A Department of Ecology Report

WASHINGTON STATE DEPARTMENT OF ECOLOGY

Dissolved Oxygen in Lake Whatcom

Trend in the Depletion of Hypolimnetic Oxygen in Basin I 1983-1997

Abstract

Available data for dissolved oxygen in Basin I of Lake Whatcom was reviewed. The rate of depletion of dissolved oxygen in the hypolimnion was examined for 1983-1997. The hypolimnetic oxygen depletion rates were calculated for the June through mid-August periods of stratification for each year using volume-weighted average concentrations of dissolved oxygen.

The hypolimnetic oxygen depletion rates in Basin I appear to be significantly increasing during the period of 1983-97. The current rates in Basin I are in the typical range for mesotrophic lakes. However, the increasing trend suggests that trophic state of Basin I may soon shift to a more eutrophic condition based on criteria suggested by Welch and Wetzel.

Introduction

Oxygen depletion in the bottom waters (hypolimnion) of Basins I and II of Lake Whatcom (Figure 1) has been well documented during the period of stratification (URS, 1985; Walker, Matthews, and Matthews, 1992; Matthews and Matthews, 1993, 1994, 1995; Matthews, Hilles, and Matthews, 1996 and 1997). The analyses to date have not included determination of hypolimnetic oxygen deficit rates (HODR) based on volume-weighted average concentrations of dissolved oxygen in the hypolimnion as recommended by standard textbooks for limnological analyses (*e.g.* Wetzel and Likens, 1991).

Dissolved oxygen is consumed during the decomposition of organic matter, which is deposited in the sediments of a lake. During the summer months the surface water (epilimnion) of the lake is heated and becomes less dense than the deeper, cooler water of the hypolimnion. The hypolimnion becomes blocked from a supply of oxygen. Dissolved oxygen in the hypolimnion decreases until the fall when the surface cools and mixes again with the deeper water in the lake.

At low dissolved oxygen concentrations, phosphorus, usually the most limiting nutrient for growth of algae, is released from the sediment into the water (Cooke *et al.*, 1986.) As summer progresses, nutrients in the hypolimnion increase in concentration and may be mixed into the lighted, warm epilimnion where they stimulate growth of algae in the process called internal nutrient loading. Desirable fish such as salmonids that prefer the cold water of the hypolimnion may be excluded from the lake due to low oxygen.

Previous Evaluations of Trends in Water Quality in Basin I

Historical data show that the hypolimnion of Basin I has had low dissolved oxygen conditions for at least the past 30 years. Matthews, Hilles, and Matthews (1997) reported a trend of decreasing

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concentrations of dissolved oxygen at the 10-meter depth during September of 1987-97. The reports by Matthews *et al* have also suggested increasing trends in ammonia and dissolved phosphorus in the hypolimnion with the increasing extent of anoxia.

Adolfson (1997) reported that total phosphorus and chlorophyll in the epilimnion did not exhibit significant increasing trends in Basin I. Adolfson (1997) also estimated HODR using arithmetic means of dissolved oxygen in the hypolimnion at the beginning and ending of the stratification season and reported that there was not evidence of an increasing trend. Adolfson (1997) acknowledged that the use of volume-weighted average concentrations of dissolved oxygen would have provided a more accurate estimate of HODR, but this was not done during their study.

Criteria for HODR

Criteria for HODR in relation to trophic state were reported by Mortimer and summarized by Welch (1980) and Wetzel (1983) as follows:

Oligotrophic < 250 $mg/m^2/day$
Eutrophic > 550 $mg/m^2/day$

The HODR is defined as the rate of depletion of hypolimnetic dissolved oxygen per unit time per unit of surface area of the hypolimnion. The overall observation time should be at least a month, and preferably longer, during the period of stratification (Welch, 1980).

Depth-Volume Relationships for Basin I

The bathymetric map of Lake Whatcom is shown in Figure 1. The areas of the 0, 5, 10, 15, and 25-meter depth contours in Basin I were determined to develop a relationship between depth and volume in the lake (Figure 2) using the procedure described by Wetzel and Likens (1991). The volumes of horizontal slices of the lake with discrete depths were estimated based on the interpolated depth-volume relationship.

The relative volumes of the discrete slices in the hypolimnion were used to assign volume-weighting factors for sampling data. For example, the 9.5-10.5 meter depth interval of the lake represents approximately 18 percent of the total volume below 9.5 meters, therefore the sample from a depth of 10 meters was assigned a volume weighting factor of 0.18 to calculate a volume-weighted average for hypolimnetic dissolved oxygen, if measurements were made at 1 meter intervals. Volume-weighted averages are widely recognized in limnology as the most representative estimate of the mass of oxygen in the water column of a lake (*e.g.* Wetzel, 1983).

Trend in HODR Between 1983-97

The volume-weighted average concentration of dissolved oxygen in the hypolimnion steadily decreases during the period of stratification (Figure 3). The rate of decrease is defined as the HODR (Wetzel, 1983), which can be expressed either as a rate of change in concentration (*e.g.* mg/L/day) or rate of consumption per unit area of the hypolimnion (*e.g.* $mg/m^2/day$). The rate of consumption per unit area is estimated by multiplying the rate of change in concentration (volume-weighted average) by the volume of the hypolimnion (hypolimnetic volume is 4.7×10^6 m^3 from 9.5 meters to the bottom) to obtain the rate of change in mass, and then dividing by the area of the hypolimnion (0.92×10^6 m^2 for the 9.5 meter depth contour).

Dissolved oxygen in the hypolimnion gradually begins to decrease between April and May when thermal stratification develops. Minimum values of hypolimnetic dissolved oxygen occur at different times from year to year depending on when de-stratification of the water column occurs. In general, the HODR is fairly constant between June and mid-August during all years. The HODR was estimated for each year by linear regression of the hypolimnetic dissolved oxygen concentrations between June and mid-August (between June 1 and August 15 of each year). The HODR is equal to the slope of the linear regression equation (Appendix A).

The HODR in Basin I appears to be significantly increasing during the period of 1983-97 (Figure 4). The trend of increasing HODR is statistically significant at the 95% confidence level based on linear regression and non-parametric trend tests (the significance level is < 0.05 based on a t-test for the slope of the linear regression, and for non-parametric Spearman and Pearson correlation tests). Data from 1993 were excluded because the measurements during that year were not sensitive below 2 mg/L. Data from 1985-87 were excluded because they were not as complete or reliable due to changes in methods (personal communication with William McCourt, City of Bellingham, Department of Public Works).

The current levels of HODR in Basin I are in the typical range for mesotrophic lakes. However, the trend in HODR suggests that the trophic state of Basin I may soon shift to a more eutrophic condition based on criteria for HODR suggested by Welch (1980).

Changes in the HODR are an indicator of eutrophication (Wetzel, 1983). Increases in HODR are usually caused by increases in production of algae, which is caused by increased loading of nutrients. Changes in the loading of organic material may also cause changes in HODR. Changes in the land use and pollution controls in the watershed are usually the cause of changes in loading of nutrients and organic material to a lake.

The following summary by Wetzel (1983) is relevant to the use of HODR for detecting trends in Lake Whatcom and other lakes:

> *"... when detailed data on productivity are lacking, the oxygen deficit can be informative about the general trophic status of the lake. Changes in hypolimnetic oxygen deficit rates over long periods of time can be indicative of overall changes in the productivity of the lake... The trend (of increases in HODR in Douglas Lake in Michigan for example) reflects an accelerated nutrient input and eutrophication associated with human activity first as a result of deforestation, and second as a result of the development of the area for recreational purposes. This pattern has been repeated many times in other lakes, but long-term data are available only rarely. The well-known rapid eutrophication of a much larger lake, Lake Erie, has been followed in a similar way..."*

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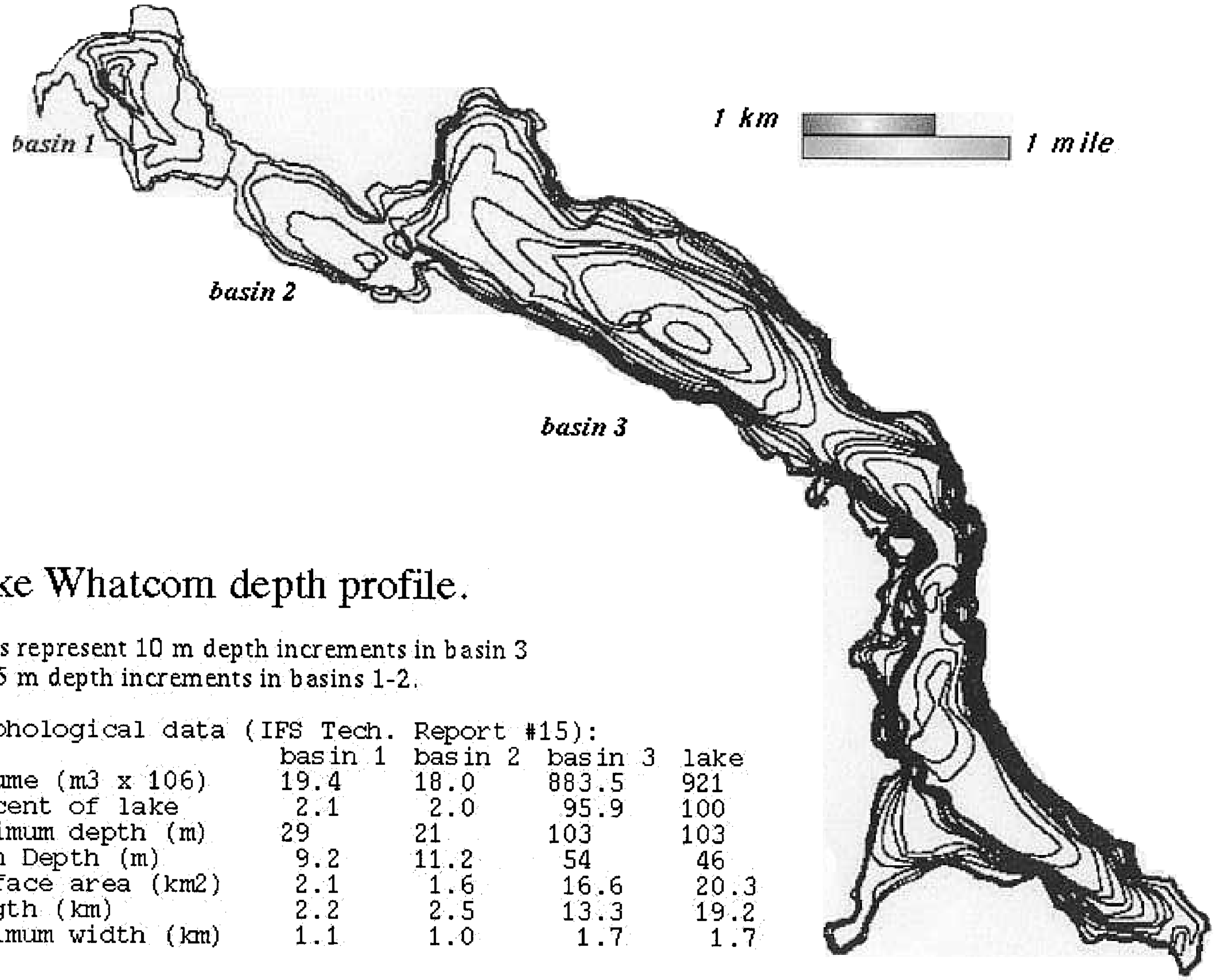
Figure 1. Bathymetric map and morphological data for Lake Whatcom.
(source: http://sanjuan.cs.wwu.edu/L_Whatcom/data/depth.html)



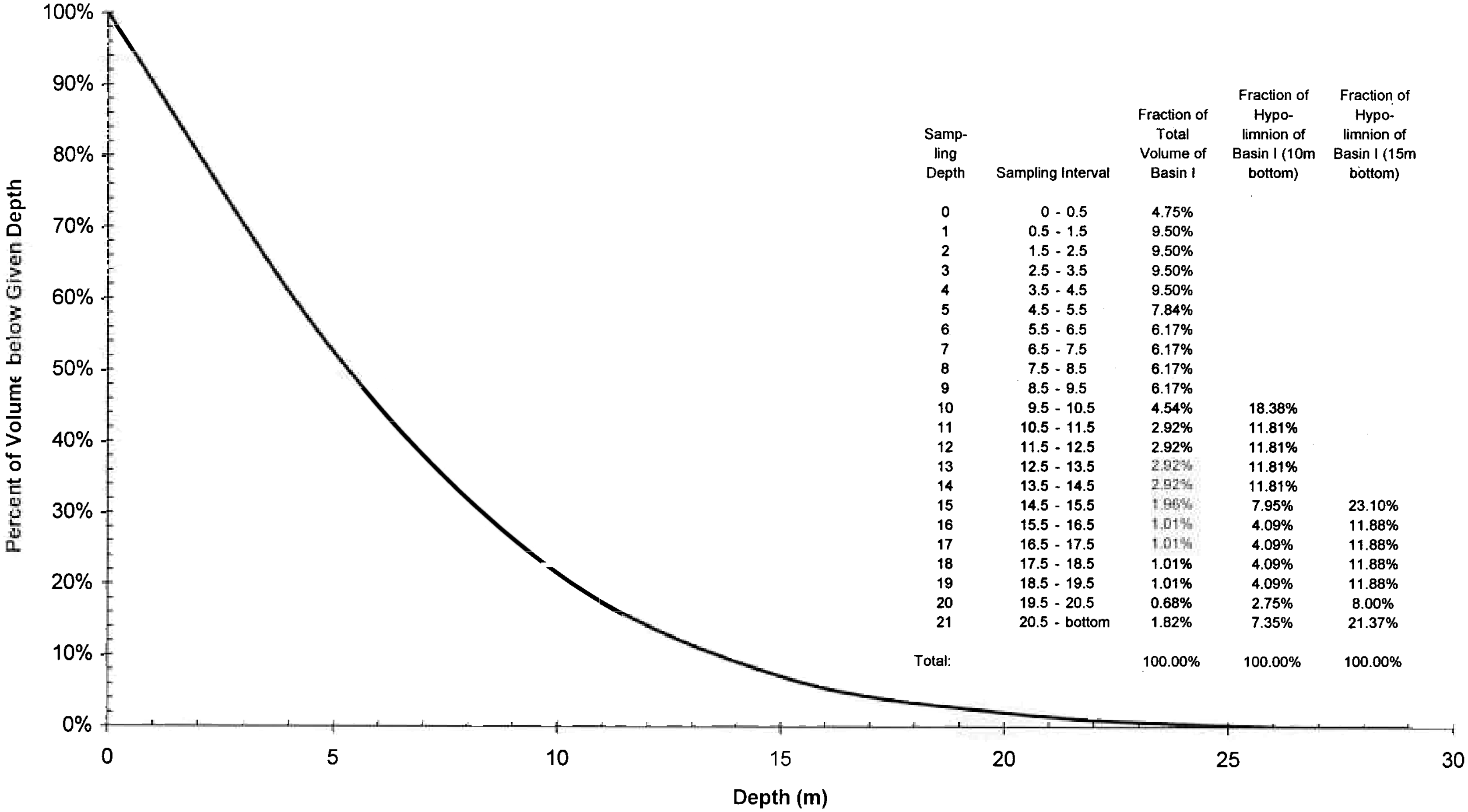
Lake Whatcom depth profile.

Lines represent 10 m depth increments in basin 3
and 5 m depth increments in basins 1-2.

Morphological data (IFS Tech. Report #15):

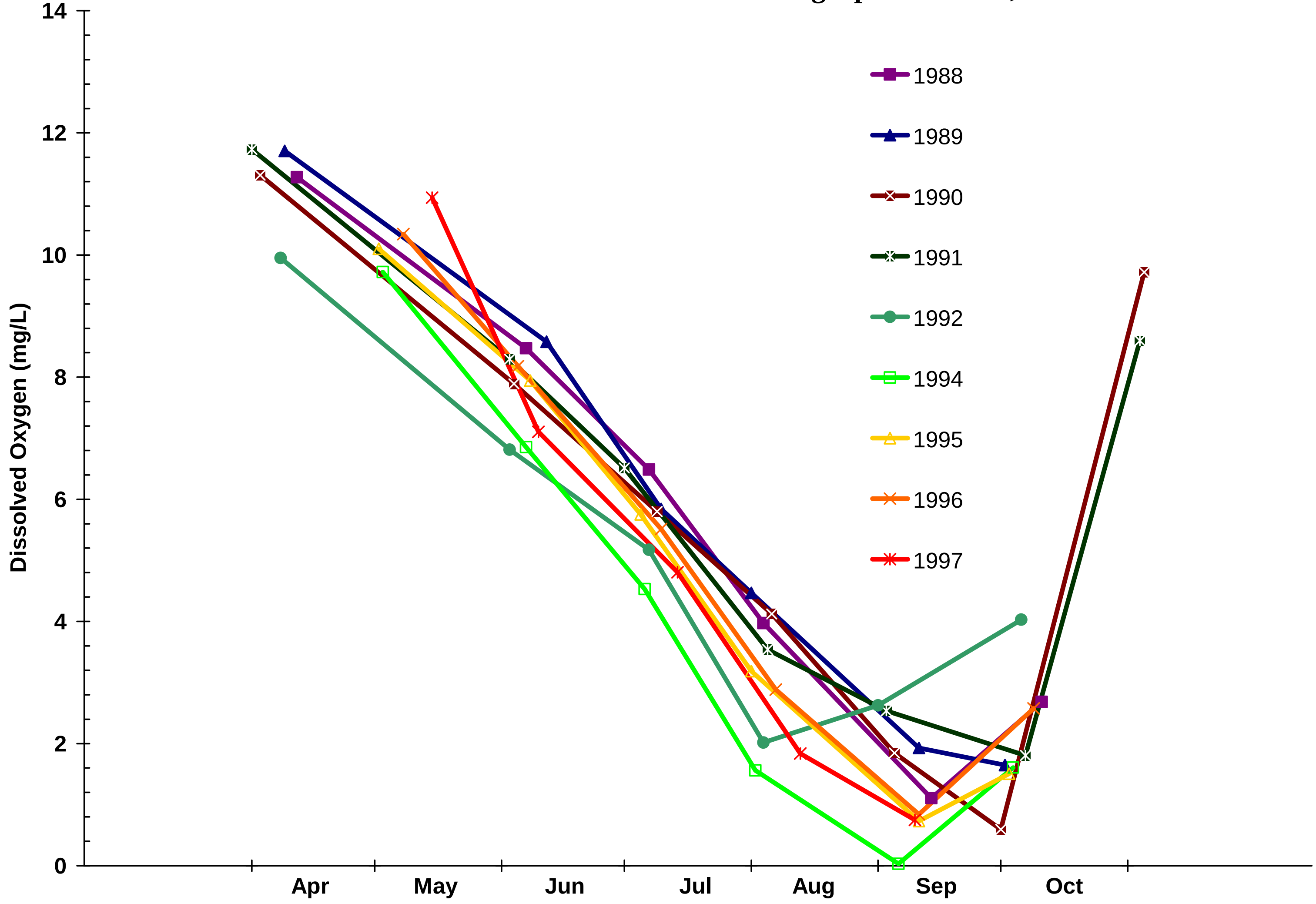
	basin 1	basin 2	basin 3	lake
Volume (m3 x 106)	19.4	18.0	883.5	921
Percent of lake	2.1	2.0	95.9	100
Maximum depth (m)	29	21	103	103
Mean Depth (m)	9.2	11.2	54	46
Surface area (km2)	2.1	1.6	16.6	20.3
Length (km)	2.2	2.5	13.3	19.2
Maximum width (km)	1.1	1.0	1.7	1.7

Figure 2. Depth-volume relationship for basin I of Lake Whatcom.



Sampling Depth	Sampling Interval	Fraction of Total Volume of Basin I	Fraction of Hypolimnion of Basin I (10m bottom)	Fraction of Hypolimnion of Basin I (15m bottom)
0	0 - 0.5	4.75%		
1	0.5 - 1.5	9.50%		
2	1.5 - 2.5	9.50%		
3	2.5 - 3.5	9.50%		
4	3.5 - 4.5	9.50%		
5	4.5 - 5.5	7.84%		
6	5.5 - 6.5	6.17%		
7	6.5 - 7.5	6.17%		
8	7.5 - 8.5	6.17%		
9	8.5 - 9.5	6.17%		
10	9.5 - 10.5	4.54%	18.38%	
11	10.5 - 11.5	2.92%	11.81%	
12	11.5 - 12.5	2.92%	11.81%	
13	12.5 - 13.5	2.92%	11.81%	
14	13.5 - 14.5	2.92%	11.81%	
15	14.5 - 15.5	1.96%	7.95%	23.10%
16	15.5 - 16.5	1.01%	4.09%	11.88%
17	16.5 - 17.5	1.01%	4.09%	11.88%
18	17.5 - 18.5	1.01%	4.09%	11.88%
19	18.5 - 19.5	1.01%	4.09%	11.88%
20	19.5 - 20.5	0.68%	2.75%	8.00%
21	20.5 - bottom	1.82%	7.35%	21.37%
Total:		100.00%	100.00%	100.00%

Figure 3. Volume-weighted hypolimnetic DO (10m-bottom) in Basin I of Lake Whatcom during April-October, 1988-97.



Appendix A. Calculation of HODR in Basin I of Lake Whatcom.

Date	Julian Day	Volume-weighted hypolimnetic DO (mg/L) 8m-bottom:	10m-bottom:	15m-bottom:
5/9/83	129	9.43	9.16	8.50
5/23/83	143	7.33	6.86	5.84
6/6/83	157	6.90	6.32	5.01
6/20/83	171	5.94	5.37	4.00
7/11/83	192	7.06	5.47	1.88
7/25/83	206	4.10	3.63	2.29
8/8/83	220	5.08	3.70	0.60
8/22/83	234	1.96	1.39	0.14
8/29/83	241	3.57	2.48	0.12
9/6/83	249	5.26	3.66	0.24
9/12/83	255	5.56	3.97	0.39
9/19/83	262	5.41	3.79	0.24
10/3/83	276	5.51	3.78	0.00
5/21/84	142	10.50	10.21	9.59
6/4/84	156	6.96	6.95	6.38
6/18/84	170	8.60	7.97	6.47
7/2/84	184	7.20	6.64	4.46
7/23/84	205	4.90	4.17	2.60
7/30/84	212	5.29	4.29	2.04
8/6/84	219	4.39	3.66	1.62
8/20/84	233	2.25	1.59	0.15
9/10/84	254	2.62	1.96	0.45
9/17/84	261	4.87	3.50	0.47
9/24/84	268	5.56	3.91	0.34
4/11/88	102	11.33	11.27	11.21
6/6/88	158	9.00	8.47	7.79
7/6/88	188	7.55	6.49	5.09
8/3/88	216	5.76	3.97	1.95
9/13/88	257	3.06	1.11	0.40
10/10/88	284	5.53	2.68	0.51
4/9/89	99	11.73	11.70	11.65
6/12/89	163	9.38	8.58	7.43
7/10/89	191	6.89	5.84	4.89
8/1/89	213	5.77	4.47	3.14
9/11/89	254	4.09	1.93	0.54
10/2/89	275	4.18	1.65	0.48

June-August Regression
HODR = slope of the regression in mg/L/day

Regression Output:	X=day (157-220), Y=DO mg/L 8m-bottom	X=day (157-220), Y=DO mg/L 10m-bottom	X=day (157-220), Y=DO mg/L 15m-bottom
Constant	11.998193	12.946395	15.217033
Std Err of Y Est	1.074372	0.5468259	0.5560065
R Squared	0.4457501	0.8402646	0.9242006
No. of Observations	5	5	5
Degrees of Freedom	3	3	3
X Coefficient(s)	-0.032685	-0.042546	-0.065862
Std Err of Coef.	0.0210427	0.0107101	0.01089

Regression Output:	X=day (156-219), Y=8m-bottom	X=day (156-219), Y=10m-bottom	X=day (156-219), Y=15m-bottom
Constant	16.706887	18.153392	20.127186
Std Err of Y Est	0.9593743	0.7895641	0.4707734
R Squared	0.7195633	0.8442702	0.9621797
No. of Observations	6	6	6
Degrees of Freedom	4	4	4
X Coefficient(s)	-0.054884	-0.065657	-0.084805
Std Err of Coef.	0.0171317	0.0140994	0.0084067

Regression Output:	X=day (158-216), Y=8m-bottom	X=day (158-216), Y=10m-bottom	X=day (158-216), Y=15m-bottom
Constant	17.875982	20.822953	23.779246
Std Err of Y Est	0.1813206	0.2801292	0.2547093
R Squared	0.9937456	0.9922876	0.9962003
No. of Observations	3	3	3
Degrees of Freedom	1	1	1
X Coefficient(s)	-0.055718	-0.077461	-0.100542
Std Err of Coef.	0.0044203	0.006829	0.0062093

Regression Output:	X=day (163-213), Y=8m-bottom	X=day (163-213), Y=10m-bottom	X=day (163-213), Y=15m-bottom
Constant	21.107973	21.97091	21.437044
Std Err of Y Est	0.3847149	0.3541797	0.1090378
R Squared	0.9782634	0.9856872	0.9987265
No. of Observations	3	3	3
Degrees of Freedom	1	1	1
X Coefficient(s)	-0.072824	-0.082935	-0.086158
Std Err of Coef.	0.0108554	0.0099938	0.0030767

Appendix A (continued).

Date	Julian Day	Volume-weighted hypolimnetic DO (mg/L) 8m-bottom:	10m-bottom:	15m-bottom:
4/3/90	93	11.42	11.31	11.15
6/4/90	155	8.56	7.89	7.36
7/9/90	190	6.93	5.80	4.91
8/6/90	218	5.62	4.12	2.91
9/5/90	248	3.62	1.85	0.84
10/1/90	274	3.50	0.60	0.23
11/5/90	309	9.75	9.72	9.60
4/1/91	91	11.73	11.73	11.70
6/3/91	154	8.94	8.29	7.74
7/1/91	182	7.42	6.51	5.21
8/5/91	217	5.20	3.54	2.54
9/3/91	246	4.52	2.54	0.61
10/7/91	280	4.35	1.81	0.43
11/4/91	308	8.71	8.60	7.90
4/7/92	98	10.24	9.95	9.62
6/2/92	154	7.84	6.81	5.91
7/6/92	188	6.75	5.17	3.97
8/3/92	216	3.78	2.02	1.37
8/31/92	244	3.47	2.63	0.88
10/5/92	279	5.60	4.03	0.48

June-August Regression
HODR = slope of the regression in mg/L/day

1990

Regression Output:	X=day (155-218), Y=8m-bottom	X=day (155-218), Y=10m-bottom	X=day (155-218), Y=15m-bottom
Constant	15.810416	17.162684	18.299069
Std Err of Y Est	0.0035569	0.0035247	0.020495
R Squared	0.9999971	0.9999983	0.9999576
No. of Observations	3	3	3
Degrees of Freedom	1	1	1
X Coefficient(s)	-0.046738	-0.059811	-0.070549
Std Err of Coef.	7.968E-05	7.896E-05	0.0004591

1991

Regression Output:	X=day (154-217), Y=8m-bottom	X=day (154-217), Y=10m-bottom	X=day (154-217), Y=15m-bottom
Constant	18.159539	20.089074	20.321641
Std Err of Y Est	0.117406	0.2707036	0.1753832
R Squared	0.9980523	0.993641	0.9977224
No. of Observations	3	3	3
Degrees of Freedom	1	1	1
X Coefficient(s)	-0.059537	-0.075805	-0.082232
Std Err of Coef.	0.0026301	0.0060642	0.0039289

1992

Regression Output:	X=day (154-216), Y=8m-bottom	X=day (154-216), Y=10m-bottom	X=day (154-216), Y=15m-bottom
Constant	18.091298	18.864463	17.248887
Std Err of Y Est	0.9284699	0.8067237	0.449371
R Squared	0.9025491	0.9452315	0.9805002
No. of Observations	3	3	3
Degrees of Freedom	1	1	1
X Coefficient(s)	-0.064351	-0.076326	-0.072571
Std Err of Coef.	0.0211453	0.0183726	0.0102341

Appendix A (continued).

Volume-weighted hypolimnetic DO (mg/L)

Date	Julian Day	8m-bottom:	10m-bottom:	15m-bottom:
5/3/94	123	10.15	9.72	9.27
6/7/94	158	7.90	6.85	5.75
7/6/94	187	6.12	4.53	2.97
8/2/94	214	4.01	1.56	0.23
9/6/94	249	2.27	0.03	0.00
10/4/94	277	3.96	1.61	0.04

June-August Regression
HODR = slope of the regression in mg/L/day

	X=day (158-214), Y=8m-bottom	X=day (158-214), Y=10m-bottom	X=day (158-214), Y=15m-bottom
Regression Output:			
Constant	18.956041	21.894208	21.338876
Std Err of Y Est	0.1910573	0.3395586	0.0615686
R Squared	0.9952037	0.9918093	0.999751
No. of Observations	3	3	3
Degrees of Freedom	1	1	1
X Coefficient(s)	-0.069486	-0.094341	-0.098495
Std Err of Coef.	0.0048239	0.0085733	0.0015545

Date	Julian Day	8m-bottom:	10m-bottom:	15m-bottom:
5/2/95	122	10.44	10.10	9.47
6/8/95	159	9.05	7.94	6.44
7/5/95	186	7.32	5.75	4.13
8/1/95	213	5.09	3.19	1.35
9/11/95	254	3.13	0.73	0.06
10/3/95	276	3.67	1.51	0.04

	X=day (159-213), Y=8m-bottom	X=day (159-213), Y=10m-bottom	X=day (159-213), Y=15m-bottom
Regression Output:			
Constant	20.811682	22.003145	21.491678
Std Err of Y Est	0.2058245	0.1526656	0.1911938
R Squared	0.9946402	0.9979418	0.9971811
No. of Observations	3	3	3
Degrees of Freedom	1	1	1
X Coefficient(s)	-0.07343	-0.088039	-0.094177
Std Err of Coef.	0.0053904	0.0039982	0.0050072

Date	Julian Day	8m-bottom:	10m-bottom:	15m-bottom:
5/7/96	128	10.54	10.34	9.92
6/4/96	156	8.74	8.18	7.65
7/9/96	191	7.16	5.52	4.34
8/6/96	219	5.10	2.88	1.26
9/10/96	254	3.46	0.84	0.18
10/8/96	282	4.78	2.58	0.20

	X=day (156-219), Y=8m-bottom	X=day (156-219), Y=10m-bottom	X=day (156-219), Y=15m-bottom
Regression Output:			
Constant	17.811874	21.321675	23.511811
Std Err of Y Est	0.3599358	0.2259558	0.1985215
R Squared	0.9805915	0.9963579	0.9980729
No. of Observations	3	3	3
Degrees of Freedom	1	1	1
X Coefficient(s)	-0.057313	-0.083721	-0.101209
Std Err of Coef.	0.0080632	0.0050618	0.0044472

Date	Julian Day	8m-bottom:	10m-bottom:	15m-bottom:
5/15/97	135	11.18	10.94	10.27
6/10/97	161	7.89	7.11	6.26
7/14/97	195	6.07	4.80	3.31
8/13/97	225	4.07	1.84	0.55
9/10/97	253	2.26	0.75	0.41

	X=day (161-225), Y=8m-bottom	X=day (161-225), Y=10m-bottom	X=day (161-225), Y=15m-bottom
Regression Output:			
Constant	17.539567	20.463138	20.616816
Std Err of Y Est	0.167347	0.4052326	0.0671771
R Squared	0.9961626	0.9882321	0.9997225
No. of Observations	3	3	3
Degrees of Freedom	1	1	1
X Coefficient(s)	-0.059541	-0.082004	-0.089042
Std Err of Coef.	0.0036955	0.0089486	0.0014835

Appendix **A** (continued).

Year	HODR mg/m2/day		
	8m-B	10m-B	15m-B
1983	194	215	302
1984	325	332	389
1988	330	392	462
1989	432	420	395
1990	277	303	324
1991	353	383	377
1992	382	386	333
1994	412	477	452
1995	435	445	432
1996	340	424	465
1997	353	415	409
1983-97			
mean	**348**	381	395
std deviation	**70**	73	57

1983-1997 trend in HODR

X=yr (1983-97), Y=8m HODR (mg/m2/d)
Regression Output:

Constant		-17478.33
Std Err of Y Est		60.069312
R Squared		0.3453288
No. of Observations		11
Degrees of Freedom		9
X Coefficient(s)	8.954496	mg/m2/d/yr
Std Err of Coef.	4.1097468	
t-statistic	2.179	
2-tail significance:	0.06	
1-tail significance:	0.03	

X=yr (1983-97), Y=10m HODR (mg/m2/d)
Regression Output:

Constant		-23884.25
Std Err of Y Est		49.743835
R Squared		0.5876556
No. of Observations		11
Degrees of Freedom		9
X Coefficient(s)	12.188613	mg/m2/d/yr
Std Err of Coef.	3.4033113	
t-statistic	3.581	
2-tail significance:	0.01	
1-tail significance:	0.00	

X=yr (1983-97), Y=15m HODR (mg/m2/d)
Regression Output:

Constant		-12094.31
Std Err of Y Est		51.119105
R Squared		0.2633411
No. of Observations		11
Degrees of Freedom		9
X Coefficient(s)	6.2732563	mg/m2/d/yr
Std Err of Coef.	3.4974028	
t-statistic	1.794	
2-tail significance:	0.11	
1-tail significance:	0.05	