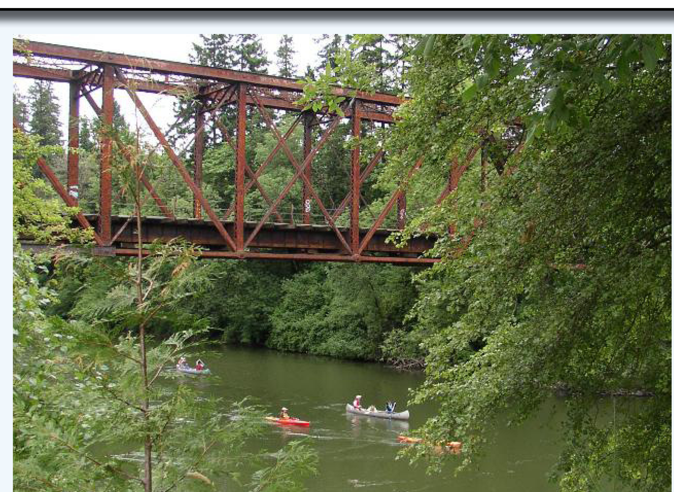
Five Examples to Illustrate Contrasting Patterns

Tualatin River at Oswego Diversion Dam, OR (14207200)

An analysis of the oxygen/temperature plot indicates that:

- Reaeration must be slow for oxygen saturation levels to range as low as 40% and as high as 250%. The river must have little turbulence and no significant waterfalls or riffles.
- Significant oxygen production can occur when temperatures exceed approximately 15 degrees Celsius. The predominance of supersaturation only at the higher temperatures is consistent with the presence of phytoplankton rather than periphyton, as the latter can grow at lower temperatures, but the former are easily flushed out at higher flows but have sufficient time and favorable conditions to grow to large populations during summertime low flows with warmer water.
- Large oxygen demands are present that force the dissolved oxygen concentration to be significantly below saturation at any temperature (and therefore year round) when not offset by photosynthetic oxygen production. The year-round oxygen demands suggest a large sediment oxygen demand and perhaps an organic-laden silty sediment consistent with a pooled and non-turbulent river system.



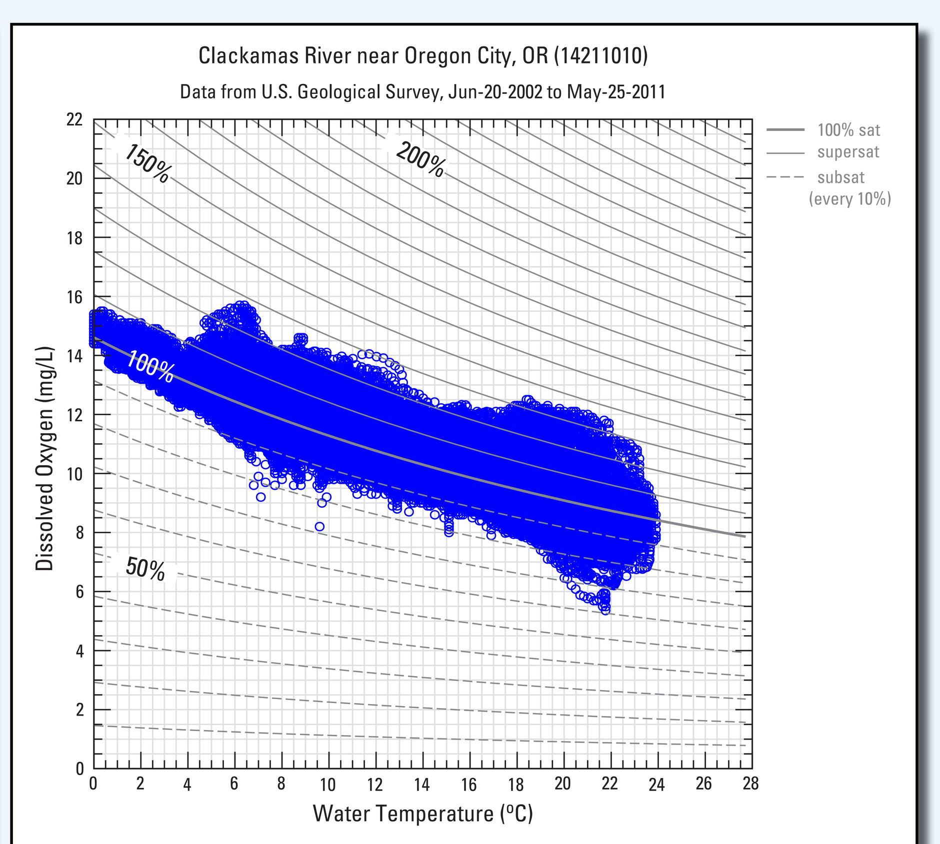


Photograph of the Tualatin River upstream of the Oswego Diversion Dam, showing the slow-moving, pooled characteristics that contribute to the patterns in the oxygen/temperature plot. Photo by Stewart Rounds, USGS.

Clackamas River near Oregon City, OR (14211010)

An analysis of the oxygen/temperature plot indicates that:

- Reaeration must be relatively fast because the degree of oxygen saturation remains near 100% year round, rarely occurring outside a range of 70-130%. The river must have a high degree of turbulence, rapids, riffles, or waterfalls.
- Cycles of photosynthesis and respiration cause daily variations in the oxygen concentration over a wide range of temperatures, even when the water is quite cold (as low as 4 degrees Celsius). In Oregon, cold water and higher flows occur in winter. Periphyton, however, can grow in cold water and are not swept away if attached to a rocky stream bottom, which is the case for this river.
- Oxygen demands are either minimal, or small enough that oxygen consumption is easily offset by reaeration and the photosynthesis and respiration of the periphyton. Low sediment oxygen demand is consistent with a rocky substrate.

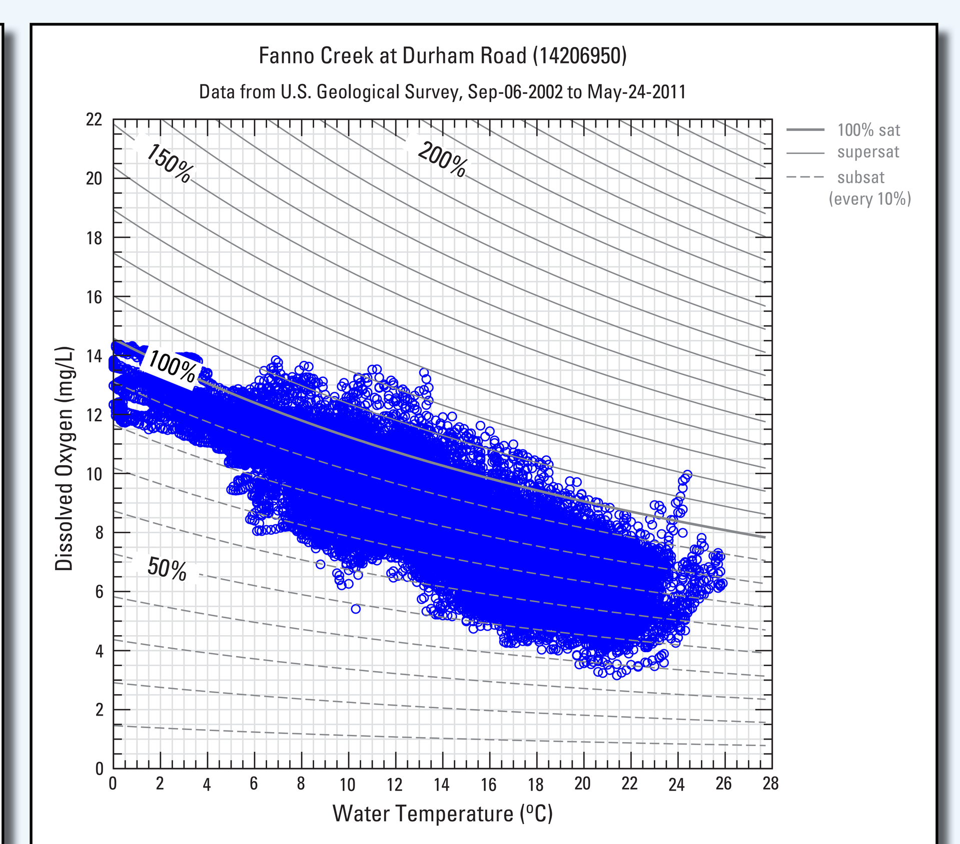


Photograph of the Clackamas River upstream of the Oregon City site, showing the turbulence and rocky substrate that contribute to the patterns in the oxygen/temperature plot. Photo by Kurt Carpenter, USGS.

Fanno Creek at Durham Road, OR (14206950)

An analysis of the oxygen/temperature plot indicates that:

- Reaeration is slow, at least during lower flows in summer, because the percent oxygen saturation can decrease to levels as low as 40% when temperatures are moderately warm. The creek must have little turbulence, few rapids or riffles, and no waterfalls.
- Oxygen production via photosynthesis is limited because supersaturation is rare, only occurring in spring (not shown here). Interestingly, the lack of photosynthetic oxygen production during summer may be due to riparian shading, as this creek is narrow and has a moderate amount of riparian vegetation. Photosynthesis can occur to a greater degree in spring before deciduous vegetation leafs out.
- Oxygen demands are moderate, as evidenced by the common occurrence of subsaturation. Greater levels of oxygen depletion occur at warmer temperatures, which is consistent with faster decomposition reactions, lower flows, and less reaeration during summer. The slow reaeration may also indicate little slope and a greater degree of organic-laden silt in the creek bottom, which increases the sediment oxygen demand.

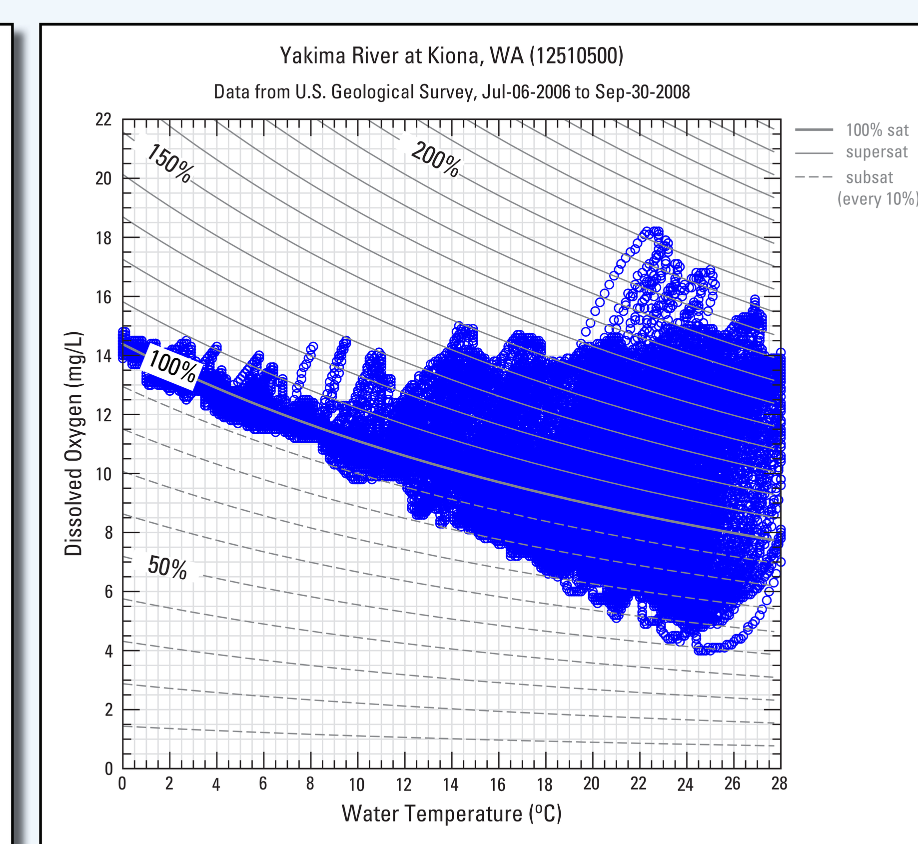


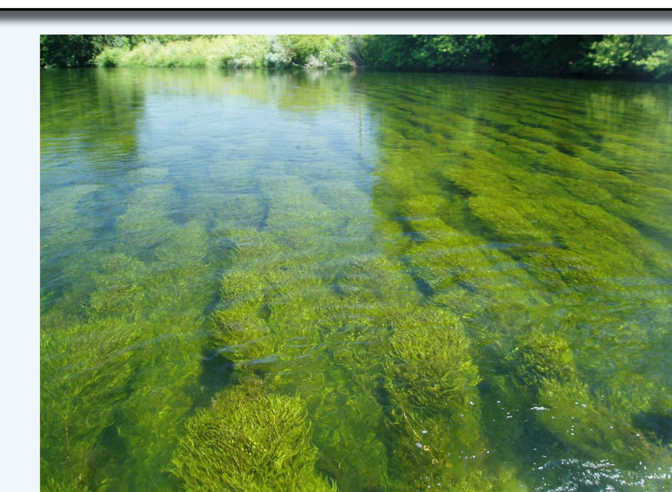
Photograph of Fanno Creek downstream of the Durham Road site, showing a narrow width, decent riparian cover, and some turbidity that contributes to the patterns in the oxygen/temperature plot. Photo by Stewart Rounds, USGS.

Yakima River at Kiona, WA (12510500)

An analysis of the oxygen/temperature plot indicates that:

- Reaeration must be relatively slow at temperatures above 10 or 12 degrees Celsius in order for the range of oxygen saturation to span 50-210%. Reaeration is either more efficient in winter (higher flows) or the source of oxygen variations is weaker at that time.
- Photosynthesis and respiration cause large daily variations in dissolved oxygen concentrations at temperatures above 10 or 12 degrees Celsius, but not below that temperature. The pattern of data in this plot is unlike either the phytoplankton pattern from the Tualatin River or the periphyton pattern from the Clackamas River. It is known that this reach of the Yakima River is dominated by a rooted aquatic plant community of stargrass that causes these large variations in dissolved oxygen in summer. It is not known whether the pattern in this plot is typical of patterns produced by rooted aquatic plants.
- Oxygen demands other than respiration by the macrophytes (rooted aquatic plants) in this system may be minor, as the plot does not indicate any substantial degree of subsaturation other than that which is tied to the macrophytes.



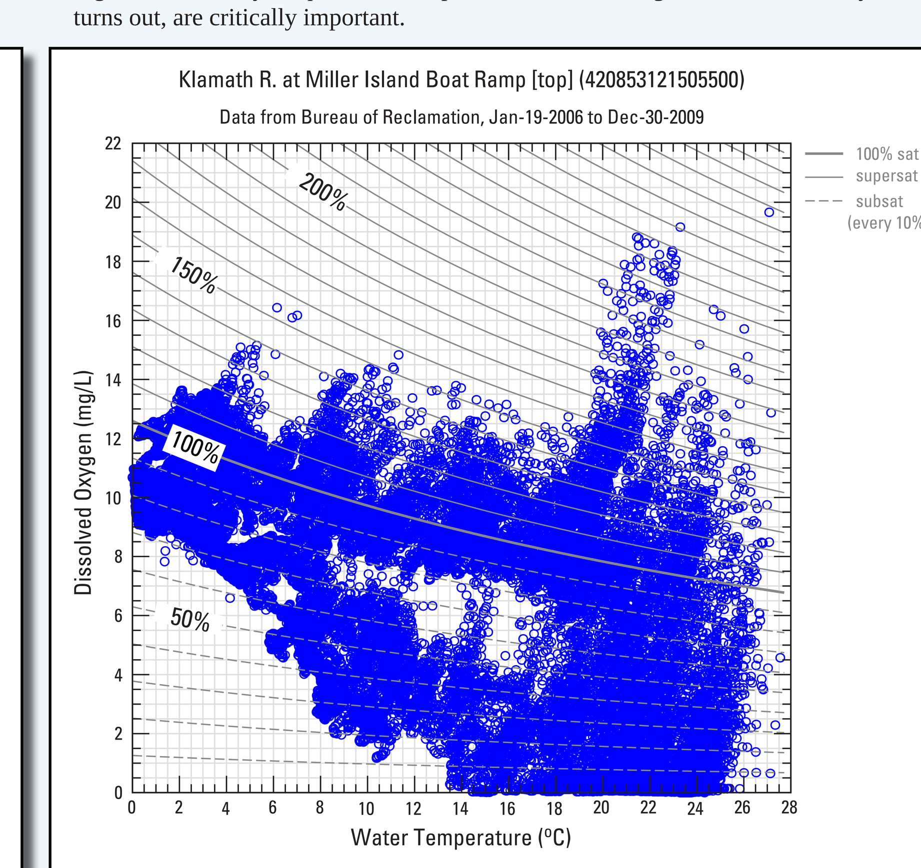


Photograph of the Yakima River at Kiona, showing the prevalence of stargrass, an aquatic plant that controls the dissolved oxygen concentrations in the river under low flows and warm water conditions. Photo by Kurt Carpenter, USGS.

Klamath River at Miller Island Boat Ramp [top] (420853121505500)

An analysis of the oxygen/temperature plot indicates that:

- The rate of reaeration is insufficient to offset the rates of oxygen production and consumption in this system during most of the year, as evidenced by the occurrence of oxygen saturation well over 150% in summer and close to zero for long periods.
- Photosynthesis and respiration cause large variations in dissolved oxygen in early summer and somewhat in spring. Algae in this system are important to the oxygen budget, but not as important as oxygen demands caused by decomposing organic matter.
- Oxygen demands in this river system must be enormous at times to produce dissolved oxygen concentrations at or near zero for extended periods near the river surface where the probe is located (1 meter depth). The seasonal cycle (months indicated in fig. 3) indicates a clockwise annual route around this somewhat triangular pattern. Oxygen demands during summer are large, diminish somewhat in autumn, and do not appear to significantly deplete oxygen levels the following spring, indicating that the decomposing organic matter may be quite labile. Upstream sources of organic matter in this system, it turns out, are critically important.



Photographs of Klamath River at Miller Island and the blue-green algae that are an important factor contributing to patterns in the oxygen/temperature plot. River photo by Simon Poulson, Univ. Nevada-Reno; algae photo by Dean Snyder, USGS.

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