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Waldo Lake Research in 2003

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Introduction

Waldo Lake may be one of the most oligotrophic lakes in the world (Larson, 2000). Secchi transparency greater than 30 m is typical and ion concentrations are extremely low in the lake (Nelson, 2000). Throughout the 20th century the lake was subject to hydropower and irrigation development (Claeyssens, 2000), fisheries enhancement through mysid and salmonid stocking (Ziller and Wade, 2000), and recreational development (Larson, 2000). Efforts to use the lake for hydropower and irrigation were halted in the 1930s, however, following the opening of a surfaced road to the lake in 1969 recreational use increased.

A volunteer team of limnologists monitored the lake between 1986 and 1998, and produced a substantial body of data that documented the limnological status of the lake. Much of this data and earlier work was summarized in an issue of the journal, *Lake and Reservoir Management* published in 2000 by the North American Lake Management Society. The authors concluded that Waldo Lake primary production by phytoplankton had increased 20-fold over a 25 to 30-year period and that there was an increased attenuation of blue light that could be attributed to increased phytoplankton density (Salinas and Larson, 2000). Phytoplankton and zooplankton communities were reported to be recovering from perturbation caused by fish and mysid stocking in the lake (Sweet, 2000; Vogel and Li, 2000; Ziller and Wade, 2000). The stocking programs may have played a major role in changes in primary production and light through trophic-cascade effects (Carpenter et al., 1985). The benthos, including invertebrates (Hoffman and Liss, 2000), cyanobacteria (Johnson and Castenholz, 2000), bryophytes (Wagner et al., 2000), and epiphytic algae (Geiger, 2000) were also described. Although rates were not measured, the benthos was recognized as an important contributor to Waldo Lake primary production and trophic dynamics (Swanson et al., 2000).

The dilute waters of Waldo Lake support a unique and potentially fragile ecosystem. Human activity in and around the lake was cited as a potential cause of changes described by authors in the 2000 *Lake and Reservoir Management* issue. The volunteer-collected data provided a basis for evaluating the condition of Waldo Lake, however, because sampling was contingent on individual resources and time it was somewhat haphazard. For the most part, the sampling was conducted as a monitoring program, with post hoc development of hypotheses. The publication of a 1995 report on Waldo Lake (Larson and Salinas), and the 2000 *Lake and Reservoir Management* issue focused attention on the U.S. Forest Service management of Waldo Lake and stimulated funding of more in-depth study.

This report summarizes the first year of an effort to develop a more complete understanding of the physical, chemical, and biological characteristics that drive the ecological processes of Waldo Lake. Modern limnology recognizes the importance of watershed processes as well as in-lake processes in lake ecosystem functioning. Therefore, the approach included consideration of watershed hydrology and forcing functions that determine hydrodynamics of the system as well physical and chemical factors that may be important in regulating primary production in the lake. Data collected since 1998 was summarized and bathymetry of the basin was mapped using state-of-the-art digital depth sounding and GPS technology. A hypothesis that UV light may play an important role in regulating phytoplankton efficiency was examined in an effort to move toward more hypothesis-driven investigations to elucidate the factors controlling productivity. A Quality Assurance/Quality Control Plan was developed to guide data collection for long-term monitoring of the lake. Lastly, initial steps were made in the development of a model of lake hydrodynamics and primary production to aid in integration of the physical, chemical, and biological data that has been collected on the lake.

Background

Location

Waldo Lake is located approximately 93 km southeast of Eugene, Oregon near McCredie Springs and Oakridge, Oregon. Waldo Lake lies in a glaciated basin with lateral and end moraines at an elevation of 1650 m (NGVD29) in the central Oregon Cascade Mountains, Figure 1.

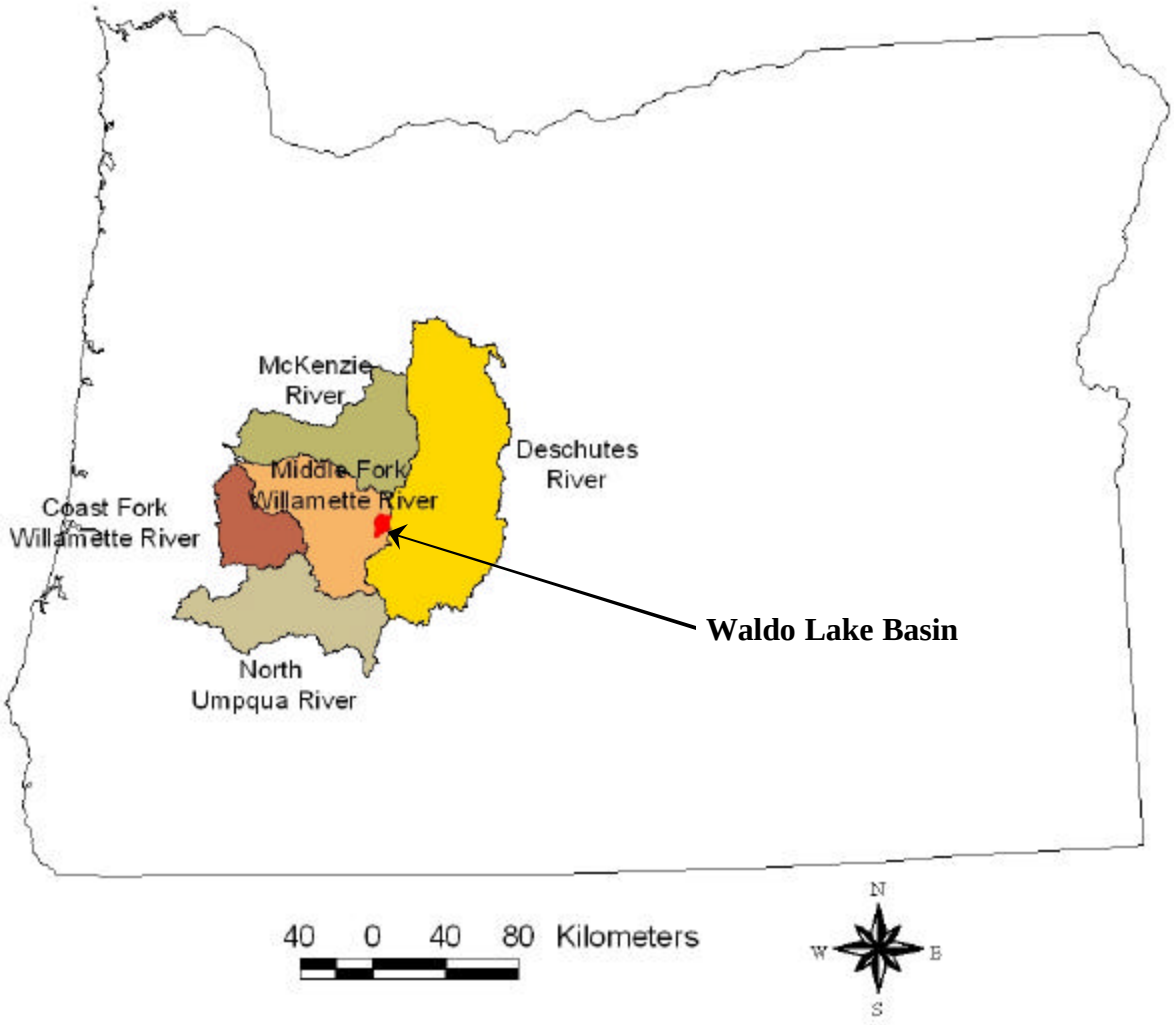


Figure 1: Waldo Lake basin in the Oregon Central Cascades

Basin Topography and Hydrology

The Waldo Lake drainage basin is approximately 77.5 km^2 and forms the headwaters of the North Fork of the Middle Fork Willamette River. The lake surface area comprises approximately 84 percent of basin area. Figure 2 shows the basin and regional topography including surrounding mountain peaks. The

basin topography ranges from an elevation of 1,645 m to 2,222 m. Surface inlet streams are ephemeral, but fractured bedrock may channel subsurface flow to the lake year-round. Waldo Lake chemistry is a function of precipitation inputs, primarily snow melt (Nelson, 2000).

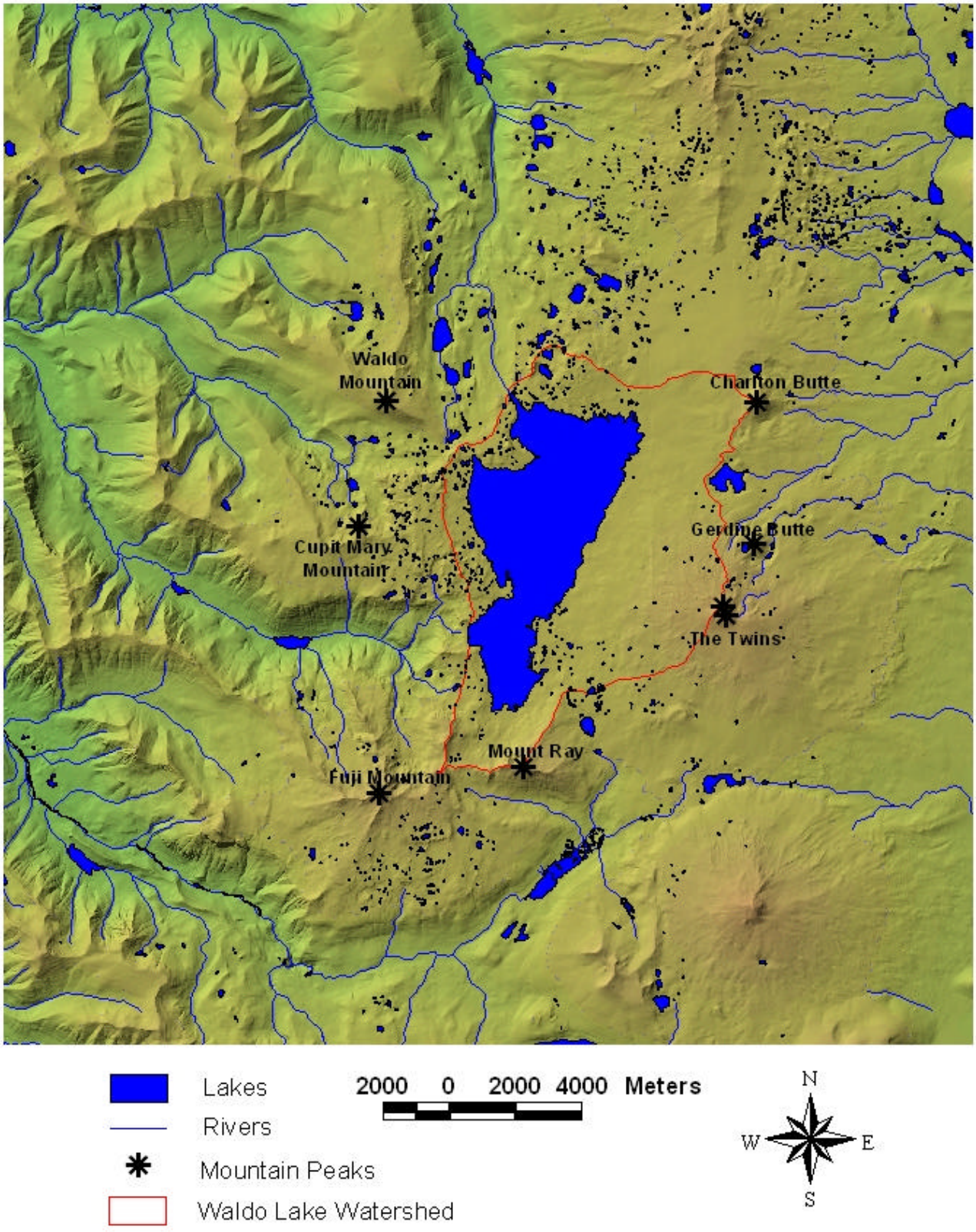


Figure 2: Waldo Lake basin and surrounding topography with geographic features.

Vegetation

The Waldo Lake drainage basin area is 80 percent forested, primarily by Douglas fir, Western Hemlock, Mountain Hemlock and True Fir (Figure 3). Additional tree species include: lodge pole pine, western white pine, and Engelmann spruce (Manhart et al., 1971).

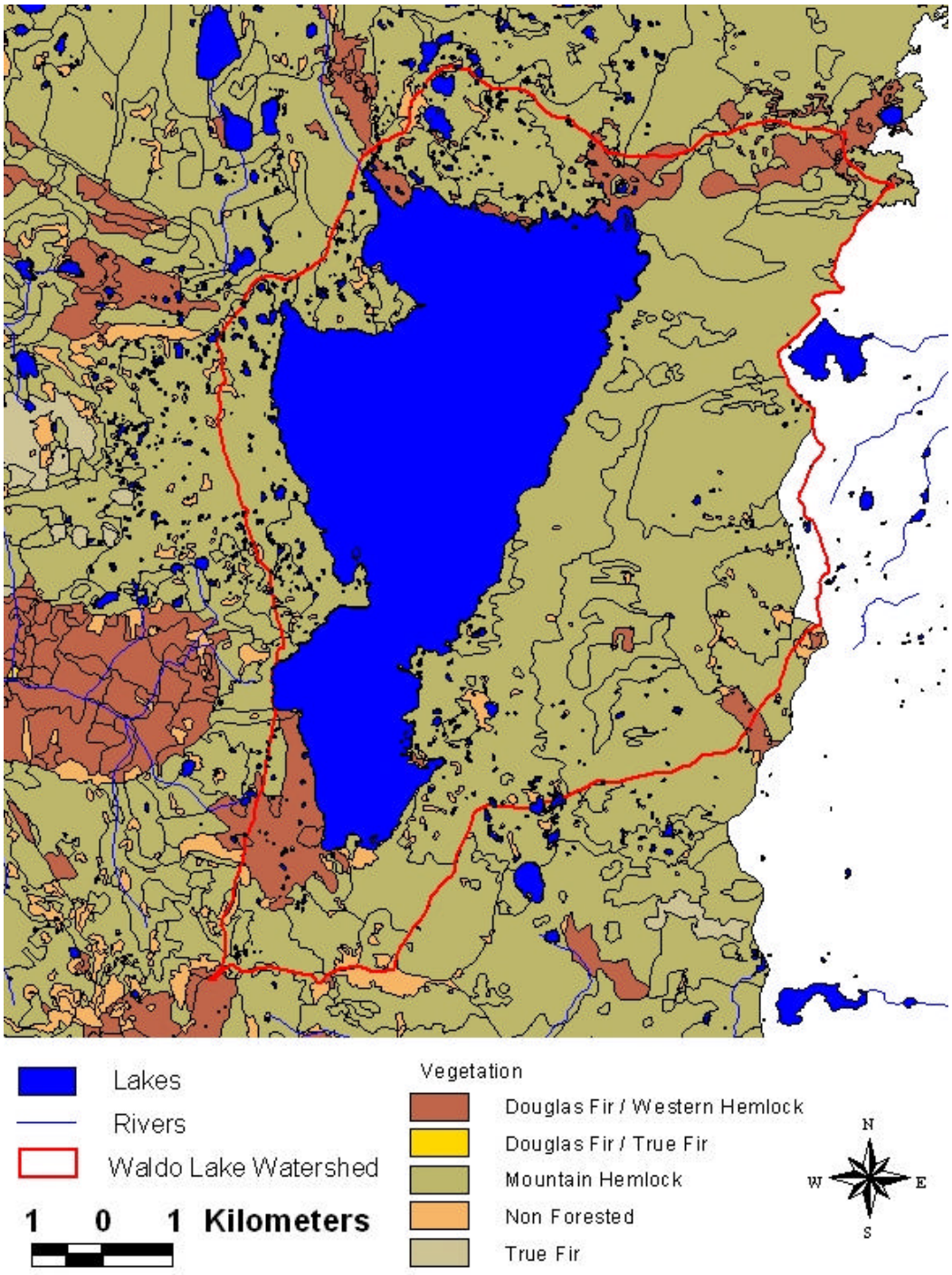


Figure 3: Vegetation cover in the Waldo Lake basin and surrounding area (Willamette National Forest Geographic Information System).

Geology and Soils

The soils in the Waldo Lake basin, particularly those areas east of the lake, derived from volcanic ejecta and glacial till. Surface soils are thin and porous deposits of pumice and ash. Subsoils are gravelly or cobbly sandy loams. Depth to bedrock is typically three to six feet (MU92) (Figure 4). Soils are slightly deeper at the south end of the lake (MU923) (Willamette National Forest, 1994).

The watershed of Waldo Lake is comprised of very young basaltic andesite lava flows covered with a thin veneer of glacial drift (Black, 2000). Rock types on the western and northern shores of the lake are comprised of older basaltic andesite (QTba) (older than 250 Ka). The eastern shores are comprised of basaltic andesite younger than 250 Ka (Qba). Southern portions of the lake are comprised of glacial drift (Qg) (Figure 5). Due to the distribution of geology types and debatable glacial movement, the origin of Waldo Lake is unclear, although conclusions reached by Black (2000) indicate a northward-moving glacier originating between Mount Ray and Fuji Mountain excavated Waldo Lake.

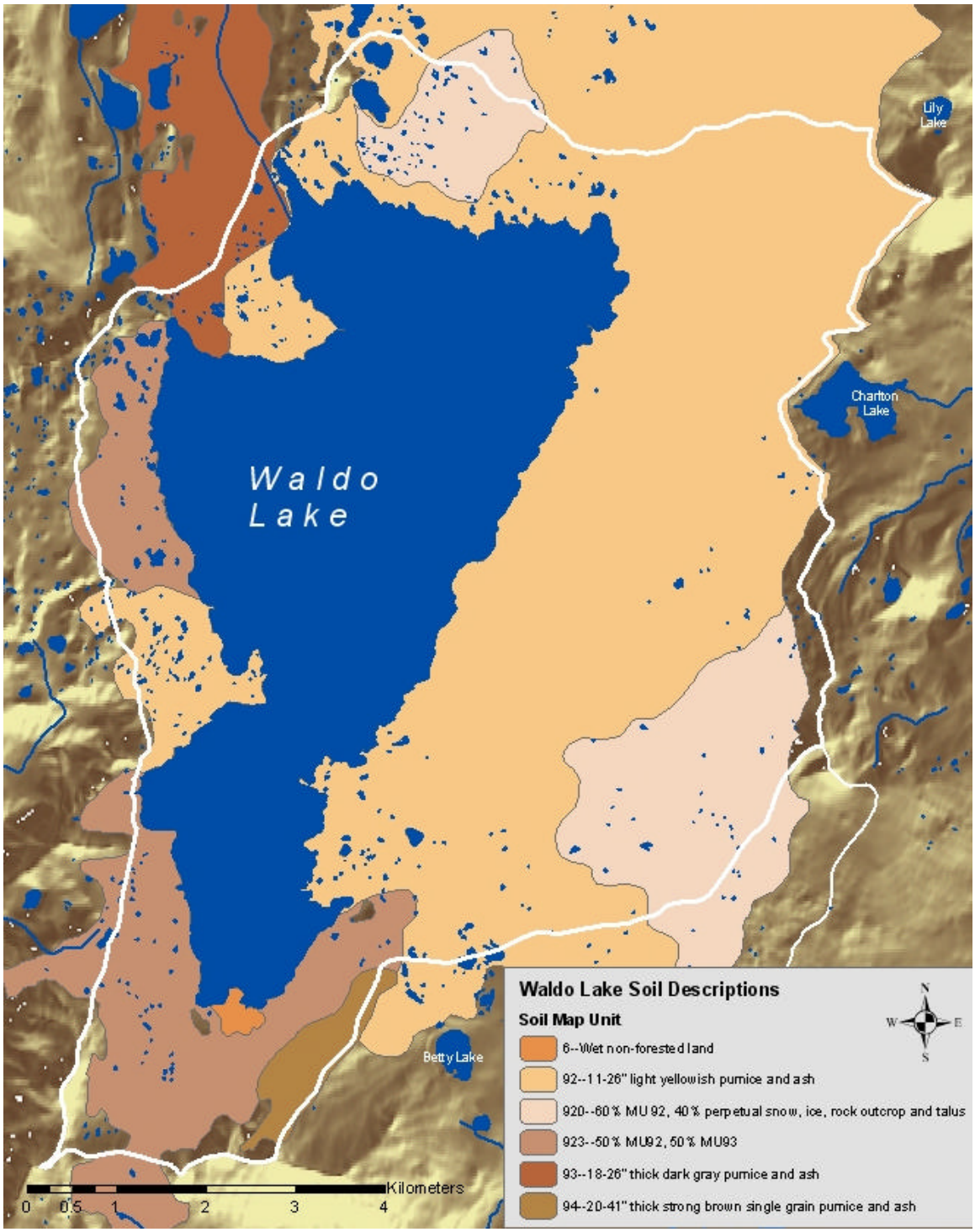


Figure 4: Soils in the Waldo Lake basin and watershed boundary. (Willamette National Forest Soil Resource Inventory, data dictionary http://www.fs.fed.us/r6/willamette/manage/gis/sri.pdf).

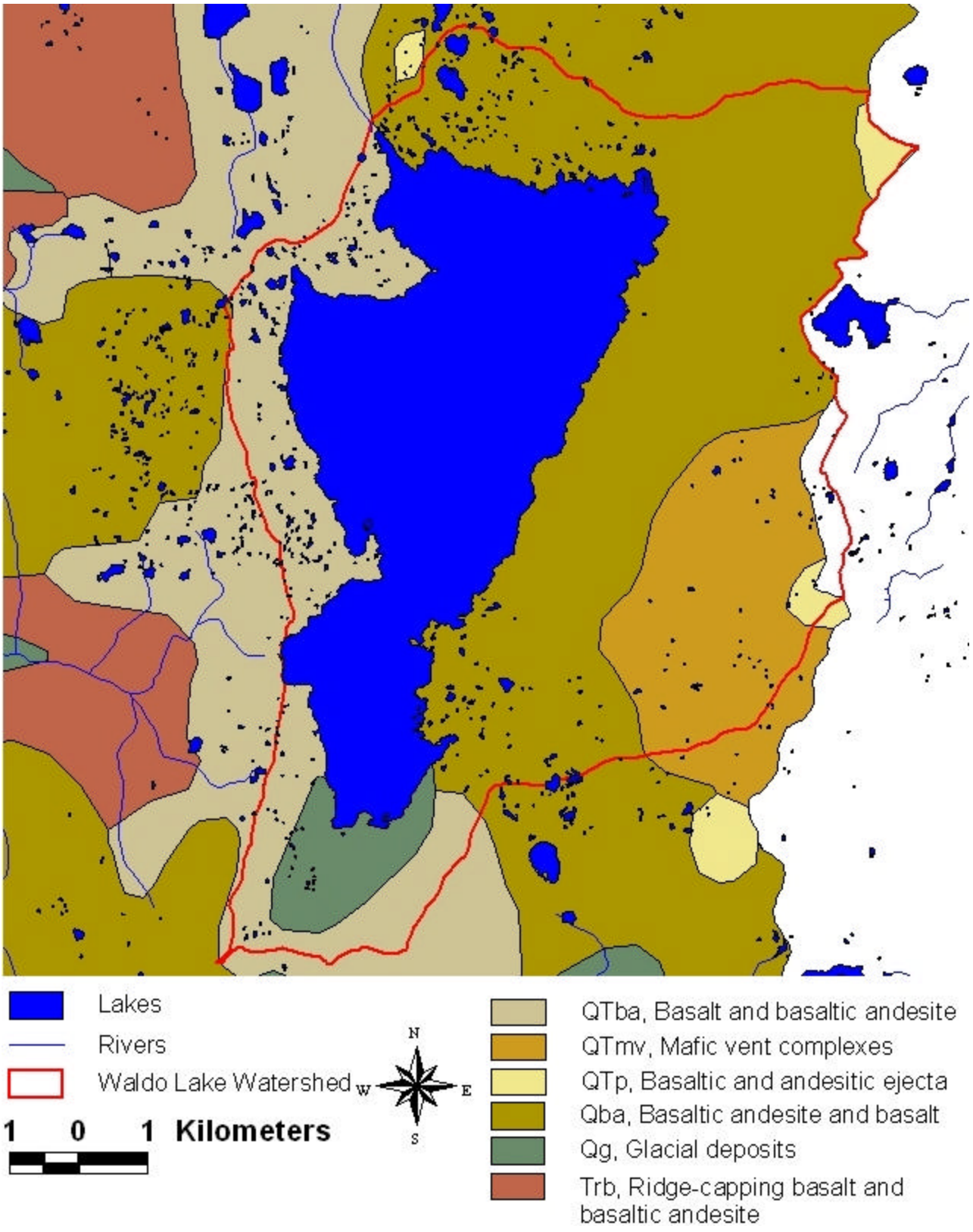


Figure 5: Geology in the Waldo Lake basin and surrounding area (Willamette National Forest Geographic Information System).

Recent Fire History

The 10,400-acre, Charlton Fire in 1996 was perhaps the most significant event in the recent history of Waldo Lake. The fire burned a significant portion of the Waldo Lake watershed in the area north of the lake near the outlet (Figure 6). The soils were altered by the intense fire. The recovery of the forest and soils in the burned area will likely take a long time due to the high elevation and short growing season in the Waldo Lake basin. Such a major disturbance within the watershed would be expected to result in chemical and perhaps biological changes in the lake through mineralization and mobilization of soil nutrients.

There are anecdotal reports that benthic periphyton growth along the north shore of the lake is more luxuriant than in areas of the lake adjacent to unburned areas. Thus, leaching of nutrients and soil erosion from the burned area by snowmelt and precipitation may be stimulating benthic production in the lake. Benthic cyanobacteria and bryophytes (Johnson and Castenholz, 2000 and Wagner et al., 2000) may account for a significant portion of primary production in Waldo Lake.

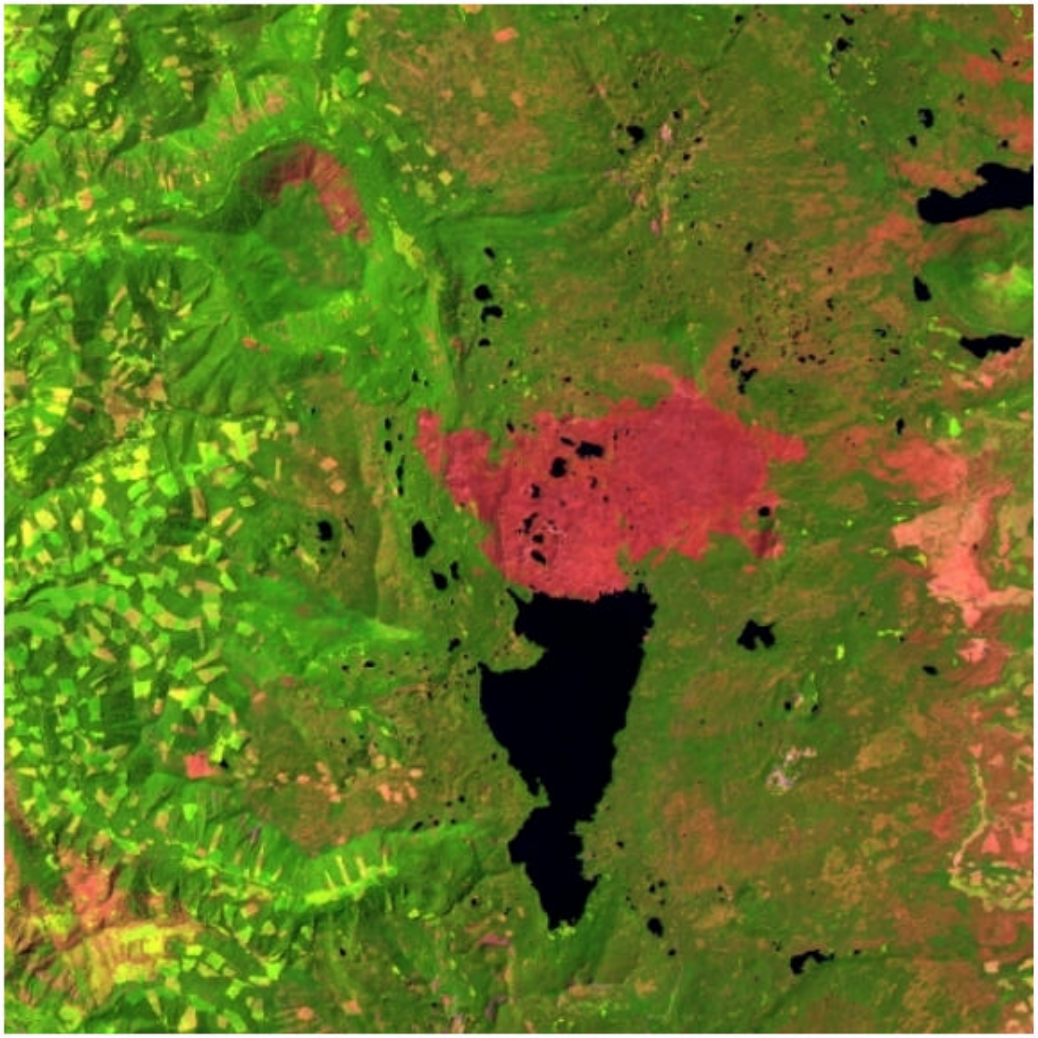


Figure 6: Location of Charlton Fire (pink area to north of Waldo Lake).

Historical Chemical and Biological Characterization of Waldo Lake

Historical information on the physical, chemical, and biological characteristics of Waldo Lake collected prior to 1998 was summarized previously (*Lake and Reservoir Management* 16, No. 1-2, 2000). This review summarizes data collected since 1998, and where possible, compares recent data to that collected previously to identify changes in lake status. Methods used for sample collection and analyses were described by Salinas (1999). Lake sampling was conducted by The Cascade Research Group, phytoplankton identification and enumeration by Aquatic Analysts, zooplankton identification and enumeration by ZP's Taxonomic Services, and water chemistry analyses by Cooperative Chemical Analytical Laboratory at Oregon State University.

Sampling of Waldo Lake occurred four times a year (May – October) in 1998 through 2003, with the exception of 2000 when no sampling occurred. Sampling occurred at the long-term monitoring site (LTM) located at the deepest point of the lake in West Bay (Figure 7). Additional sampling of nutrients, chlorophyll, and phytoplankton occurred at the North Waldo Lake Campground boat ramp and swim area (NS) and along the north shore of the lake in 1998, 1999 and 2001, following the 1996 fire. Klovdahl Bay was sampled for nutrients in 2000. Other stations with unknown locations were sampled for nutrients in 1996 (Boat Dock, Pontoons South End of Cove, Pontoons North End of Cove) and 1997 (EB, NP, NBI, WNI).

Data available from samples collected since 1998 were scattered and incomplete (Table 1). A fairly complete dataset of in situ profiles of temperature, pH, specific conductance, and dissolved oxygen exists, however, quality assurance protocols for equipment deployment were inconsistent (e.g., depths where measurements were made and field checks of calibration). Quality control checks on field duplicate analyses, when they were done, were not evaluated. In some cases, methods were changed and metadata were not available to document changes. Laboratory reporting included values below method detection limits and standard curves were not prepared that spanned the range of sample concentration. Reported values below method detection and below the minimum standard were sometimes flagged, but not always. SCUFA data was collected only in 2003, when the manufacturer provided equipment for testing purposes. Split samples for quality assurance on zooplankton and phytoplankton analyses were not evaluated. Zooplankton and primary production data were collected in 2003 but are not yet available. Additional details on data completeness and quality are discussed below.

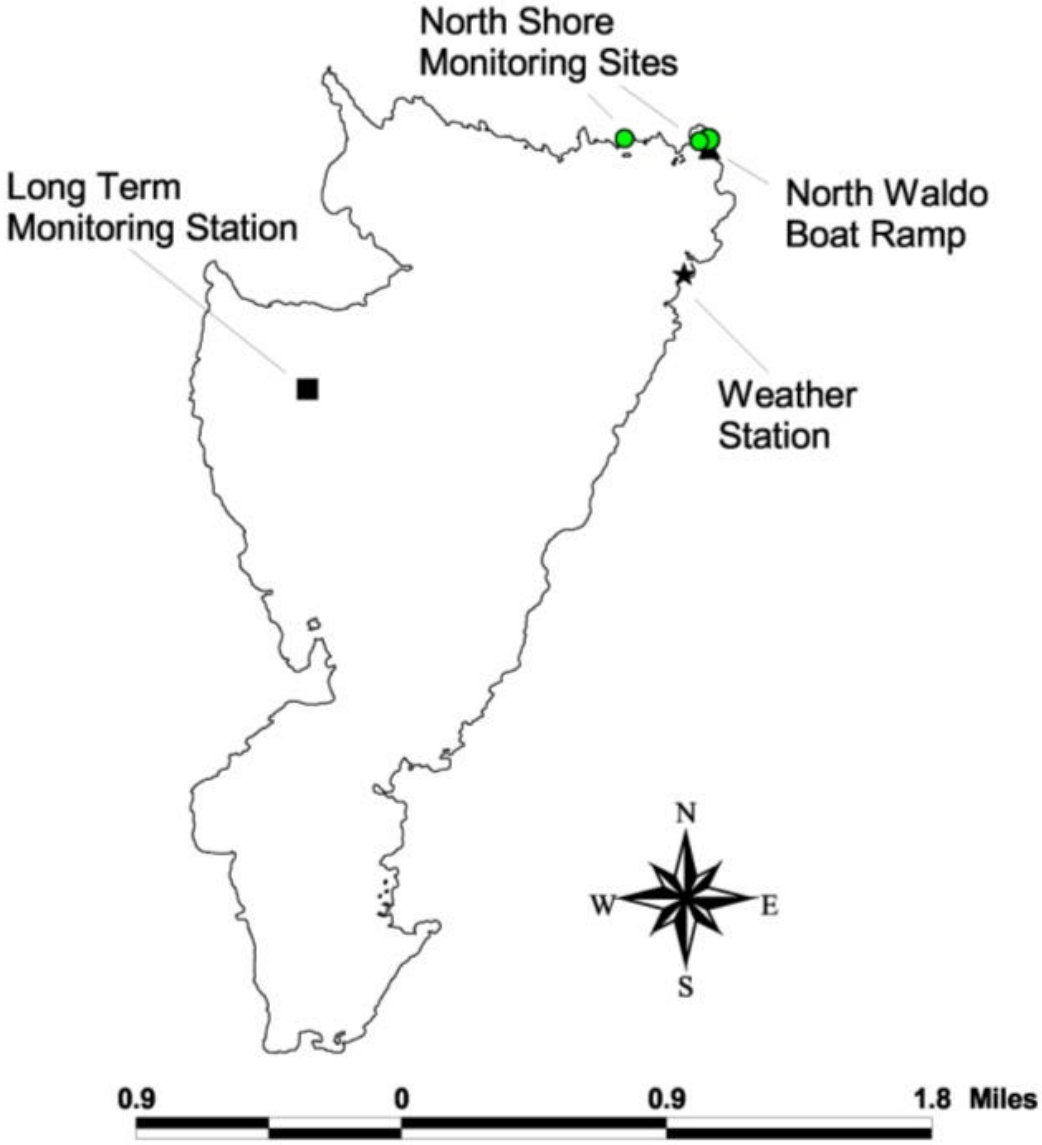


Figure 7: Locations of sampling sites between 1998 and 2003.

Table 1: Data available for review (Con.= time, cloud cover and wind speed; In-situ= pH, dissolved oxygen, specific conductance, temperature profiles; Light trans.= light transmission with Seatech 25-cm path length transmissometer; Photo.= Kahl photometer; Trans.=Secchi transparency; Chl=chlorophyll *a*; SCUFA= Turner Self-contained Underwater Fluorescence Apparatus; Primary Prod.= C^{14} productivity of phytoplankton; Phy=phytoplankton; Zoo=zooplankton; Chem=laboratory analyses ; Inorg. C=inorganic carbon). Blank cells indicate that data was not collected. N indicates that data was collected but not available for analysis.

Date	Con.	In-situ	Light Trans.	Photo.	Trans.	Chl.	SCUFA	Primary Product.	Phy.	Zoo	Chem.	Inorg. C
07/01/2003	Y	Y	Y	N/A	Y	Y		N	Y	N	Y	
08/04/2003	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	
08/25/2003	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	
09/21/2003	Y	Y	Y	Y	Y	Y		N	Y	N	N	
06/29/2002	Y	Y	Y	N/A	Y	Y		Y	Y	N	Y	
07/29/2002	Y	Y	Y	Y	Y	Y		Y	Y	N	Y	
08/19/2002	Y	Y	Y	N/A	Y	Y		Y	Y	N	Y	

Date	Con.	In-situ	Light Trans.	Photo.	Trans.	Chl.	SCUFA	Primary Product.	Phy.	Zoo	Chem.	Inorg. C
09/18/2002	Y	Y	Y	Y	Y	Y		Y	Y	N	Y	
05/27/2001	Y	Y	N/A	Y	Y	Y		Y	Y	N	Y	
07/07/2001	Y	Y	Y	Y	Y	Y		Y	Y	N	Y	
08/19/2001	Y	Y	Y	Y	Y	Y		Y	Y	N	Y	
09/09/2001	Y	Y	Y	Y	Y	Y		Y	Y	N	Y	
05/04/2000											Y[1]	
08/30/2000											Y[1]	
09/26/2000											Y	
07/26/1999	Y	Y	N	Y[2]	Y	N		Y	Y	Y	Y	
08/31/1999	Y	Y	N	Y	Y	N		Y	Y	Y	Y	
09/19/1999	Y	Y	N	Y	Y	N		Y	Y	Y	Y	
10/09/1999	Y	Y	N	Y	Y	N		Y	Y	Y	Y	
06/20/1998	Y	Y	Y	Y	Y	N		N	N	N	Y	Y
07/20/1998	Y	Y	N	[3]	Y	N		N	N	N	Y	
08/16/1998	Y	Y	Y	Y	Y	N		N	N	N	Y	
10/03/1998	Y	Y	Y	N	Y	N		N	N	N	Y	
06/30/1997	Y	Y	Y	[4]	Y	N		N	Y	N	Y	
09/13/1997	Y	Y[5]	Y	[4]	Y	N		N	Y	N	Y	
09/06/1996	Y	Y	Y	N[6]	Y	Y		Y	Y	N	Y	
10/15/1995	Y	Y	Y	N/A	N/A	N		N	N	N	N	

N/A measurement was not collected during that particular sampling event
[1] Klovdahl Bay
[2] cannot interpret depths, not a useable profile
[3] only to 10 m, not useable profile
[4] incomplete, only to 7 meters
[5] missing conductivity
[6] conditions indicate it should have been used, but it was not

Current Work

Work conducted in 2003 was designed to build on historical work on Waldo Lake and to set a foundation for a more hypothesis-based Waldo Lake Limnology Program that will lead to more complete understanding of the physical and ecological processes that regulate lake trophic status. More specifically the objectives were to:

- conduct science inquiries to better understand the lake dynamics and ecology;
- collect and analyze field data to support the science inquiries, including reviewing and analyzing historical data in the same context with current data; and
- allow science-based management of Waldo Lake through application of analytical and computational models.

During the initial year of the Waldo Lake Limnology Program historical data was consolidated and reviewed for quality, lake basin bathymetry was mapped, studies of the hydrology of the basin and control of phytoplankton productivity were initiated, and modeling options were examined. The first year's work resulted in a number of recommendations for additional work that are discussed below.

Bathymetry

Introduction

Basin morphometry determines water retention time and mixing characteristics of lakes; two characteristics that are fundamental to lake ecosystem function, and key to accurate modeling of physical, chemical, and biological responses to management activities. Waldo Lake bathymetry was measured by the Oregon Department of Fish and Wildlife in 1958 (Johnson et al., 1985, Table 2.1). Modern GPS and depth sounding technologies can produce more accurate maps than were previously possible. As an example, volume estimates generated with modern equipment in several other Oregon lakes were up to 14 percent different and averaged 4 percent different than volume estimates created using traditional methods (Johnson et al., 1985).

Methods and Analysis

Method overview

Depth and location data collected using GPS and Sonar combined with digital elevation models data were used to interpolate a model of Waldo Lake's morphometry.

Navigational transect setup

East-west oriented transects spaced 100 meters apart were created using Arc View 3.2 GIS. Locations at which transects intersected the lake's outline were converted into latitude and longitude points and were uploaded onto an Alto G12 GPS receiver to serve as waypoints for navigation. The lake outline was obtained from the Willamette National Forest's GIS spatial data library and was compared against USGS black and white digital ortho-quadrangle photographs (DOQ's) of Waldo Mountain and Waldo Lake USGS quads (image source date 8/29/1994). The lake outline was corrected to match the DOQ's when necessary.

Data collection

Data were gathered along the transects in August and September of 2003 using a Biosonics Inc. DE4000 Series digital scientific echo sounder paired with an Alto G12 differential GPS receiver (Corvallis Microtechnologies). The GPS receiver was corrected using the Coast Guard beacon to provide real-time horizontal positional accuracy of plus or minus 100 cm. Locations were recorded once every three seconds at a boat speed of less than eight km/hr to provide a maximum of seven meters between sample points along the transects (Figure 8). Simultaneous echo soundings were recorded at a threshold of -40dB. Visual Acquisition software from Biosonics Inc. was used to integrate the data.

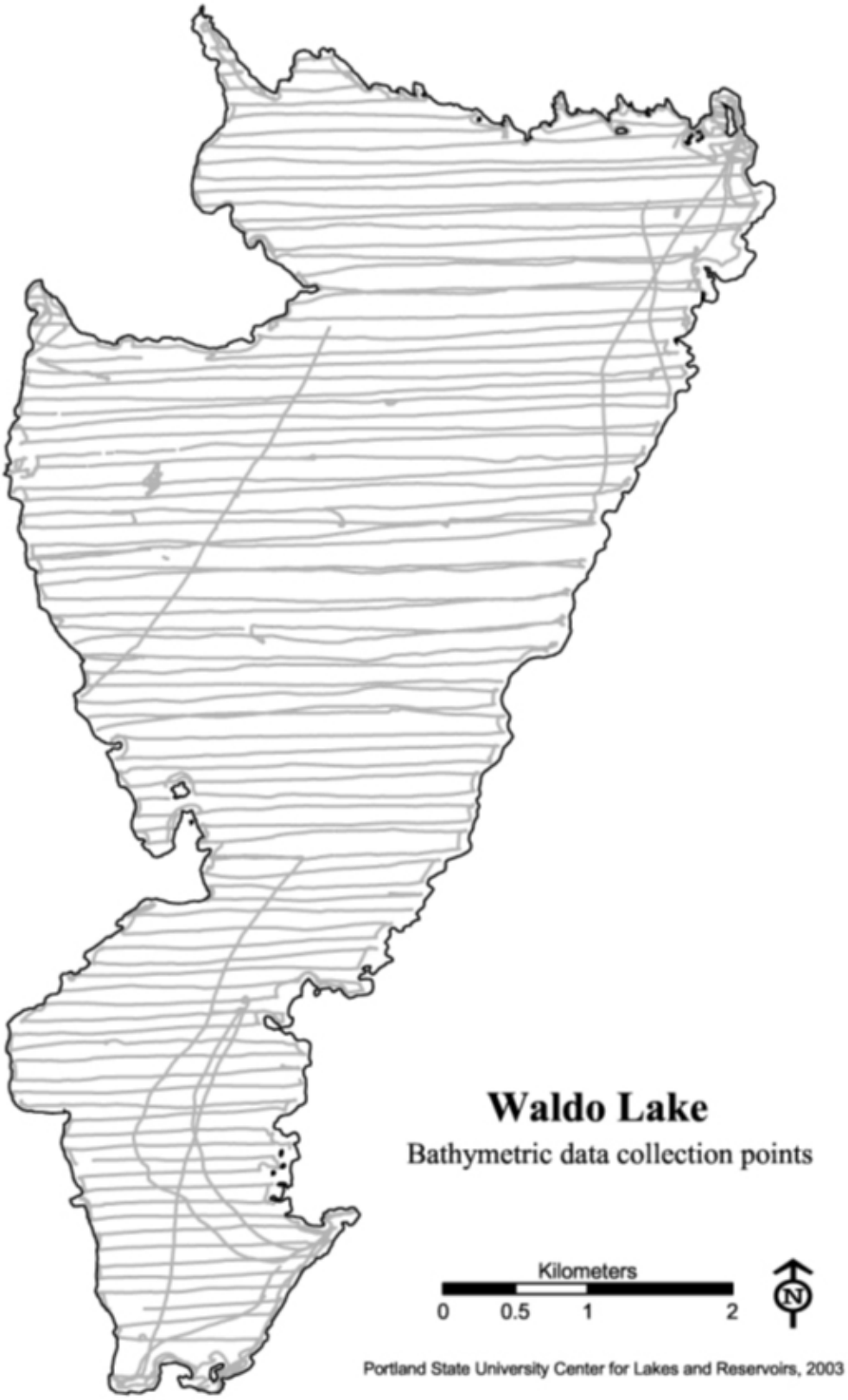


Figure 8: Bathymetric data collection cruise paths followed at Waldo Lake during the summer of 2003.

Bottom tracking

Biosonics Inc.'s Analyzer software was used to determine depth from the echo sounding data. A 30dB threshold was used for determining the sediment interface. The bottom generated was examined for inconsistencies and edited when necessary. Database files were created that included latitude, longitude, and depth.

Conversion of depth to elevation

Two assumptions were required to convert depth data to elevations since the benchmark used to measure water level changes during data collection has not been surveyed. First, a 10-meter resolution USGS digital elevation models (DEM's) of the lake was obtained. The lake surface elevation is 1,650 meters in the vertical datum of NGVD29. The fly-over that generated the elevation was done in 1981; however, no more specific date was available. The flight was assumed to be in early July. The second assumption was that the rate of water level drop from early July through the summer of 2003 was similar to other years in which the Forest Service collected water surface elevation data from the same benchmark. After the benchmark is surveyed, the bathymetric data can be corrected. To extend volume/elevation relationships to higher water surface elevations than those encountered at the time of bathymetric data collection, DEM data from a 200-m buffer surrounding the lake were added to the bathymetric data.

Surface interpolation and elevation curve

Three-dimensional surfaces were interpolated from the bathymetric and DEM data using ArcGIS Geostatistical Analyst. Kriging and radial basis functions (RBF) were explored for interpolation were to determine the method that provides the best surface estimation. RBF was chosen since the surface it generated passed through nearly all sample points while Kriging smoothed the surface so some sample points were above and below the surface. Surfer was used to generate the volume elevation curve.

Since the water surface elevation benchmark site has not been surveyed, bathymetric maps and a volume elevation curve are preliminary. Final maps and elevation curve can be created after the benchmark site is surveyed.

Results

The preliminary bathymetric map (Figure 9), volume development curve (Figure 10), and morphometric parameters (Table 2) estimated using the new data were similar to results of the Oregon Department of Fish and Wildlife 1958 study of the lake (Johnsen et al., 1985). Based on the bathymetric data and light data collected during 2003, 63 percent of the lake sediment area and 82 percent of the lake volume are in the euphotic zone (exposed to greater than one percent of surface irradiance). The depth of the euphotic zone during 2003 averaged 49 m.

Table 2: Comparison of bathymetric data collected in 2003 with data collected by the Oregon Department of Fish and Wildlife in 1958.

Statistics	PSU-CLR 2003	ODFW 1958	Percentage difference from 1958 data
Water surface elevation (m)	1650	1650	0
Volume (cubic hectometers)	953.67	970.86	-1.8
Maximum depth (m)	128	128	0
Surface area (km^2)	24.63	25.49	-3.4
Mean Depth (m)	39	38	+1

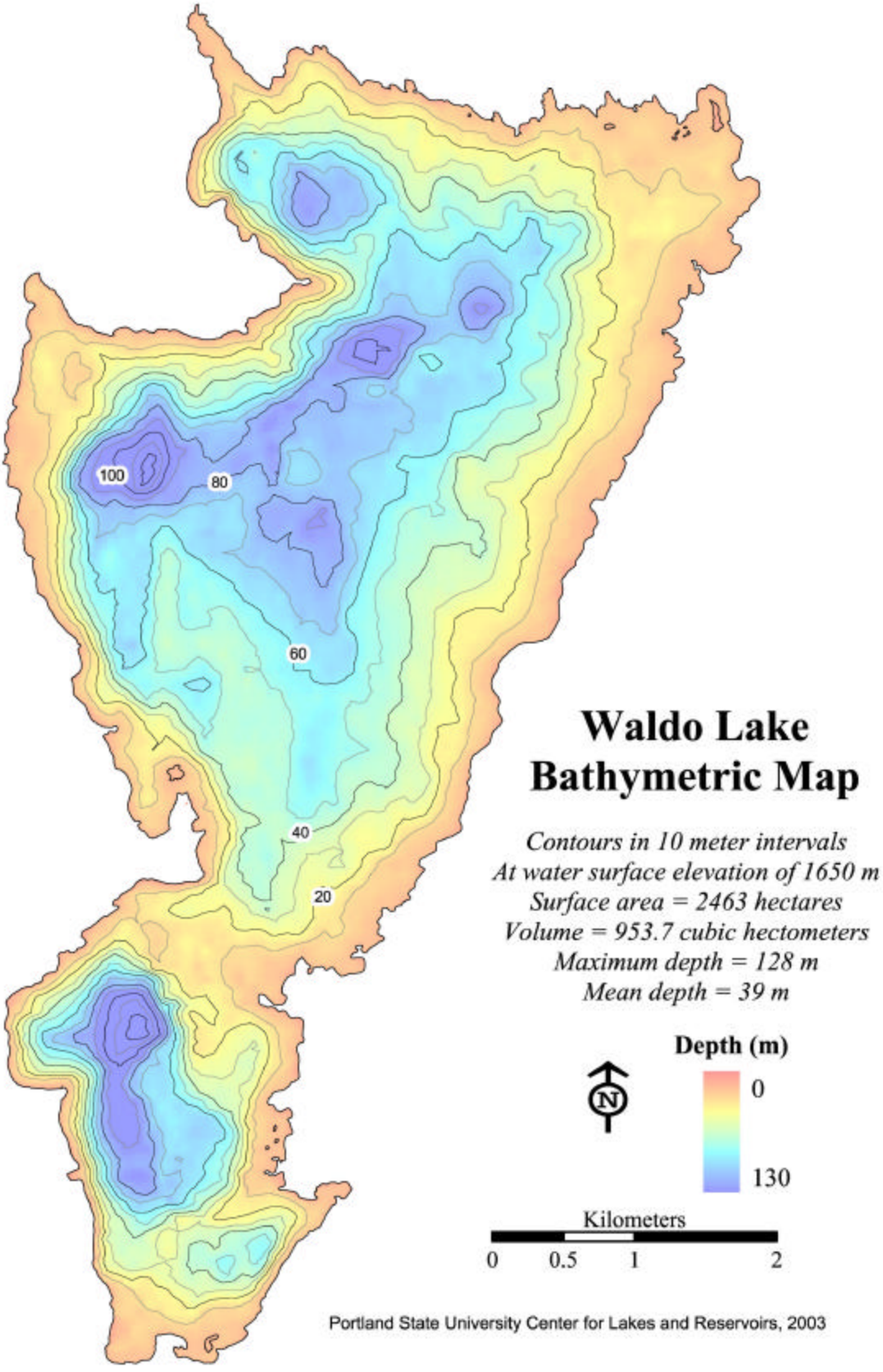
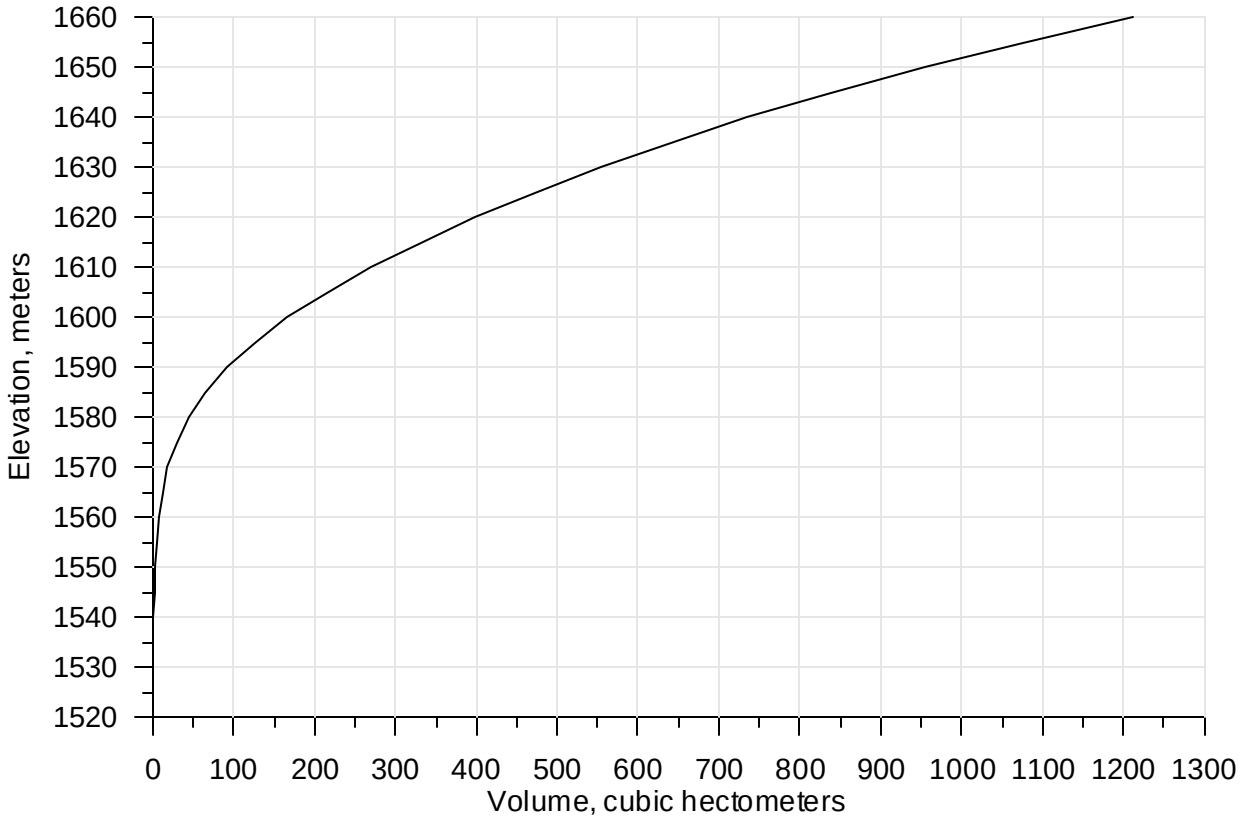


Figure 9: Waldo Lake bathymetric map interpolated from data collected during the summer of 2003.



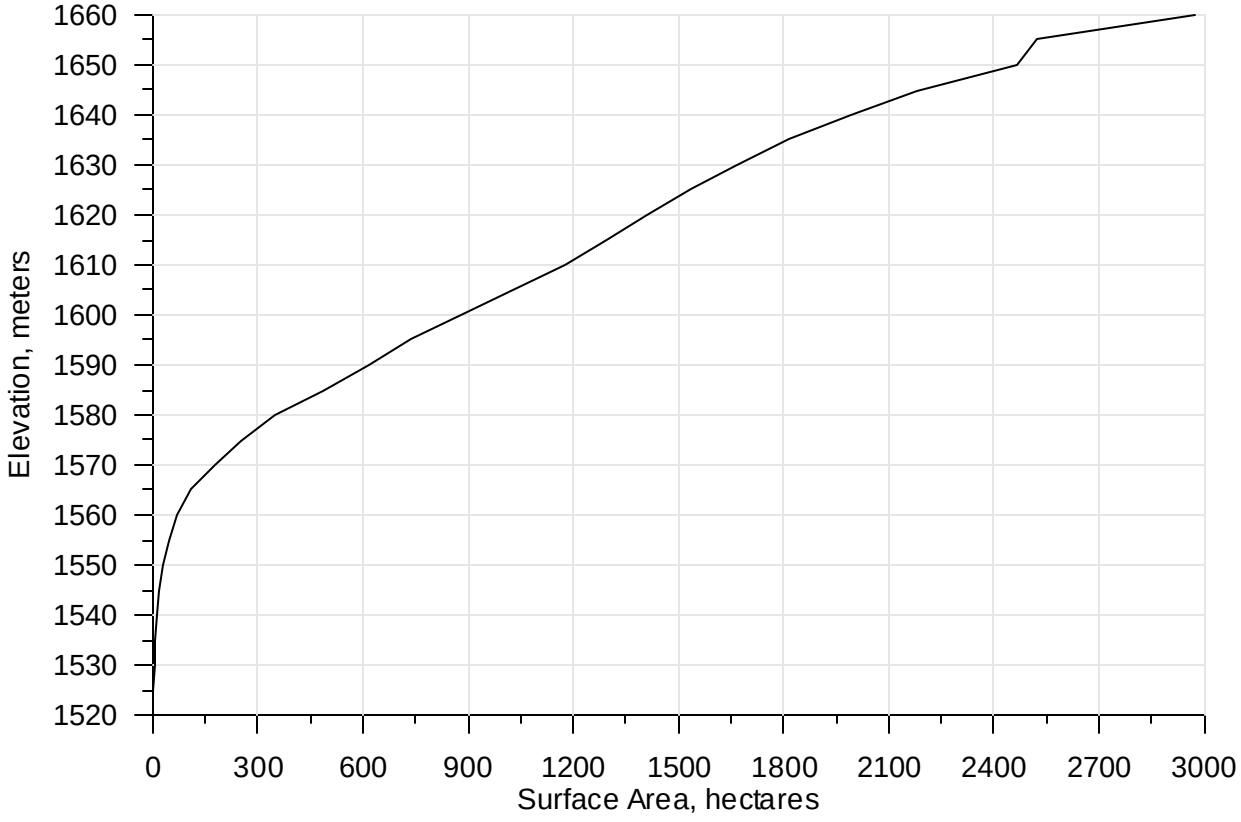


Figure 10: Waldo Lake volume-elevation and surface area-elevation curves.

Conclusions and Recommendations

Proper surveying of the Islet Campground benchmark site is necessary to complete the bathymetric analysis. The surveyed benchmark will establish the correct lake volume over elevation which will influence any water budget analyses. In the current status, the newly generated surface and volume-elevation curve will be extremely valuable for the development of water and nutrient budget and for developing a water quality model. The data will also be very important for determining the relative importance of benthic and pelagic organisms to production in the lake.

This bathymetric analysis can be enhanced with a minimal amount of work during the summer of 2004. 2003 sonar data can be reanalyzed with Biosonics Inc.'s Bottom Typing software to produce a map of substrate type as well as a map of the well-developed mats of liverworts and mosses living in the deeper sections of the lake. This analysis would require the collection of a small number of sediment and benthic mat samples to ground-truth software inferences.

Climate and Hydrology

Introduction

The objective of evaluating the climate and hydrology of Waldo Lake is to provide a context for the other analyses undertaken as part of the study. The quantity and quality of water flowing into the lake and the variation within the year and from one year to the next are determined by the variability of the climate and the physical setting and characteristics of the watershed.

Some general observations can be made based on the setting of Waldo Lake and its watershed. The lake and its watershed are located on the west slope of the Cascade Range near the crest as shown previously in Figure 1. Elevations range from about 5400 ft (1646m) at the surface of the lake to a maximum of 7280 ft (2219m) at the crest of Cascades. The area of watershed is 30.5 sq. mi. (7899 hectares) and the area of the lake is about 9.5 sq. mi. (2460 hectares), so that the surface of the lake is nearly one-third of the entire watershed area. The large area of the lake relative to the watershed suggests that direct precipitation onto the lake and evaporation from the lake surface are important to the water balance of the watershed. The location of the watershed near the crest of the Cascades also means that snow accumulation and melt play a key role in the hydrologic input to the lake. The soils consist of porous pumice and ash that is rapidly to excessively drained, at least in the upper layers and the watershed is, for the most part, forested. These factors combined with an absence of surface drainage features suggest that the flow pathways within the watershed to the lake are in the subsurface. The presence of a significant snowpack and the likelihood of subsurface flow pathways suggest that the inflow to the lake in response to precipitation events on the watershed will be relatively slow and that any response of the lake to storms will be primarily due to direct precipitation. The lake will respond to annual fluctuations in moisture as combination of direct precipitation onto the lake's surface and subsurface inputs from the watershed. These propositions are the basis for the subsequent analysis of historic variations in the climate and resulting streamflow.

Data

Historic data on climate and streamflow exist in the vicinity of the Waldo Lake watershed but data within the watershed are limited. Figure 11 shows the locations where data are available in and around the watershed and Table 3 is a listing of the locations where data are collected including the type of data that are available, the period of record and any qualifications on the quality of the data. Specifically, there are data on precipitation, temperature, snow water equivalent (SWE) and streamflow. Within the watershed, data are only available on SWE at the Waldo Lake Snow Course (discontinued in 1978) and streamflow at the outlet of the lake, discontinued in 1984.

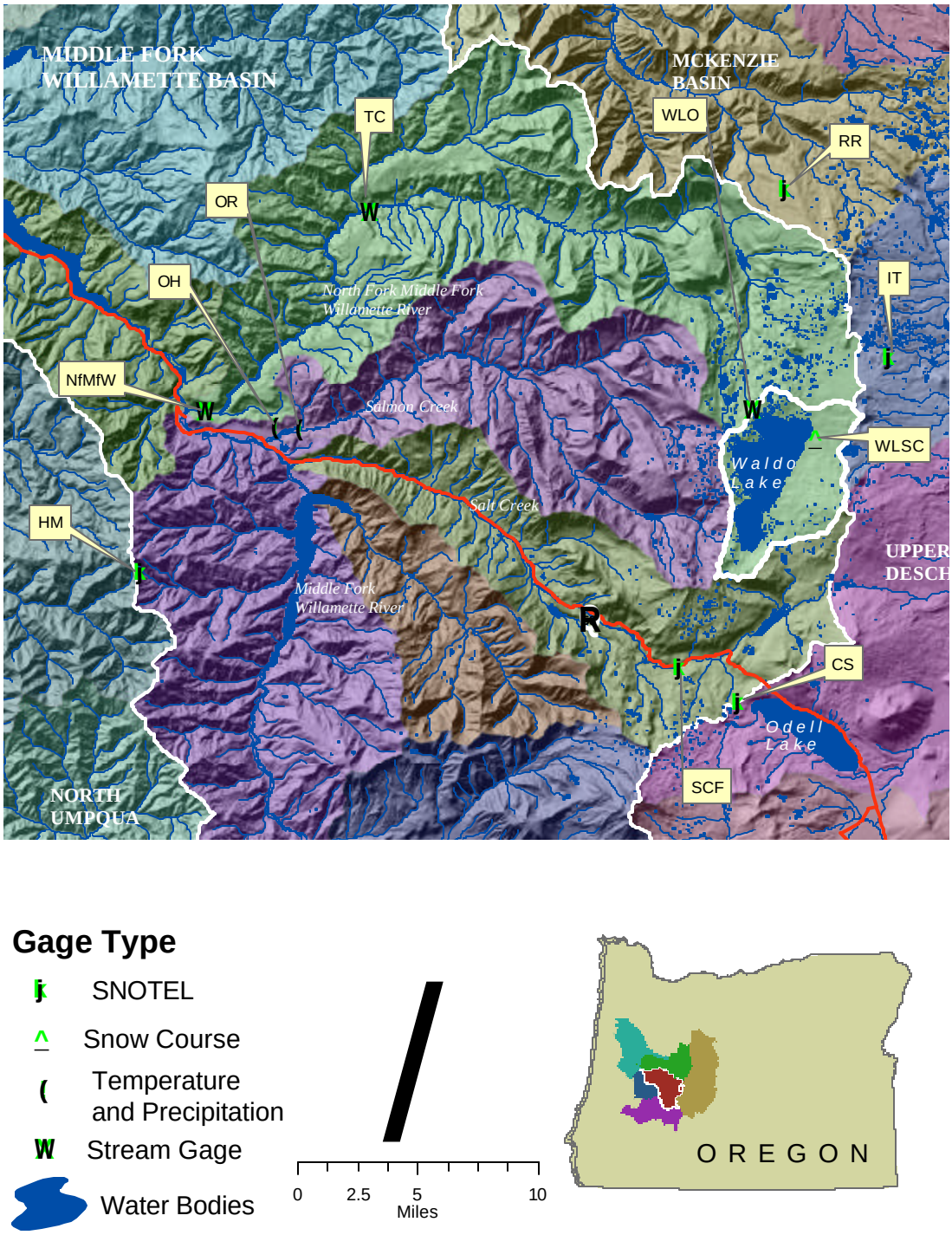


Figure 11: Waldo Lake and the surrounding area showing the locations where climate and stream flow data are available.

The precipitation and temperature data are available from two sources: the National Weather Service (Oakridge Ranger Station and Fish Hatchery, used as a continuous data set) and at Natural Resources Conservation Service (NRCS) Snotel sites (the other locations in Table 3 with precipitation and temperature data). Snow water equivalent (SWE), the accumulated liquid water in the snowpack, is available at NRCS snow courses (prior to the late 1970's or early 80's) and then at Snotel sites that replaced the snow courses, usually in the same vicinity. In addition to streamflow data at the outlet of

Waldo Lake, data were also collected by the US Geological Survey on the North Fork of the Middle Fork, Willamette River, downstream of Waldo Lake (basin area 246 sq. mi.).

Table 3: Locations where climate and streamflow data are available in and near the Waldo Lake watershed. The type of data (precipitation, snow water equivalent (SWE), temperature and streamflow) is indicated along with the period of record at each location.

Station Name	Precipitation	SWE	Temperature	Streamflow
Railroad Overpass (RO)	1981-03	1950-02	*1993-03	NA
Salt Creek Falls (SCF)	1981-03	*1929-80*, 81-02	*1985-03	NA
Cascade Summit (CS)	1981-03	*1929-80*, 81-02	*1990-03	NA
Irish Taylor (IT)	1979-03	*1939-78*, 79-02	*1990-03	NA
Roaring River (RR)	1982-03	*1929-80*, 81-02	*1990-03	NA
Waldo Lake Snow Course (WLSC)	NA	1938-78	NA	NA
Holland Meadows (HM)	1981-03	*1937-81*, 82-02	*1984-03	NA
Oakridge Ranger Station (OR)	1948-77	NA	1948-77	NA
Oakridge Hatchery (OH)	1977-03	NA	1977-03	NA
North Fork Middle Fork Willamette River (NFMFW) (#14147500)	NA	NA	NA	1909-16, 1936-94
Waldo Lake Outlet (WLO) (#14147000)	NA	NA	NA	1937-53, 69-82, 84
Tumble Creek (TC) (peak flow) (#14147400)	NA	NA	NA	1964-77
Waldo Lake (gage height) (#14146950)	NA	NA	NA	1969-72, 75-79, 81-84

A reasonably long record of precipitation and temperature data was available at the Oakridge site and a consistent spatial set of climate data, in particular precipitation data, was available from the early to late 1980's to the present, mostly at the Snotel sites. However, temperature data at the Snotel sites were not completely reliable. An evaluation of the data revealed a reasonably large number of observations with unrealistic values. This was confirmed by NRCS personnel who speculate that the problem was instrumental error. Since the data have not undergone strict quality control, they were not used in this analysis. Streamflow on the North Fork of the Middle Fork was only available through 1994. Data collection for the outflow from Waldo Lake was discontinued in 1984 but was reactivated during the summer of 2003.

Inter-annual variation of climate and stream flow

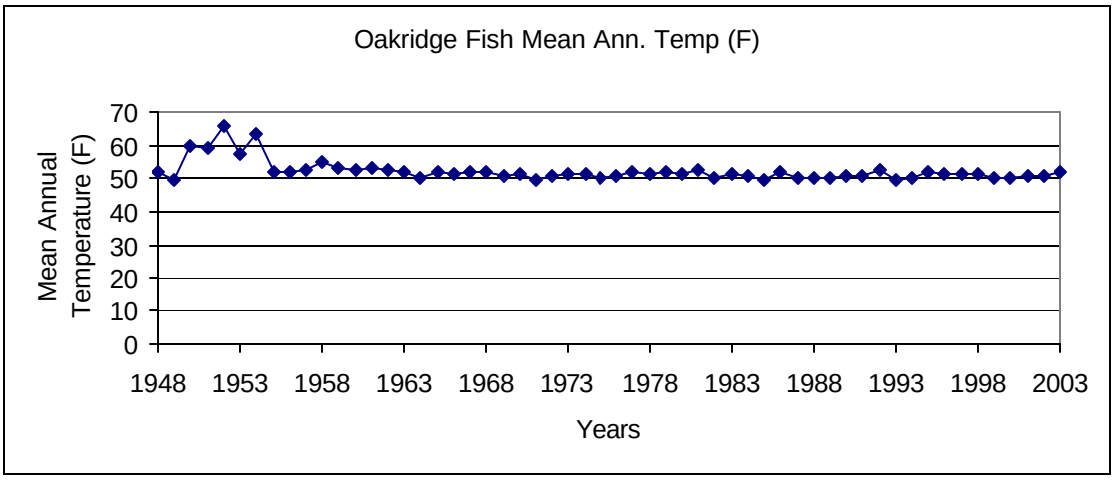
The long term variation of climate and streamflow in the vicinity of Waldo Lake can be inferred from data at two locations in the basin: precipitation and temperature data at the Oakridge Ranger Station and

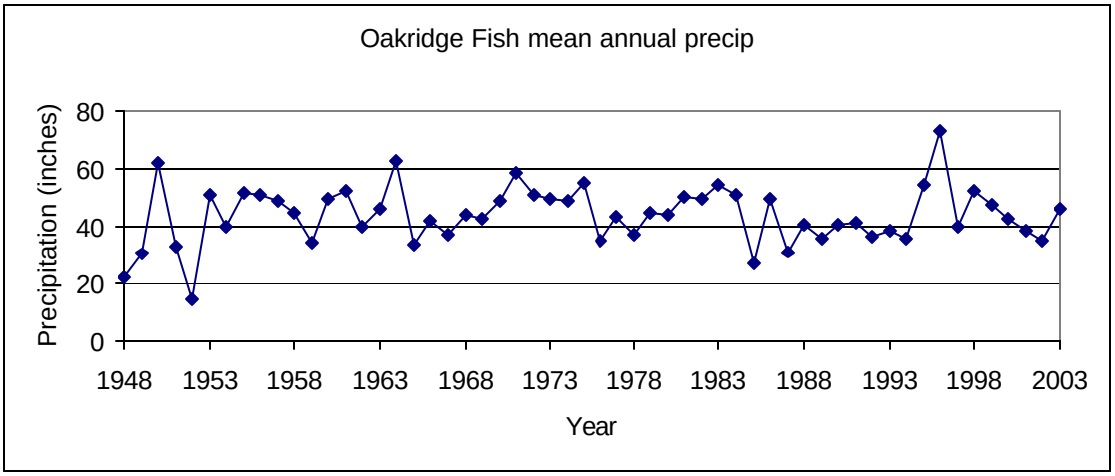
Fish Hatchery and streamflow data for the North Fork of the Middle Fork of the Willamette River. A time series plot of each of these data sets is shown in Figure 12. Of interest is whether there are relationships between the variables, in particular precipitation and streamflow, and whether there are any systematic trends or other temporal structure in the data.

Relationship between climate and stream flow

There was a reasonably strong relationship between precipitation, SWE and streamflow in the vicinity of Waldo Lake, as shown in Figure 13, indicating that inter-annual variation in flow in the river system below Waldo Lake is closely related to inter-annual variation in precipitation. No similar relationship exists between either temperature and precipitation or temperature and streamflow.

Another relationship that is of interest is between the streamflow in the North Fork of the Middle Fork (NFk MFk), Willamette River and the Waldo Lake Outlet. Streamflow data were available at the Waldo Lake Outlet for intermittent periods beginning in 1937 but there was a significant break between 1953 and 1969 and the station was discontinued after 1984. A strong relationship between the two sites would allow the longer, more continuous record for the NFk MFk to be used as an indicator of the Waldo Lake Outflow, at least in terms of evaluating inter-annual variability. A sufficiently strong relationship would also allow the Waldo Lake Outflow to be estimated using the NFk MFk flow. Time series plots of the annual streamflow at these two locations and a scatter plot of the Waldo Lake Outflow as a function of the NFk MFk flow are presented in Figure 14. Streamflow at the two sites was strongly related with the NFk MFk streamflow explaining over 92% of the variability in the streamflow at the Waldo Lake Outlet. The NFk MFk flow can be used both as an indicator of long term variability and to estimate with reasonable accuracy the Waldo Lake Outflow during those years when no data area available.





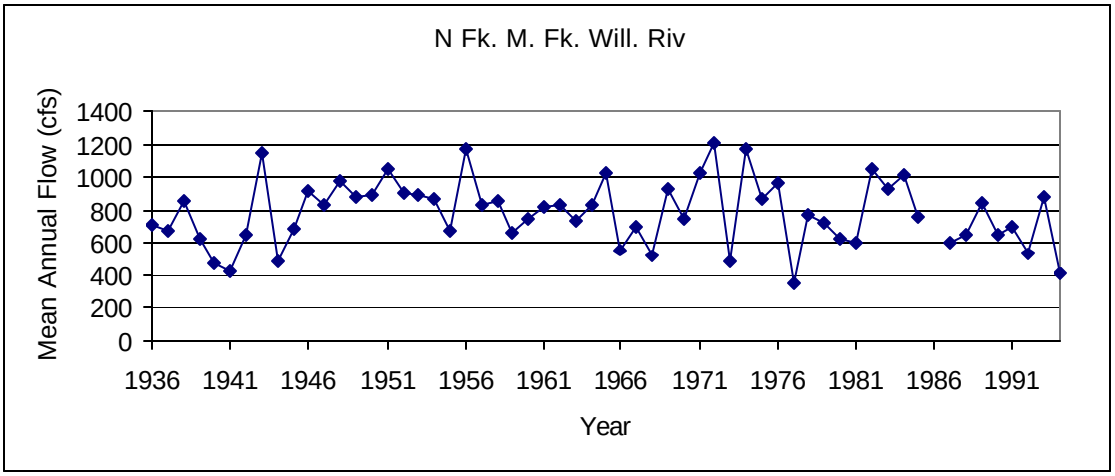
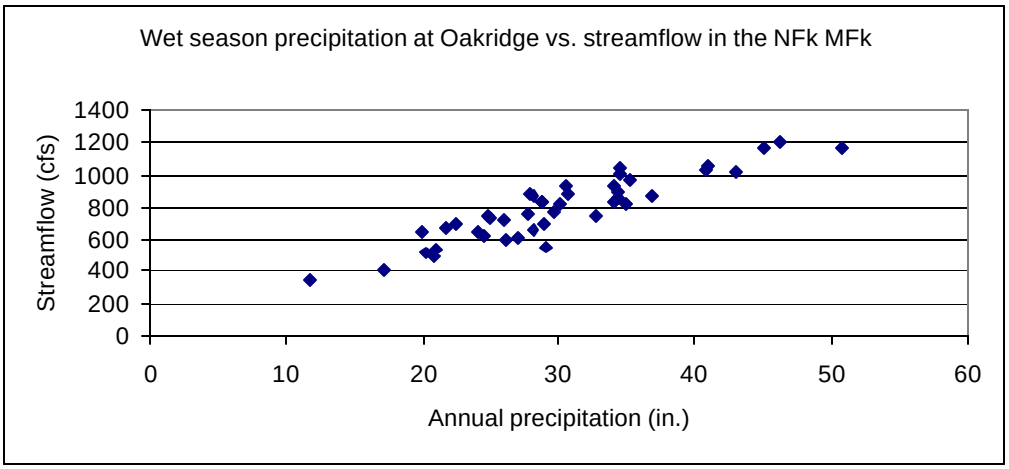


Figure 12: Annual average temperature and annual precipitation at Oak Ridge and annual streamflow for the North Fork of the Middle Fork, Willamette River.



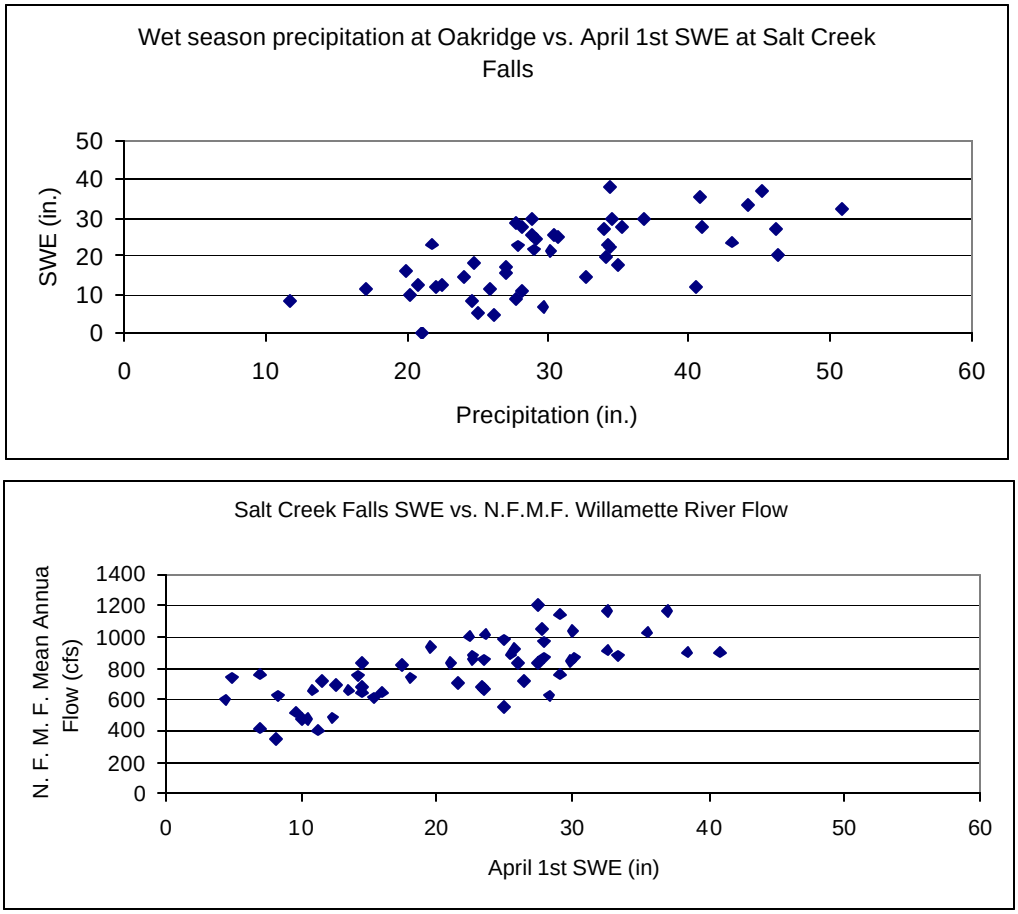
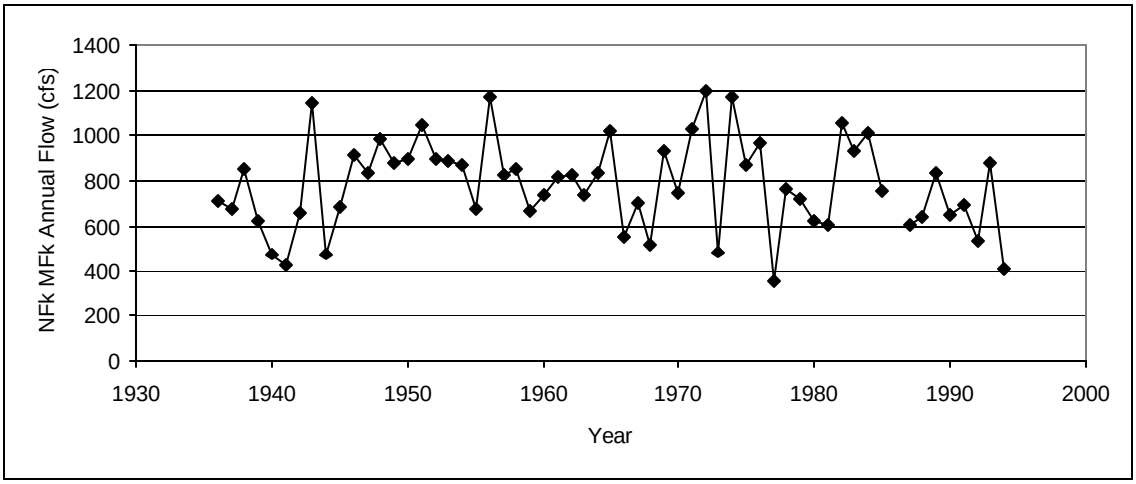


Figure 13: Scatter plot of annual average streamflow for the North Fork of the Middle Fork, Willamette River and SWE at Salt Creek Falls vs. total annual precipitation at Oakridge Fish Hatchery and North Fork of the Middle Fork, Willamette River streamflow vs. SWE at Salt Creek Falls.



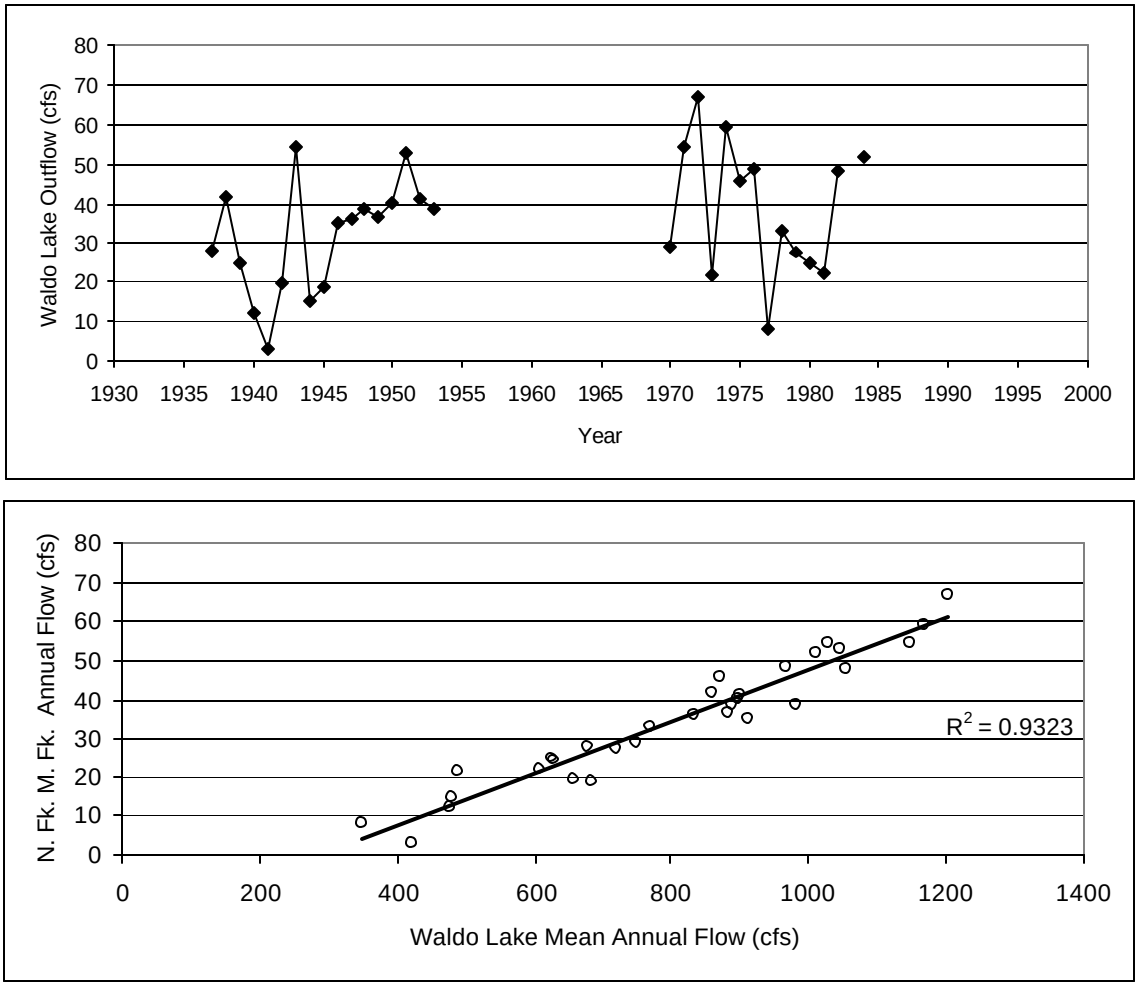


Figure 14: Time series plots and scatter plot showing the relationship between annual streamflow for the North Fork of the Middle Fork, Willamette River and the Waldo Lake Outlet.

Time trends in the data

There were no visibly apparent time trends in either the precipitation or streamflow data although other temporal patterns were investigated in the subsequent section. Time series plots of annual average maximum and minimum temperature and annual average temperature suggested a downward trend in at least maximum temperature was present. Trend tests using a linear regression of annual average maximum as a function of time were conducted on the three temperature time series. The results indicated a statistically significant, decreasing trend in maximum and average temperatures but not in the minimum temperature. The trend in average temperature was less than the trend in the maximum temperature since average temperature was computed as the average of the observed maximum and minimum temperatures. The analysis was further refined to determine if these trends were restricted to a particular season. Similar time trend analyses were conducted on average maximum and minimum temperatures for the Winter period (November through February) and the Summer period (June through September). Statistically significant trends were also observed in the seasonal maximum temperatures. Time series plots of annual, Winter and Summer maximum temperatures are presented in Figure 15. Results of the trend tests on maximum temperatures are show in Table 4.

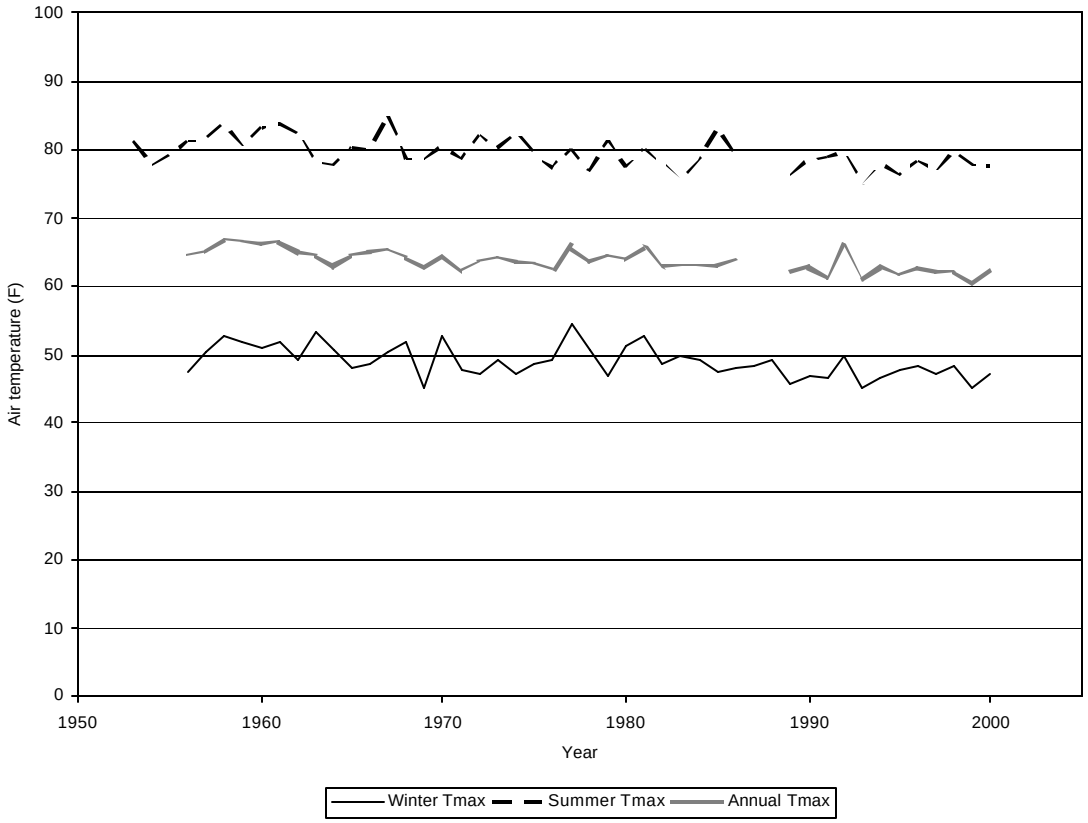


Figure 15: Time series plots of the annual, Winter (Nov-Feb) and Summer (June-Sep) averaged maximum temperature at the Oakridge Fish Hatchery. The apparent downward trend in all three series was confirmed using a linear regression trend test.

Table 4: Results of temperature trend tests for Oak Ridge Fish Hatchery. P values less than 0.05 are considered statistically significant.

Temperature variable	Magnitude of the trend (^{o}F per year)	Statistical significance (p value)
Annual average maximum temperature	-0.12	0.0000
Winter (Nov – Feb) maximum temperature	-0.09	0.0005
Summer (June-Sept) maximum temperature	-0.10	0.0000

Temporal structure in the inter-annual variability

There is a significant body of evidence to indicate that there are patterns of variations within climate and hydrologic data that are only obvious when viewed against the larger context of regional or global scale variations in the climate and oceans. Two significant ocean/atmosphere features related to climate in the Pacific Northwest are the El Niño/Southern Oscillation (ENSO) (Redmond and Koch, 1991), and the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997 and Koch and Fisher, 2002). These variations in sea surface temperature and atmospheric circulation explain a statistically significant portion of the variability in surface climate, in particular precipitation, and streamflow at many locations in the

Western United States. Typically, during El Niño events, precipitation and streamflow in the Pacific Northwest tends to be below average with the opposite occurring during La Niña events. Surface temperature does not appear to vary with ENSO. During cool PDO periods, precipitation and streamflow are above average while the opposite occurs during warm periods. Temperature may also vary with PDO. In addition, the relationship between precipitation or streamflow and ENSO has been shown to vary with the PDO period (Koch and Fisher, 2002).

For Waldo Lake, surface climate and streamflow were related to PDO in a manner that was consistent with other locations in the Pacific Northwest as shown in Figure 16. Both precipitation and streamflow have statistically significantly higher values during the cool phase of the PDO and lower values during the warm phase. In addition, summer maximum temperatures have been higher during the cool phase of the PDO than during the warm phase. The difference in maximum temperature during the PDO periods is a likely explanation for the decreasing trend in maximum temperature noted previously. Finally, to put the temperature effects in some context, Figure 17 shows the time series of maximum summer temperature along with the average maximum temperature for each of the PDO periods and the primary productivity data gather historically for Waldo Lake (Larson, 2000). The higher primary productivity observations all occurred during a period of generally lower temperatures and lower precipitation (Figure 16).

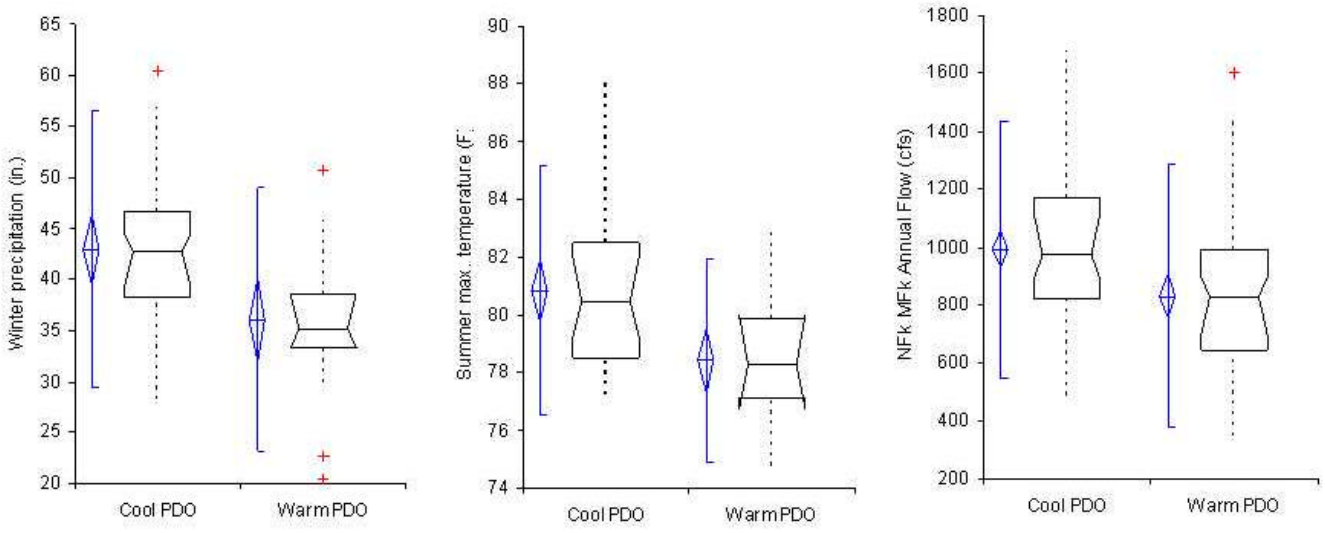


Figure 16: Variation of winter precipitation, summer maximum temperature and annual streamflow with the phase of the PDO. In each case there is a statistically significant difference in the two samples (a=0.05).

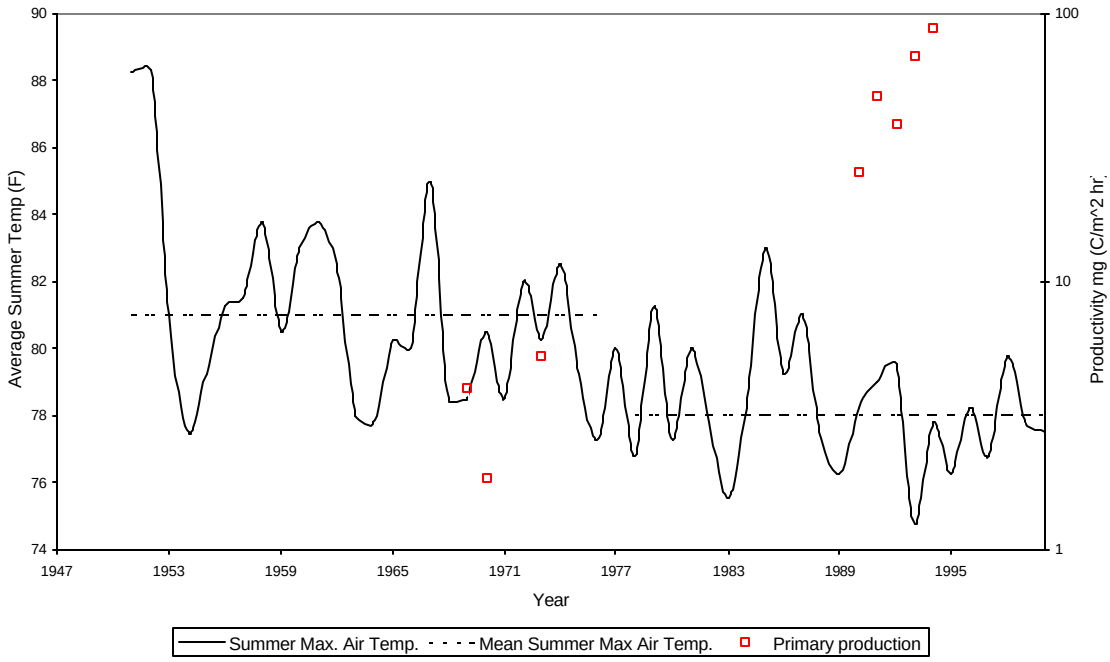
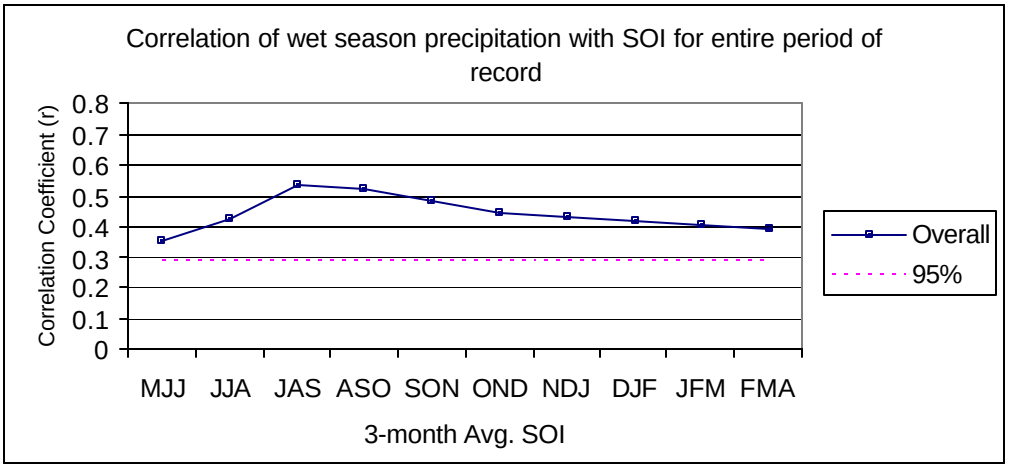
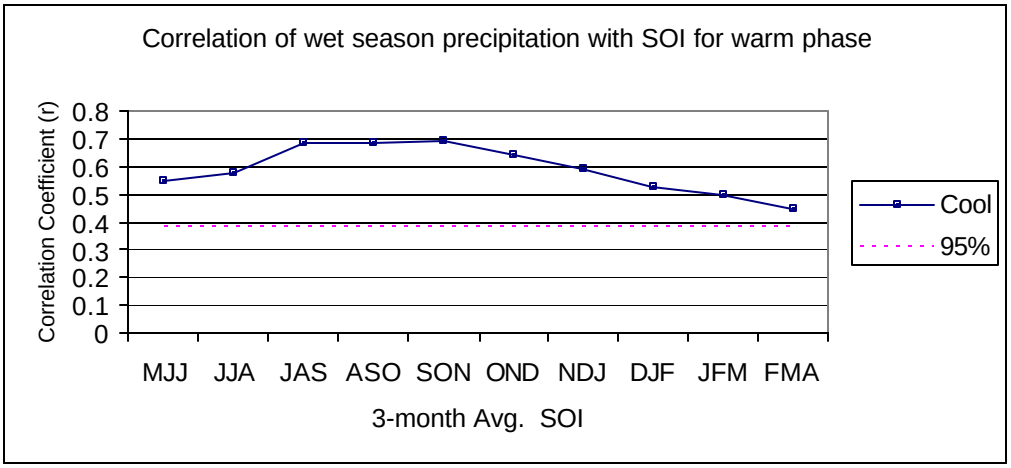


Figure 17: Time series of summer (June-Sep) maximum temperature, average summer maximum temperature for the two PDO periods (cool between 1947 and 76 and warm between 1977and 1994). Also shown are the primary productivity measurements presented by Larson (2000).

To examine the relationship of surface climate and streamflow to ENSO and how that relationship is affected by the PDO, wet season precipitation (November through March) and streamflow (November through May) were correlated with the three month averaged value of the Southern Oscillation Index (SOI), a measure of the strength of the ENSO. Using the entire data set, the correlations with precipitation were reasonably strong with a maximum value of 0.56 occurring when the SOI, averaged over the previous July-August-September (JAS) period, was correlated with the subsequent wet season precipitation (Figure 18). Similar results were observed for streamflow using all of the years of data (Figure 19). A maximum correlation coefficient of 0.52 was observed between the JAS averaged SOI and wet season streamflow. This indicates that both precipitation and streamflow were above average when the SOI was positive (La Niña) and below average when the SOI was negative (El Niño).

However, the phase of the PDO affects the relationship of surface climate and streamflow to ENSO. The PDO is an index of a large scale feature of sea surface temperature in the North Pacific Ocean exemplified by cool water near the coast of the Pacific Northwest and a large pool of warmer water in the North Pacific (the cool phase) or the opposite (the warm phase). These patterns are persistent over decades and Mantua et al (1997) have identified four distinct periods during the last century. During the period before 1925 and between 1947 and 1977, the PDO was in the cool phase while during the periods between 1925 and 1947 and after 1977 (possibly ending in 1995) the PDO was in the warm phase. During the cool phase of the PDO, the effects of the ENSO are amplified in the Pacific Northwest while during the warm phase, they are suppressed. This is indicated in Figure 18 and Figure 19 where the correlations with SOI were stronger during the cool phase of the PDO (0.66 for wet season precipitation and 0.61 for winter streamflow) but were not statistically different from zero during the warm phase.





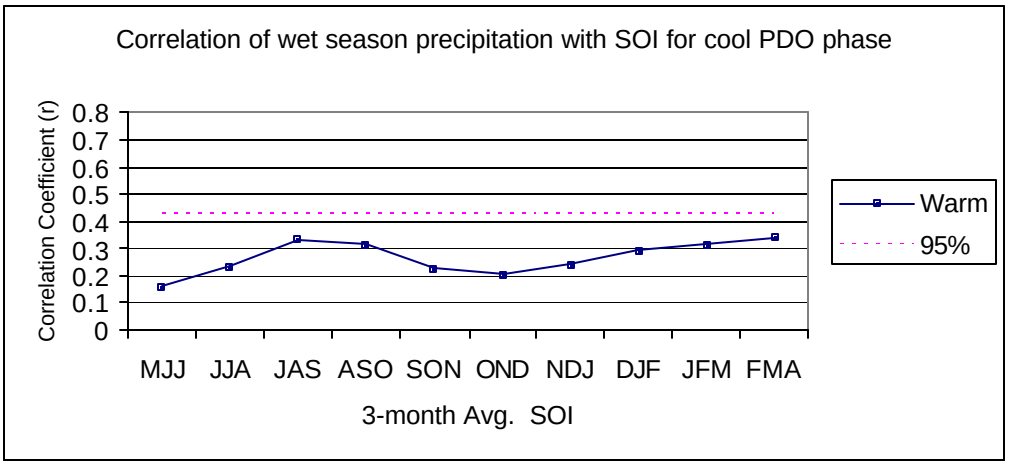
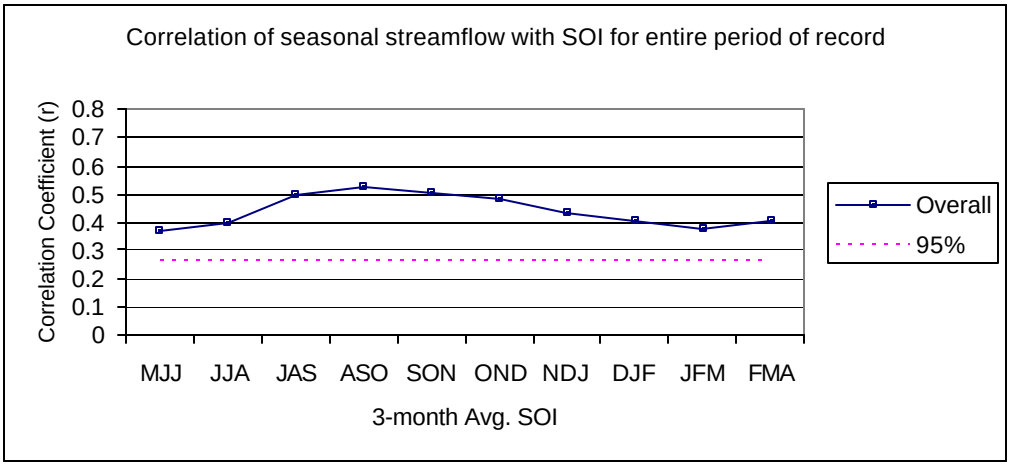
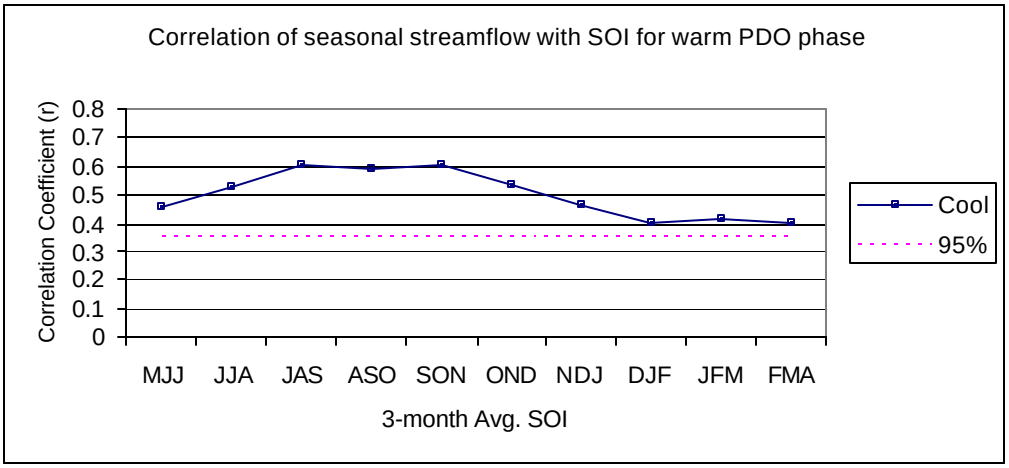


Figure 18: Correlation of wet season precipitation (November through March) at Oakridge with the Southern Oscillation Index (SOI) for consecutive and overlapping three month periods (e.g. MJJ is the averaged SOI value for the previous May, June and July). The upper panel shows correlation using the entire period of record while the middle and lower panels show the correlations during cool and warm PDO phases, respectively.





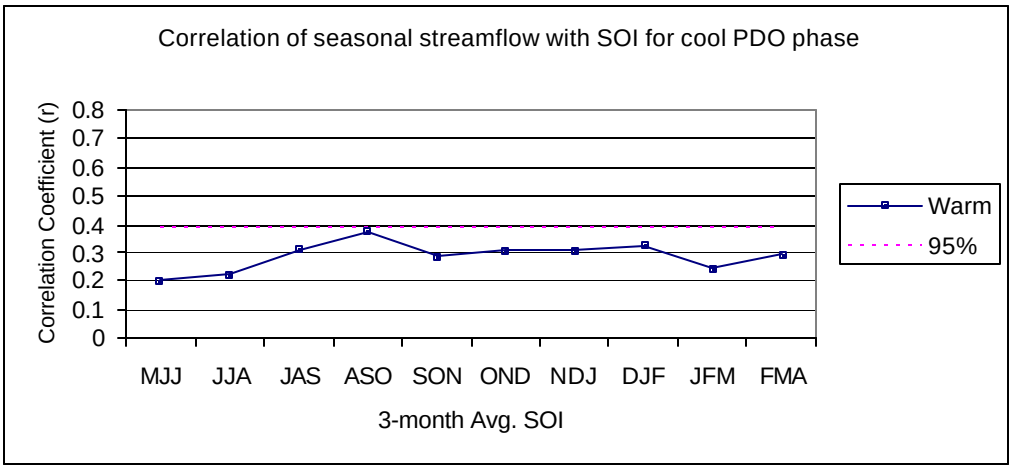


Figure 19: Correlation of wet season streamflow (November through May) at Oakridge with the Southern Oscillation Index (SOI) for consecutive and overlapping three month periods (e.g. MJJ is the averaged SOI value for the previous May, June and July). The upper panel shows the correlation using the entire period of record while the middle and lower panels show the correlations during cool and warm PDO phases, respectively.

Seasonal variation of climate and stream flow

Variation of climate and streamflow within the year is important to the dynamics of Waldo Lake and the associated aquatic ecosystem. Temperature follows the typical northern hemisphere cycle with

minimum values observed in the winter (December in this case) and maximum values in the summer (July) as indicated by the box plots in Figure 20. Variability in temperature from year to year was relatively low. Precipitation follows the cycle typical of the Pacific Northwest, as shown in Figure 21, with increasing rainfall amounts through the Fall reaching a maximum in the Winter (January in this case) and decreasing through the Spring to a minimum value in the Summer (July). Variation of precipitation from year to year was highest in the months of high rainfall with a few extreme values noted in November and December.

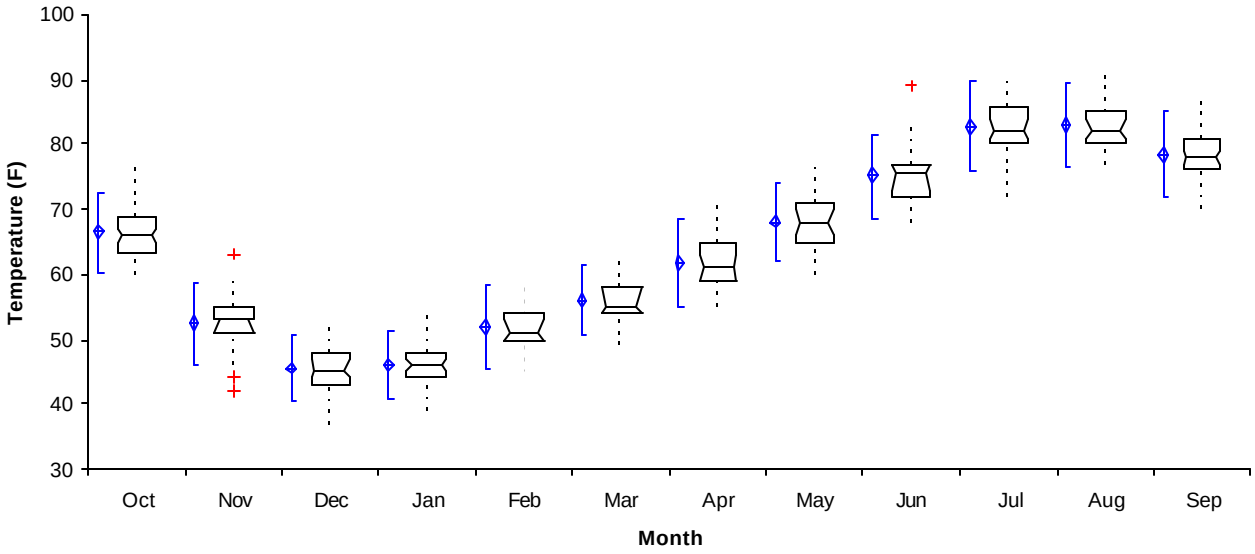


Figure 20: Monthly average temperature (^{0}F) at Oakridge Fish Hatchery, (1977-2003)

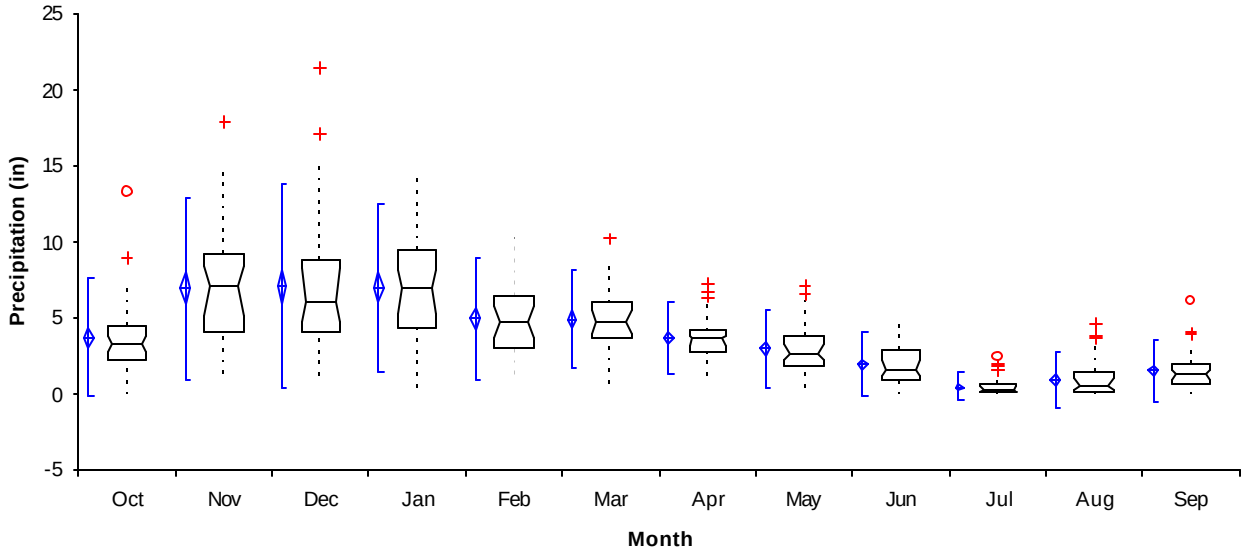


Figure 21: Monthly precipitation (inches) at the Oakridge Fish Hatchery, (1977-2003)

Snow water equivalent (SWE) integrates the accumulation of precipitation with temperature. SWE increases during the wet winter months to the extent that precipitation falls as snow and temperature and other factors do not cause the accumulated snow to melt. The general trend in SWE was similar at two of the Snotel sites (formerly snow courses) near the Waldo Lake watershed: Salt Creek Fall Snotel (elevation 4000 ft, Figure 22) and Irish Taylor Snotel (elevation 5500 feet, Figure 23). The Irish Taylor

site was over the crest of the Cascades in the Deschutes River basin but it correlates very strongly with the discontinued site at Waldo Lake (*r=0.968*) and, because of its long continuous record, was used as an example of a high elevation site. The major differences between the sites were the amount of snow accumulated and the month in which the maximum snow water equivalent was typically achieved. Both are related to elevation since precipitation tends to increase while temperature tends to decrease with elevation. Significantly higher SWE was observed at the Irish Taylor site and was more indicative of the conditions in the Waldo Lake Basin. Further, the maximum SWE was observed to typically occur in May, indicating a later snowmelt and therefore a delayed input of flow into the lake.

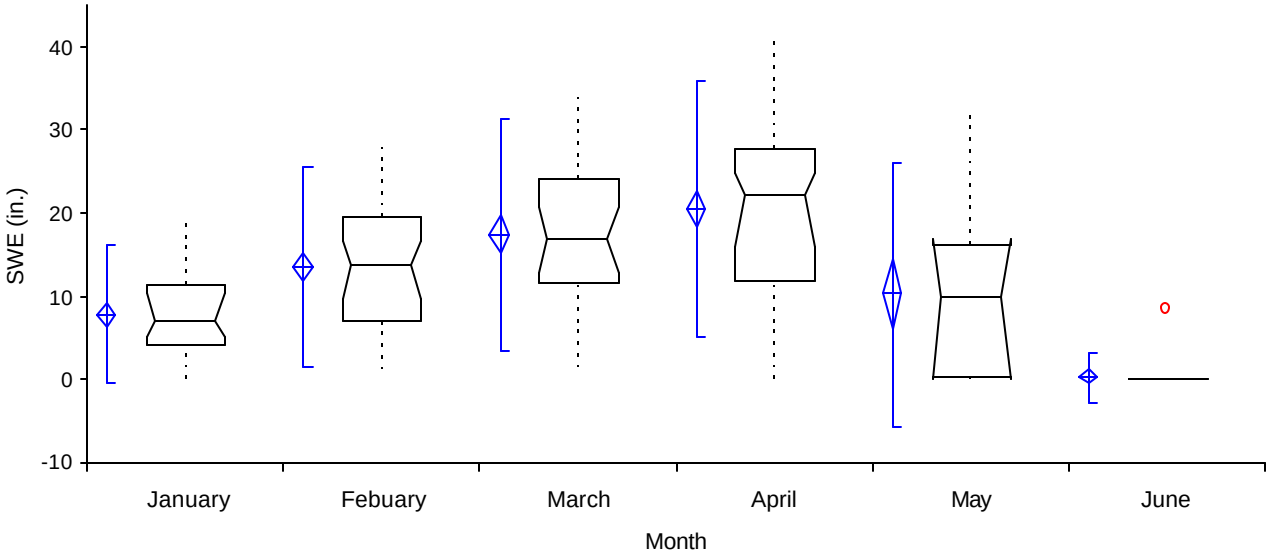


Figure 22: Monthly snow water equivalent (inches) at the Salt Creek Falls Snow Course (1929-1980) and Snotel (1981-present), elevation 4000 ft.

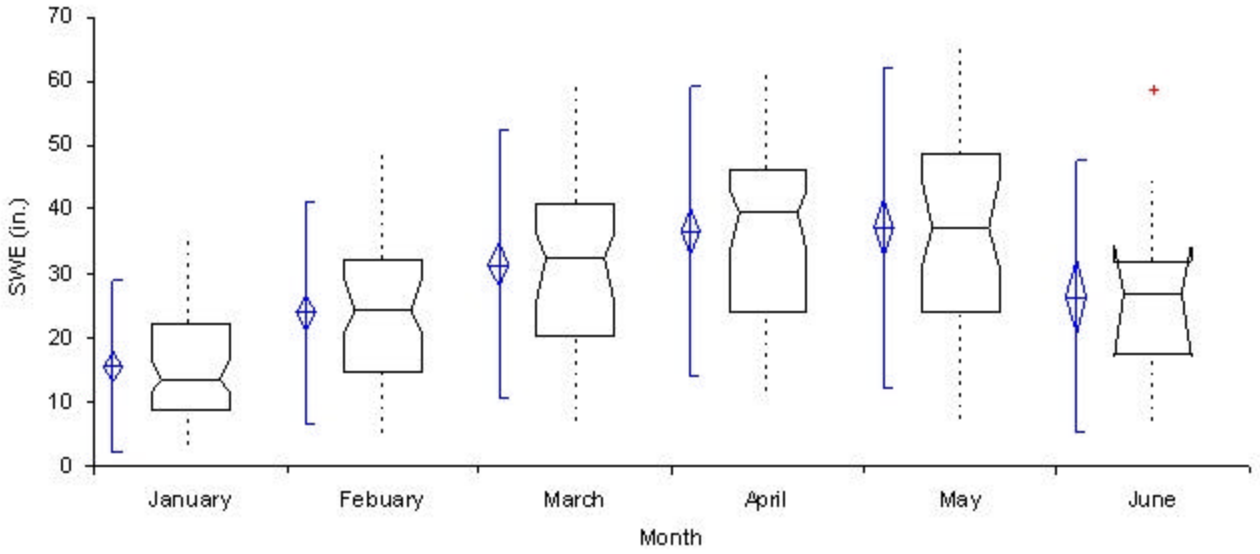


Figure 23: Monthly snow water equivalent (inches) at the Irish Taylor Snow Course (1939-1988) and Snotel (1979-present), elevation 5500 ft.

The annual cycle of precipitation was attenuated by the accumulation and melting of a seasonal snowpack to produce streamflow. As shown in Figure 24, the median flow in the NFk MFk, increases

during the Fall maintaining a high flow through out the Winter and Spring with a slight increase in flow in April as a result of the snowmelt. Extreme high flow events occurred in December and March. The seasonal pattern at the outlet of Waldo Lake, shown in Figure 25, was similar but the high flows were attenuated even longer, most likely due to a combination of a later snow melt due to the higher average elevation of the watershed and the storage effects of the lake. The extreme event during this shorter period of record was observed to occur in March.

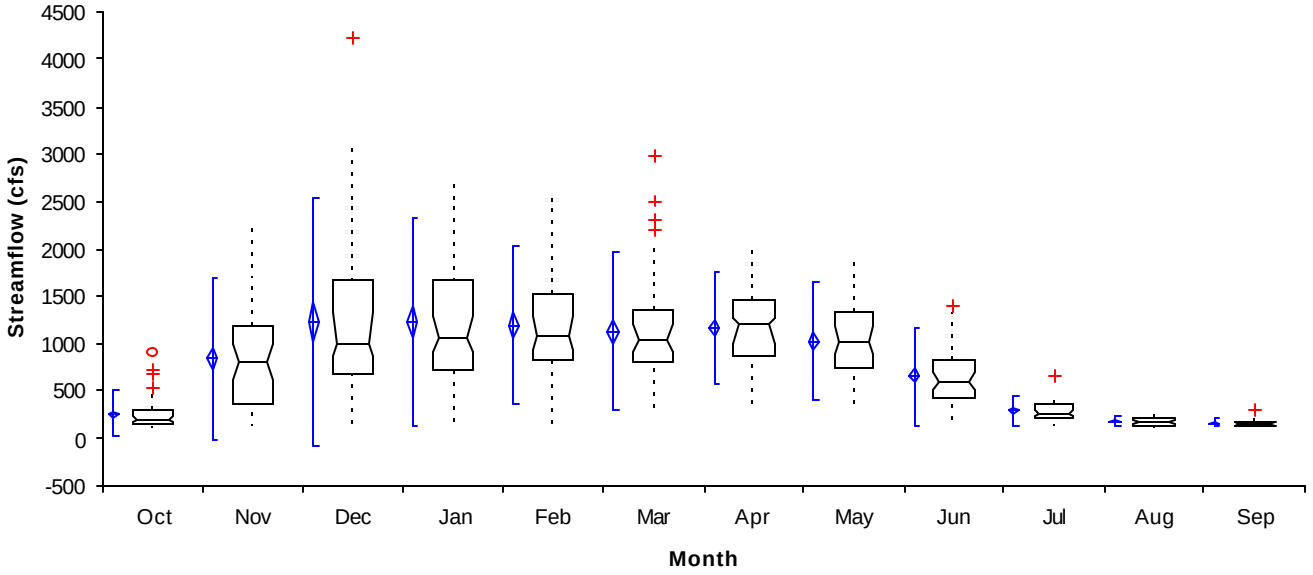


Figure 24: Monthly streamflow (cfs) for the North Fork or the Middle Fork, Willamette .River

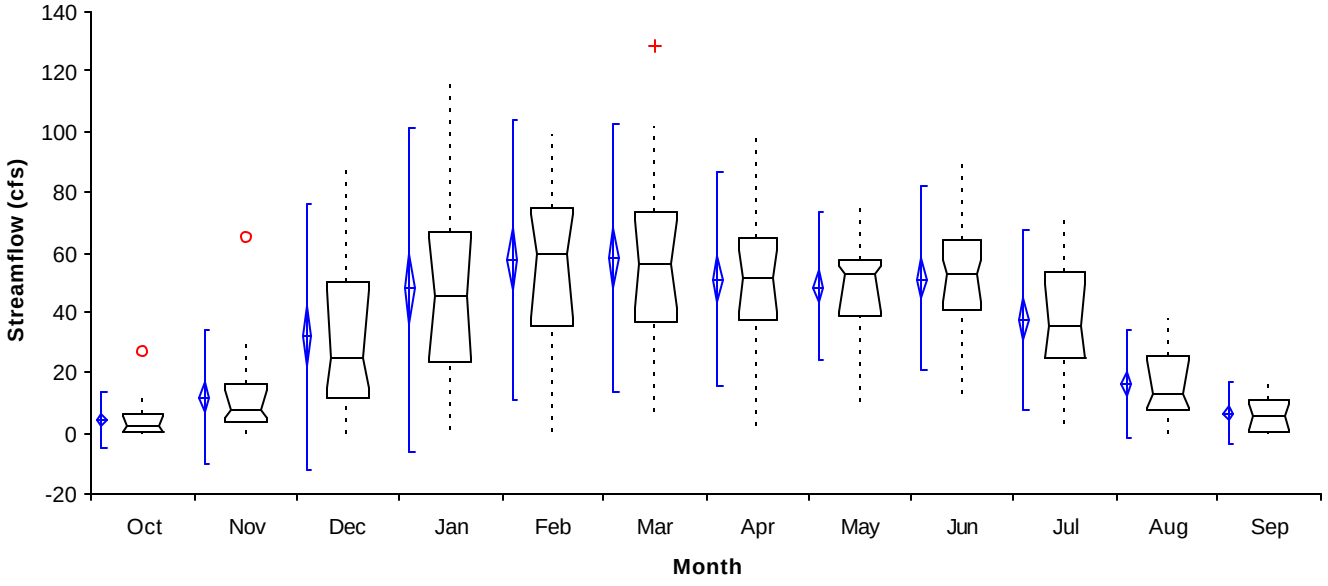


Figure 25: Monthly streamflow (cfs) at the Waldo Lake Outlet

Long term water balance of the Waldo Lake Watershed

To integrate the climate and hydrologic data that exist for the basin, a preliminary examination of the water balance for Waldo Lake was undertaken. Only the historic data on precipitation and streamflow were used in the evaluation. The watershed water balance accounts for the inputs, outputs and storage of water in the watershed and can be written in an aggregated form as:

$$\Delta WS = P - ET - Q_S - Q_G$$

where *?WS* is the change in the amount of water stored in the watershed, *P* is the precipitation onto the watershed, *ET* is water leaving the watershed as a combination of evaporation and transpiration (including direct evaporation from the lake), Q_S is the outflow from the watershed by surface streams and Q_G, is the outflow from the watershed by groundwater that does not appear in the surface streams and is assumed to recharge the regional groundwater aquifers. Depending on the time scale for evaluation, the change in storage term may or may not be included. If a time averaged water balance is applied over a number of years, it is often assumed that the average change in storage is negligible, thus the water balance becomes:

$$P - ET - Q_S - Q_G = 0$$

Since data were only available for precipitation and streamflow, it was not possible to isolate either the ET or the groundwater recharge component. However, it was possible to determine the relative amounts of water that enter the watershed as precipitation, leave as streamflow and, through the simple water balance, the aggregate amount of water that combines to produce ET and recharge. Calculation of the water balance required the outflow from Waldo Lake which had been measured or can be estimated from the NFk MFk gage streamflow data and an estimate of the aggregate precipitation over the watershed. The aggregate or averaged precipitation was estimated based on data at a number of surrounding locations.

Basin-averaged precipitation

The total annual precipitation for the Waldo Lake watershed for any year, or alternatively, the mean areal precipitation (MAP) computed as the total volume of precipitation divided by the watershed area, was estimated using available precipitation data. Most of the proximate locations were Snotel sites at elevations similar to the watershed but had a shorter period of record. As a result, the period over which MAP could be determined was restricted to approximately 1980 to the present.

The data represented a range of elevations and the elevation dependence of precipitation was evident in the data. As a result, the MAP calculation procedure, using ARC-GIS, was devised to account for this behavior as follows:

1. For each year of record, a linear function was fit to the precipitation-elevation data.
2. The deviation from the straight line estimate was computed for each location.
3. The deviation was interpolated over the watershed using the reciprocal distance squared technique.
4. The precipitation at each grid point was computed as the interpolated residual and the precipitation-elevation trend for that year.
5. The precipitation for each grid point was then averaged to determine the average precipitation for the entire watershed.

An example of the interpolated precipitation field is shown in Figure 26. Using this technique, the precipitation field closely follows the topography of the area. Maximum precipitation amounts occur at the highest elevation points to the east of Waldo Lake as indicated by the darker shading in Figure 26.

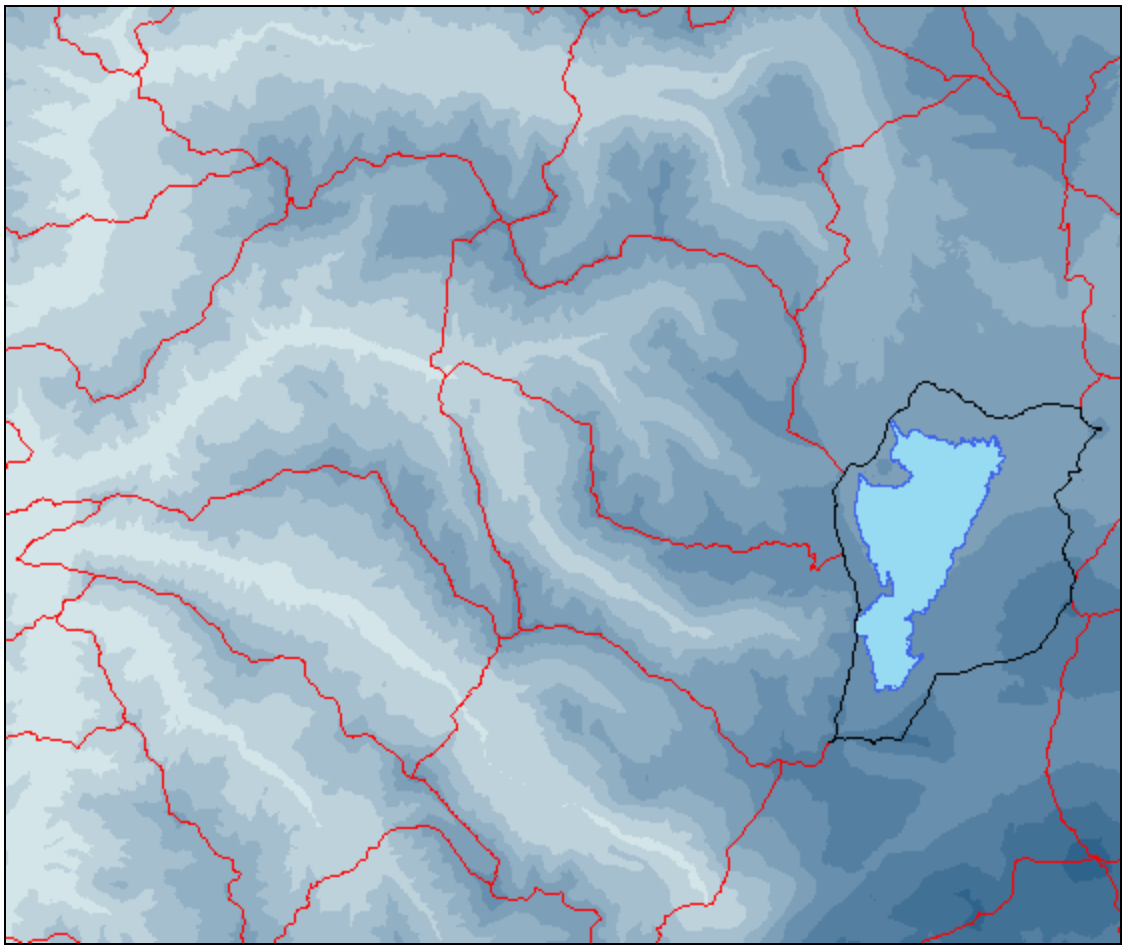


Figure 26: Interpolated precipitation field for water year 2000 for the Waldo Lake watershed and vicinity. Darker shading indicated higher amounts of precipitation. The Waldo Lake watershed is outlined in black. Other drainage basins are outlined in red.

A time series of the estimated MAP for the Waldo Lake watershed is shown in Figure 27 for the period of 1981 to 2002, the time period when precipitation data were available for all of the sites. The maximum annual rainfall during this period is estimated to be approximately 95 inches in 1982 and the minimum was 47 inches in WY 1994. The average over this period was estimated to be 73.6 inches.

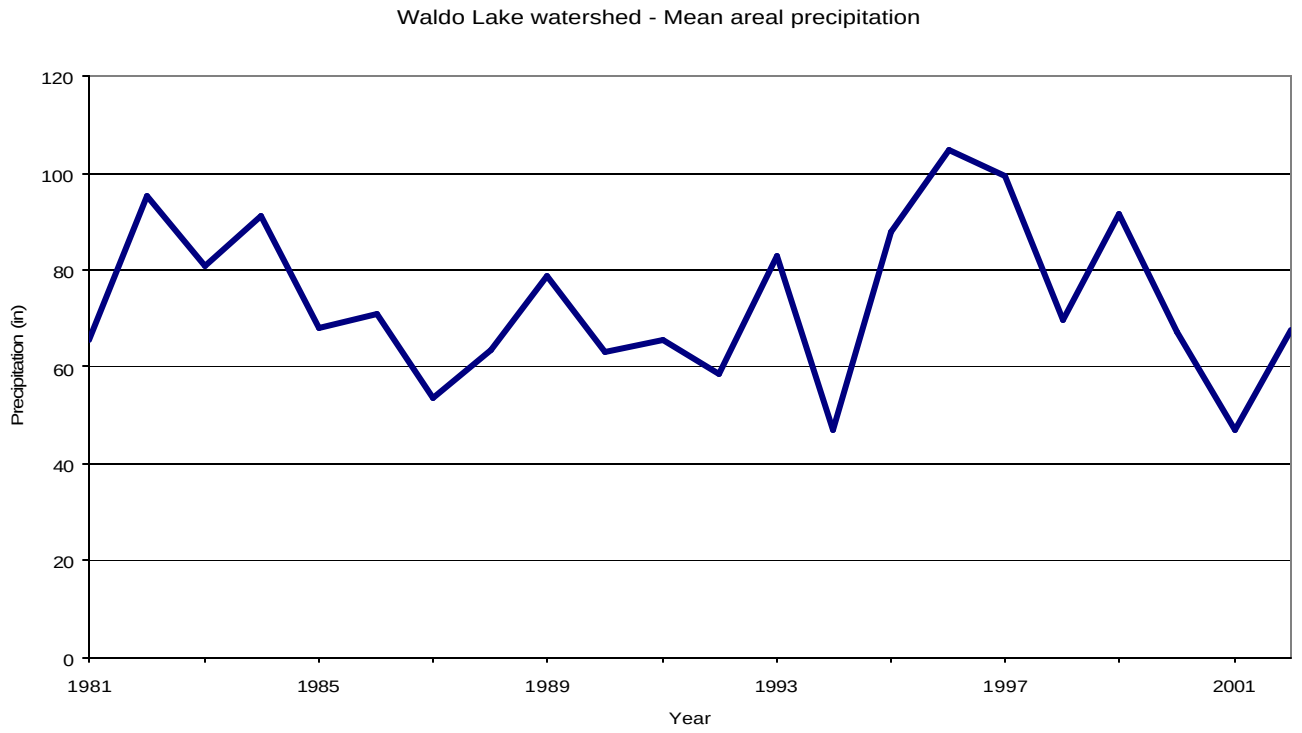


Figure 27: Time series of Mean Areal Precipitation for the Waldo Lake watershed based on interpolated data for surrounding locations.

Time-averaged Water Balance

Given the MAP, it was possible to estimate the total amount of water that left the Waldo Lake basin as a combination of evapotranspiration and groundwater recharge. The calculation could only be computed for the time period from 1981 through 1994 based on streamflow data availability. The MAP time series started in 1981 and the streamflow data at NFk MFk, the basis for estimating the outflow from Waldo Lake, stopped in 1994. The results indicate that, of the average annual precipitation of 73.6 inches, 56.6 inches of water leave the basin as either ET or groundwater recharge. That is an annual average of 81% of the streamflow. Thus the vast majority of water entering the basin does not exit as outflow from the lake.

Given this large fraction of "lost" water, the question arises as to the importance of the watershed on the hydrology of the lake; that is does the watershed actually provide water to the lake at all? To provide some insight to this question, the direct precipitation onto the lake was computed as the total volume of rainfall falling on the lake divided by the total watershed area to make the values compatible with the other quantities in the water balance. Time series of the precipitation and streamflow components of the water balance along with the direct precipitation onto the lake are show in Figure 28. Streamflow from the lake averaged 60% of the direct rainfall onto the lake. The difference between the direct precipitation onto the lake and outflow from the lake was, on average, 26.8". Since it was expected that the annual evaporation from the lake exceeds this value, there very likely was a contribution to the lake from the watershed, at least during portions of the year.

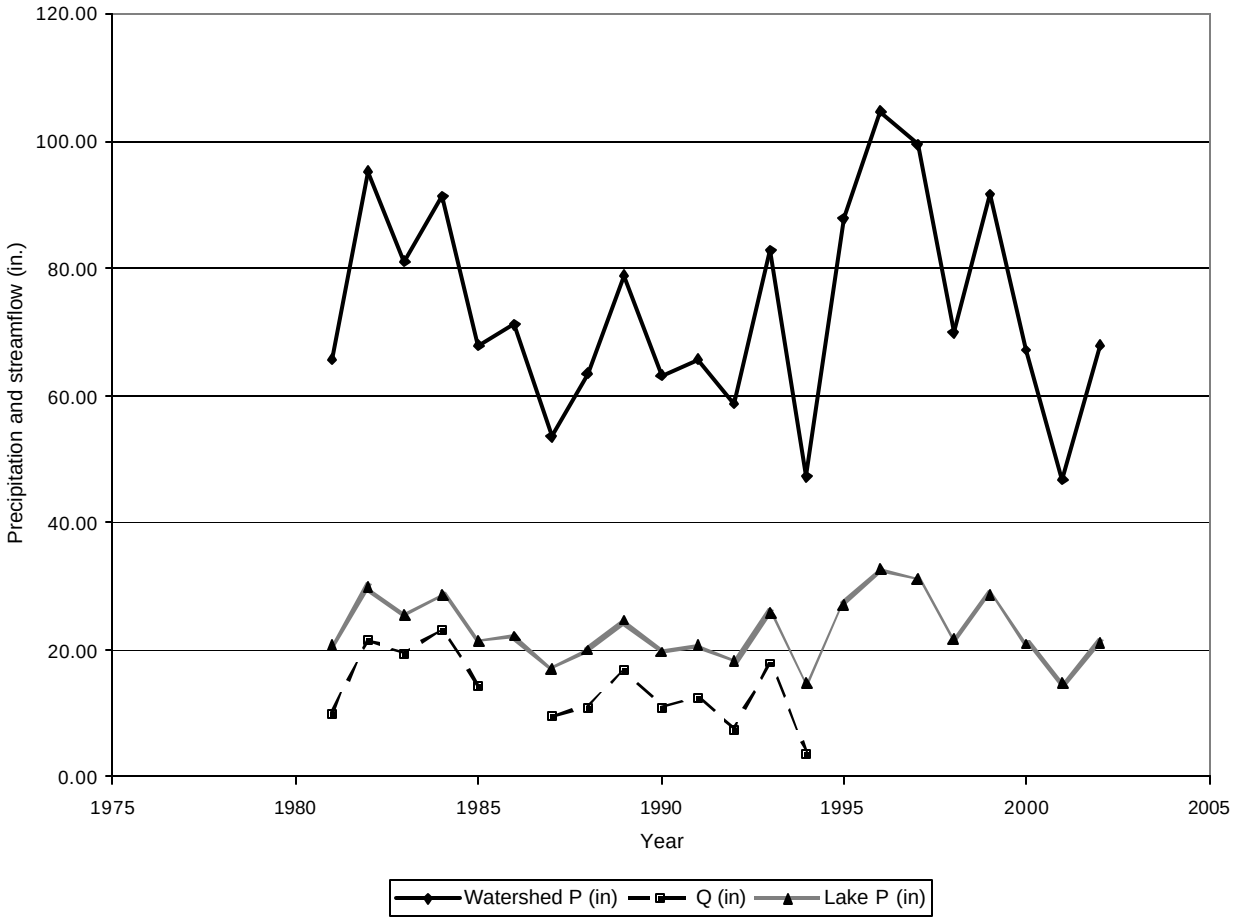


Figure 28: Time series of annual precipitation over the Waldo Lake watershed, streamflow out of Waldo Lake expressed and inches of water over the watershed, and direct precipitation onto the lake, also expressed as inches of water over the entire watershed.

Conclusions

1. **Data.** There are considerable data available in the vicinity of Waldo Lake to provide information on the historic variation in local climate and streamflow. However, streamflow data at the outlet of the lake outlet is available for only a short period of record. Re-establishing this gaging site is important to the study. Although the Snotel sites appear to provide an accurate record of precipitation, the temperature data are not reliable so there is no historic temperature data at the elevation of the lake. Again, this makes site specific climatological data collected for the lake very important.

2. **Historic variability of climate and streamflow**. At lease certain aspects of precipitation, temperature and streamflow have shown significant associations with large scale climate variation, in particular the ENSO and PDO. For the PDO in particular, there appear to be different average characteristics of all three of these variables depending on the phase of the PDO. These large scale features of the ocean and atmosphere are important in understanding the historic and future variation of Waldo Lake.

3. **Annual water balance**. Based only on observed precipitation and streamflow, the averaged annual water balance for Waldo Lake indicates that a very large proportion of the precipitation (in excess of

80%) does not flow out of the lake but is lost either to evapotranspiration or groundwater recharge. This suggests that the watershed and potentially the lake are sources of recharge to the regional groundwater system. It further suggests that the watershed may only play a minor role in the water balance of the lake since direct precipitation on the lake is more than sufficient to produce the observed outflow.

Recommendations

1. **Refine the annual water balance for Waldo Lake and develop a monthly water balance.**
   To determine the importance of the watershed to the hydrology of the lake, the annual water balance must be refined to provide an estimate of the contribution of the watershed to the lake water balance. Two major tasks are required to refine the annual water balance:
   - The evapotranspiration for the watershed and the evaporation from the lake must be estimated.
   - An estimate of groundwater contribution from the watershed to the lake must be made

2. **Establish observation wells to determine groundwater levels and quality in the vicinity of Waldo Lake**.
   Observation wells would support both the refinement of the water balance and provide information on the quality of the groundwater entering the lake. Installation of at least a few observation wells in the vicinity of the lake would be useful in establishing the direction of groundwater flow between the lake and the watershed. Should it indicate that water is flowing into the lake from the local groundwater system, information on the groundwater geochemistry would be useful in establishing the chemical characteristics of water flowing into the lake.

3. **Develop more detailed understanding of the relationship of local, short term climate variability to long term, large scale variations (ENSO, PDO).**
   The short term variation of local climate in the vicinity of Waldo Lake (precipitation, temperature, solar radiation, etc.) provides the forcing for the dynamics of the lake and its ecosystem. However, this variation occurs in the larger context of patterns governed by global-scale features in the ocean-atmosphere system. In particular, inter-annual variations related to ENSO, superimposed on decadal scale persistence influencing the local climate as a result of the PDO, provide a backdrop against which the variation in ecosystem indicators must be viewed. In particular, the occurrence and persistence of cloudy vs. clear days and its impacts on light, temperature and precipitation are all important to the dynamics of the lake system. Persistent patterns of more or less light or higher or lower temperature related to the large scale persistence in the climate, which is suggested in the preliminary analysis, could explain some of the underlying natural variation in the system.

4. **Development of climate and hydrologic forcing scenarios for the Waldo Lake hydrodynamic model.**
   The 2-D hydrodynamic model can be calibrated using the limited historic data on lake outflow and other data collected over the past summer. However, to use the hydrodynamic model to evaluate various scenarios of lake behavior, it is necessary to develop forcing, in particular sequences of climate variables including precipitation, temperature, solar radiation, etc., that drive the hydrodynamic model. Based on the understanding of the relationship of short term climate fluctuations to larger scale and longer term patterns (Recommendation 3, above) the local data can be used to develop models of the occurrence and variation in these characteristics and, working with other members of the team, various scenarios will be developed to test hypotheses related to the lake ecosystem.

Optical Characteristics

Light Attenuation

The vertical attenuation of solar radiation in the water column was measured with a Khal photometer on 15 days between 1998 and 2003 (Table 5). Measurements in 1998 and 1999 were made with a Lake Lite photometer. In 2001-2003 a Kahl photometer was used. Measurements were made on days when cloud cover was relatively constant. The photometer recorded light intensity as $\mu W/cm^2$, which was converted to percent of surface light intensity for three bands of light between 400 and 720 nm. The instrument measured blue light between 400 and 500 nm, with a peak response at 450 nm; green light was recorded between 470 and 610 nm, with a peak response at 520 nm; and red light was recorded as wave lengths between 590 and 720 nm, with a peak response at 640 nm. Photosynthetically active radiation (PAR) was measured unfiltered, with the highest response (over 50 percent relative response) from 440 to 660 nm.

Sampling methods differed between years. In 1998 and 1999 measurements were recorded at every meter. In 2001-2003 measurements were recorded every five meters. One profile was measured on each sampling event, with no repeat measurements for quality control. The photometer was typically used between 1000 and 1400 hours, with the exception of 18 September 2002 and 4 August 2003 when the profile began at 1500. No time was recorded for the 29 July 2002 profile. No metadata was available to assist in explaining peculiarities in the data.

Table 5: Number of sampling events the photometer was used

Year	Sampling events when photometer was used
1998	2
1999	4
2001	4
2002	2
2003	3

Profiles measured in 1998 and 1999 were very erratic (Figure 29), possibly due to intermittent cloud cover or instrument malfunction. The erratic nature of these profiles limited their usefulness.

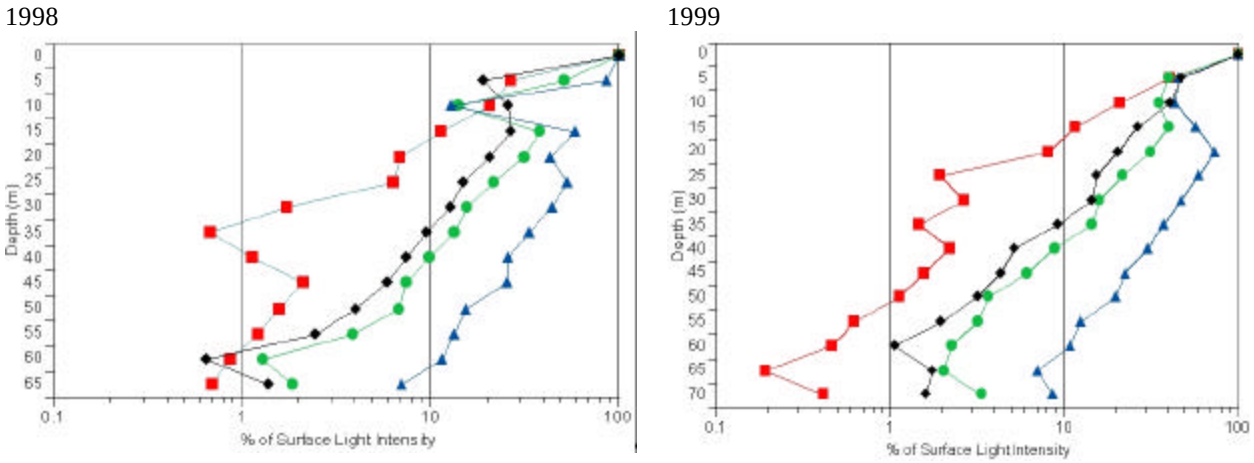
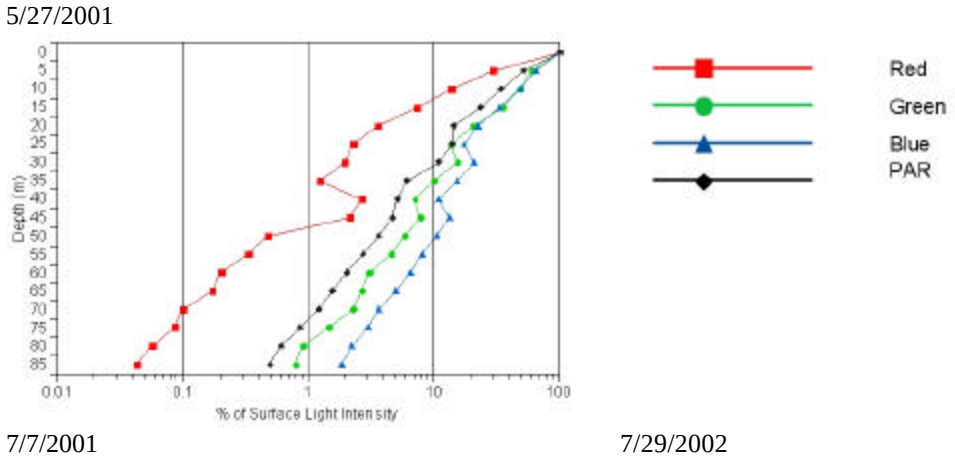


Figure 29: Attenuation of PAR, red, green, and blue wavelengths with depth in Waldo Lake in 1998-1999.

The 2001 through 2003 profiles exhibited the expected pattern of attenuation of light with depth (Figure 30 and Figure 31). Light in the red wavelength was attenuated rapidly in the upper 20 meters of the water column. Green wavelengths and PAR penetrate very deeply, one percent of surface light reached 70 to 80 meters. Blue wavelengths penetrated deeper than the cable length on the photometer. A change in slope of the light attenuation curve occurred typically at the five-meter depth, perhaps due to a high concentration of phytoplankton near the surface, cf., chlorophyll-a distribution in the water column. A similar change in slope was evident in the blue light attenuation curve on 7 July 2001 at 25 m, which suggests a lens of phytoplankton at depth. An increase the number of measurements in the upper 15 m (from every 5 meters to every 1 meter) would provide a more detailed profile of changes in light attenuation in the epilimnion.

Light attenuation increased (penetration decreased) as the summer progressed and resulted in changes in the depth of the photic zone (one percent of PAR) (Figure 32). There was a gradual decline in the depth of the photic zone from 75 to 65 meters between May and September 2001. Other years also show a similar trend, but had fewer sampling events to illustrate the changes.



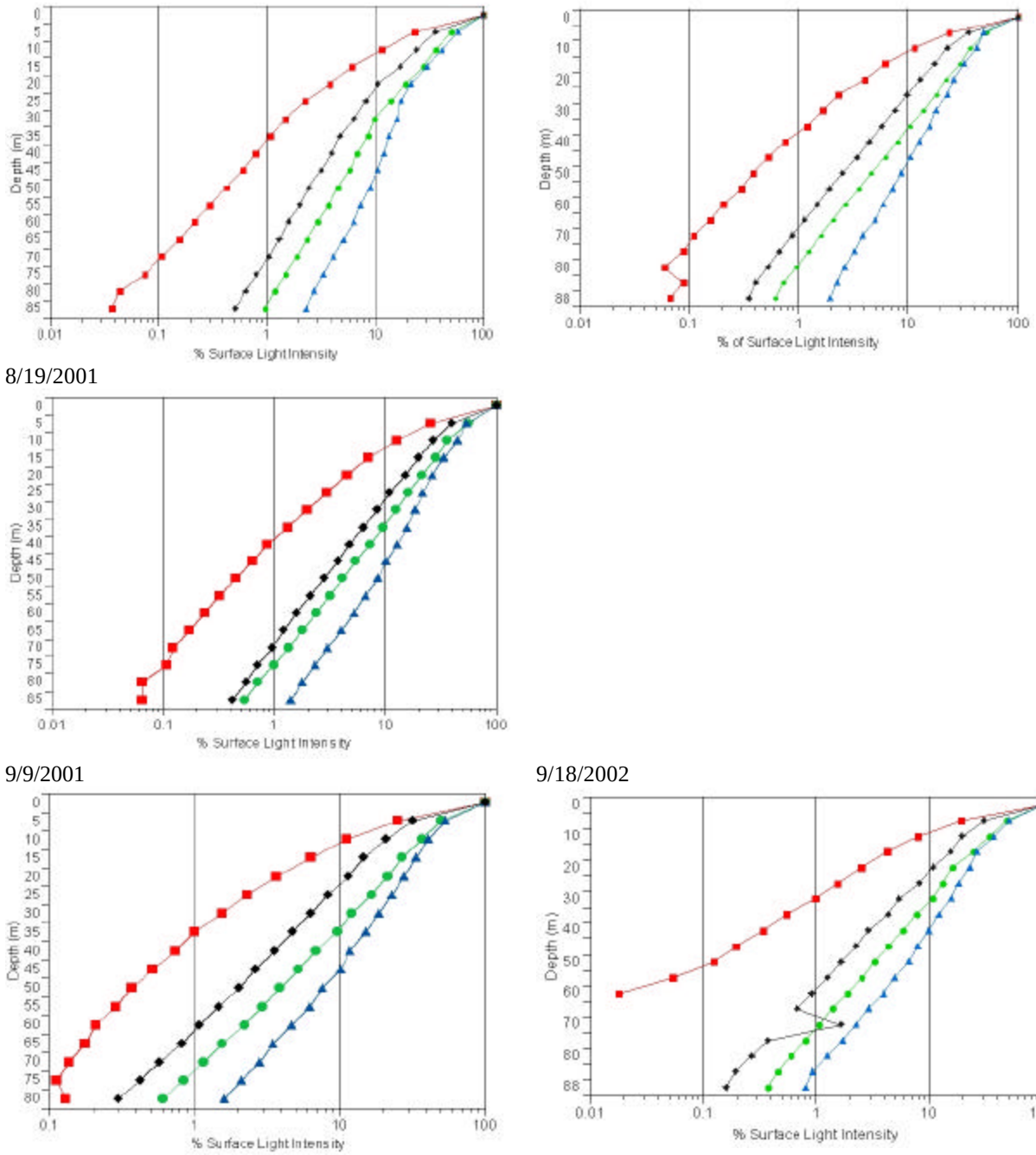
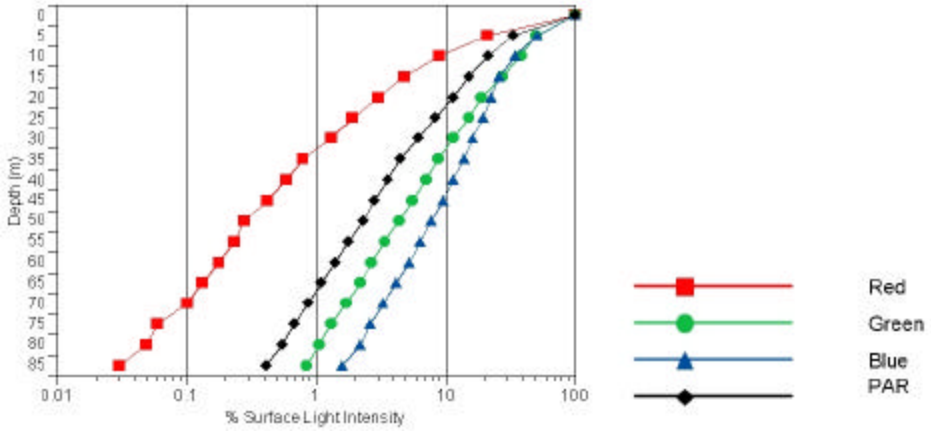
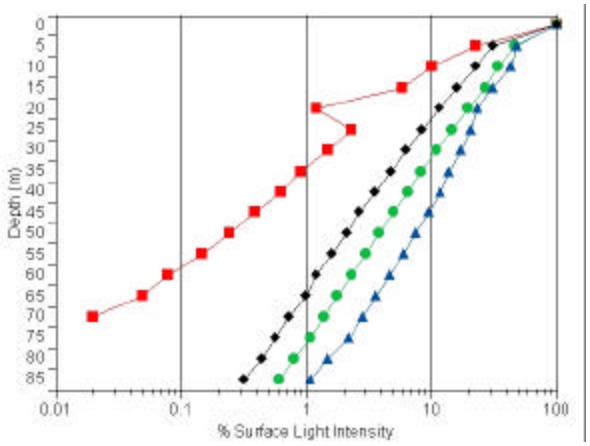


Figure 30: Attenuation of PAR, red, green, and blue wavelengths with depth in Waldo Lake in 2001 and 2002.

8/4/2003



8/25/2003



9/21/2003

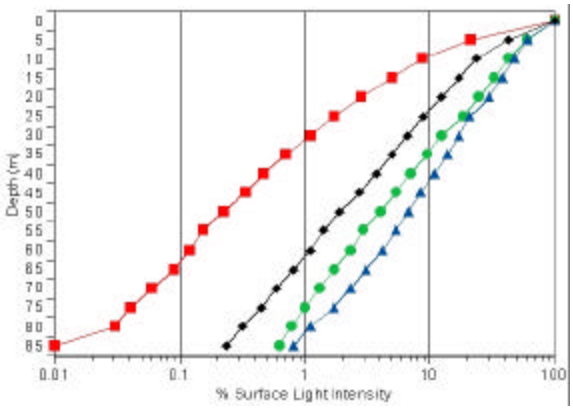


Figure 31: Attenuation of PAR, red, green, and blue wavelengths with depth in Waldo Lake in 2003.

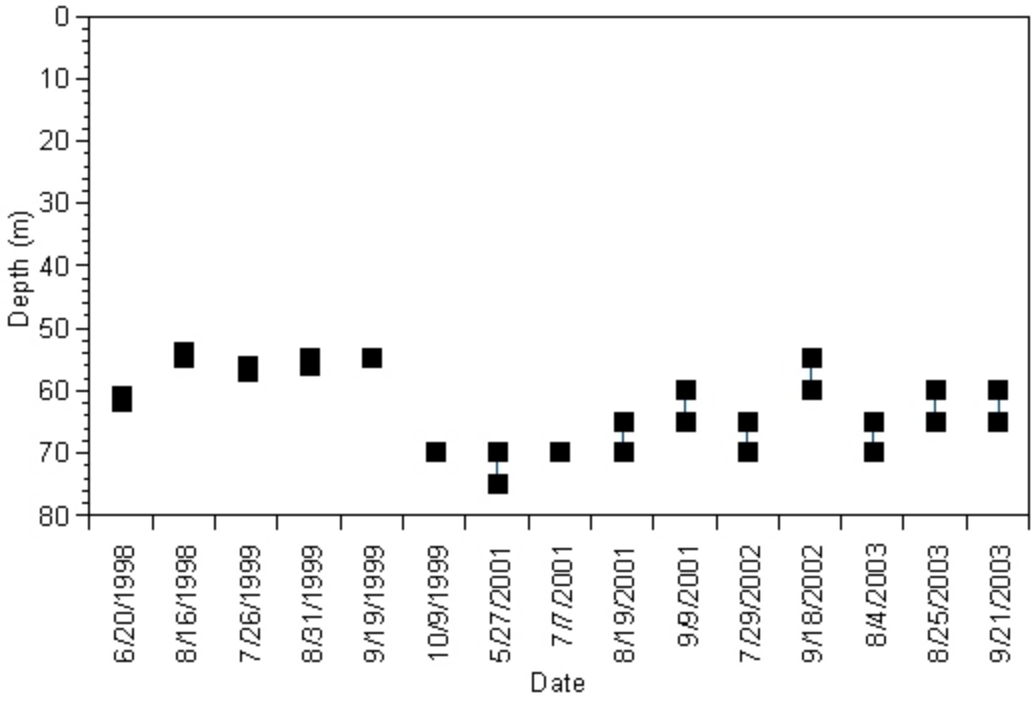


Figure 32: Depth of one percent of PAR at Waldo Lake. Squares indicate the depth where one percent of surface light between 420-700 nm. Where two squares occur for one sampling event, one percent occurred between depths recorded with the photometer.

There is evidence that the optical characteristics of Waldo Lake have changed in recent years. Attenuation of PAR and blue wavelengths, particularly in 10 to 40 m strata, was more strongly attenuated in 2002/2003 than in 1969 (Figure 33 and Table 6). These results support the conclusions of Larson and Salinas (2000) who reported a decline in optical quality in Waldo Lake.

Optical characteristics provide an early signal of change in the lake. Light quality in water is altered by dissolved and particulate material, i.e., dissolved organic material (DOM) and phytoplankton and sediments. Thus, the optical characteristics of the lake may provide the most sensitive measure of water quality change. More thorough study of the optical characteristics of Waldo Lake is required. Deployment of a scanning spectroradiometer in 2004 will provide more detailed characterization of attenuation over a wider range of wavelengths, including ultraviolet wavelengths, than was possible previously.

Table 6: Attention of PAR, red, green, and blue wavelengths with depth in Waldo Lake in early summer (May-June), mid-summer (July), and late summer from 1969 to 2003. (All values represent percent of surface light at depth rounded to the nearest whole number).

6/21/1969[1]					5/30/1992[2]					5/27/2001[3]				
DEPTH (m)	RED	GREEN	BLUE	PAR	DEPTH (m)	RED	GREEN	BLUE	PAR	DEPTH (m)	RED	GREEN	BLUE	PAR
1	71	94	92	83	0					0	100	100	100	100
10	5	48	66	48	10	11	60	68	47	10	14	48	48	34
20	<1	23	33	29	20	<1	33	36	23	20	4	20	22	14
30	<1	11	22	19	30	1	15	20	11	30	2	15	21	11
40	0	6	14	8	40	<1	8	13	5	40	3	7	11	5
50	0	3	8	5	50	<1	5	7	3	50	0	6	10	4
60	0	1	5	3	60	<1	8	4	2	60	0	3	7	2
					70	<1	5	2	<1	70	0	2	4	1
					80	<1	3	<1	<1	80	0	1	2	1

7/23/1969[1]					7/22/1989[2]					7/29/2002[3]				
DEPTH (m)	RED	GREEN	BLUE	PAR	DEPTH (m)	RED	GREEN	BLUE	PAR	DEPTH (m)	RED	GREEN	BLUE	PAR
1	71	85	91	90	1	8	89	93	80	0	100	100	100	100
10	4	43	50	44	10	16	51	53	34	10	11	37	42	23
20	<1	15	38	25	20	5	25	25	17	20	4	22	26	13
30	<1	8	27	15	30	2	13	16	8	30	2	14	18	8
40	<1	4	17	10	40	<1	8	10	4	40	1	8	13	4
50	<1	2	9	4	50	<1	4	6	2	50	0	5	9	3
60	<1	1	6	2	60	<1	3	4	1	60	0	3	6	1
					70	<1	1	2	<1	70	0	2	4	1
					80	<1	<1	<1	<1	80	0	1	3	1

8/6/1969[1]					8/7/1989[2]					8/4/2003[3]				
DEPTH (m)	RED	GREEN	BLUE	PAR	DEPTH (m)	RED	GREEN	BLUE	PAR	DEPTH (m)	RED	GREEN	BLUE	PAR
1	61	80	95	88	1	76	93	95	83	0	100	100	100	100
10	3	43	61	46	10	16	51	51	37	10	9	38	35	23
20	<1	22	32	26	20	5	24	24	17	20	3	19	23	13
30	0	8	21	16	30	2	13	13	8	30	1	11	16	8
40	0	5	14	10	40	<1	7	7	4	40	1	7	11	4
50	0	2	10		50	<1	4	4	2	50	0	4	8	3
					60	<1	2	2	1	60	0	3	5	1
					70	<1	1	1	<1	70	0	2	3	1
					80	<1	<1	<1	<1	80	0	1	2	1

[1] Larson, 1970; [2] Larson and Salinas, 1995; [3] this study period

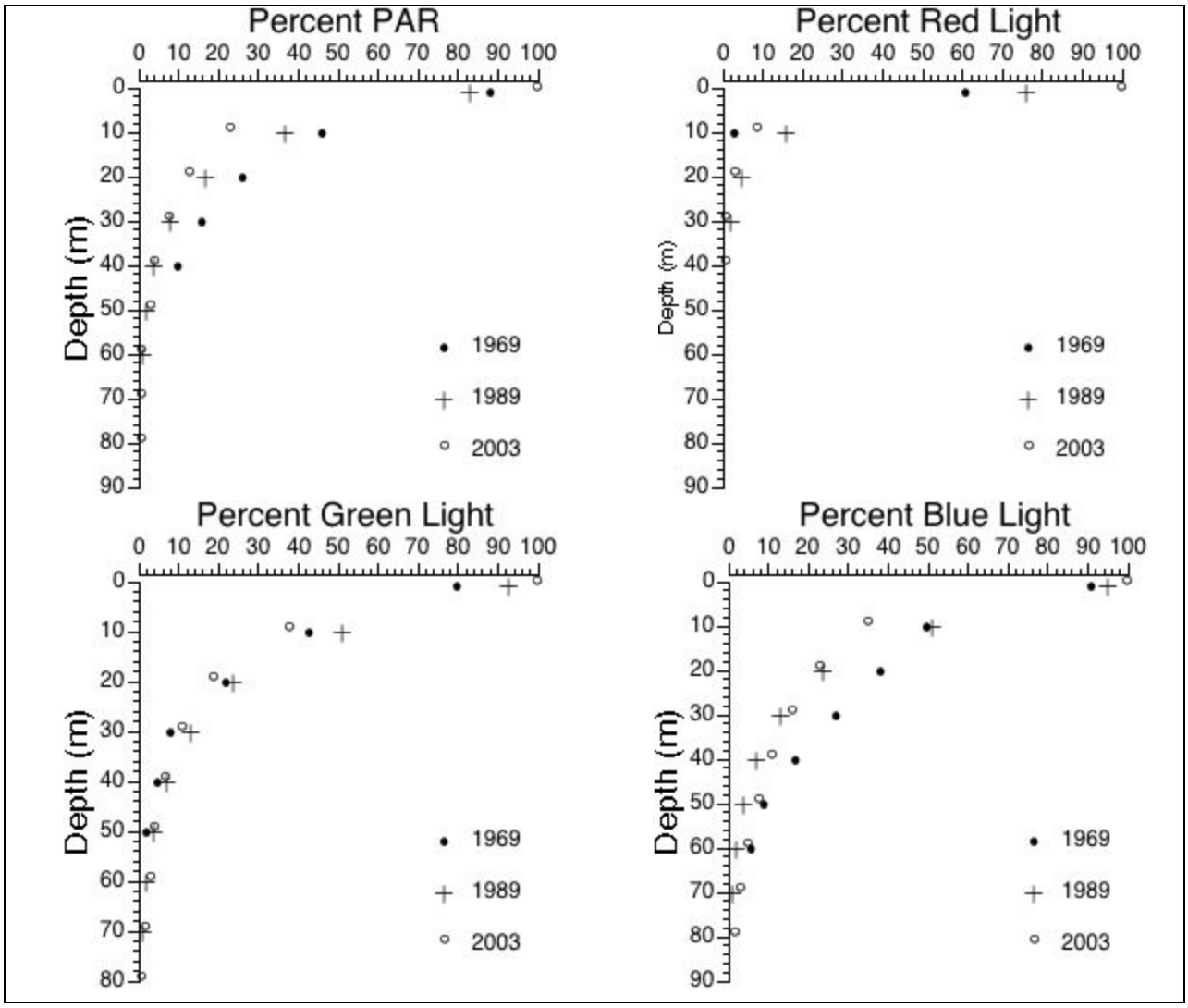


Figure 33: Attenuation of PAR, red, green, and blue light with depth in Waldo Lake in 1969, 1989, and 2003 (August data from Table 6 shown).

Secchi Transparency

Secchi transparency data were available for 35 days between 1990 through 2003 (Figure 34). From one to seven measurements were made on each day (total of 75). No measurements were made in 1995 or 2000. On 16 of the 35 days no duplicate measurement were made for quality assurance purposes.

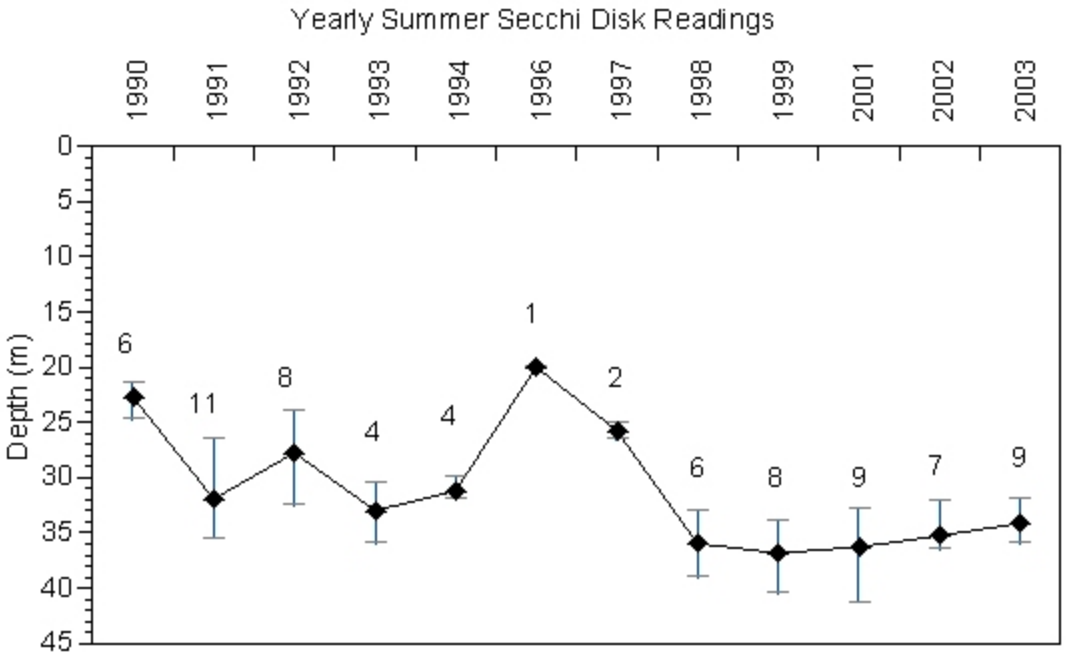


Figure 34: Secchi disk readings collected at Waldo Lake between 1990 and 2003. Dots indicate the average values, bars indicate range and numbers above are the number of readings recorded each year.

Wind and cloud cover can influence Secchi transparency measurements. Optimal conditions for Secchi disk use include consistent cloud cover or a relatively clear sky, with no wind or waves, and minimal solar angles (between 1000 and 1400). Metadata collected with Secchi transparency allowed evaluation of conditions and reliability of measurements. Wave and sky conditions were rated on a scale of one (ideal) to eight (poor). On nine days over the 1996 to 2003 period conditions were classified as good (scale rating less than three and between 1000 and 1400 hours) and on six days they were rated bad (Table 7). The mean Secchi transparency on "bad" days was 3.7 meters less than "good" days, which represents a 10 percent reduction in Secchi transparency that can be attributed to conditions.

Table 7: Secchi disk conditions for readings from 1996 through 2003

"Good" conditions		"Bad" conditions	
Date	Secchi Disk Reading (m)	Date	Secchi Disk Reading (m)
06/20/1998	37.5	09/06/1996	20
06/20/1998	39.1	09/19/1999	35
08/16/1998	33	09/19/1999	35.5
07/26/1999	40	05/27/2001	33
07/26/1999	40.5	06/29/2002	32.2
08/31/1999	35	07/29/2002	36.2
10/09/1999	34	07/29/2002	36.5
10/09/1999	34.2	09/21/2003	34
07/07/2001	41.3	09/21/2003	35
08/19/2001	39.8	09/21/2003	36
09/09/2001	34.2		
08/19/2002	35.8		
Total days 9		Total days 6	
Average 37 m		Average 33.3 m	

Methods for Secchi transparency measurement differed between years. An underwater viewer was used for viewing the Secchi below the water's surface for some measurements in 2002 and 2003, thereby eliminating interference by surface wave action and glare. Paired measurements were made with and without the underwater viewer three times. The underwater viewer measurements were from 0.6 to 2.7 m greater than measurements made without the underwater viewer. The relative percent difference between measurements ranged from 1.6 to 7.7 percent. While the underwater viewer resulted in slightly greater Secchi transparency measurements, the improvement was modest and it did not fully compensate for the surface effects caused by less than optimal conditions noted above.

Secchi transparency ranged from 20 to 40.5 m from 1990 through 2003. Lowest mean annual transparency occurred in 1990 and immediately after the fire in 1996 and 1997. The fire effect on transparency, if real and not related to inter-annual variation, was short. Mean Secchi transparency from 1998 through 2003 (35.7 m) was 18 percent greater than in the 1990 and 1994, pre-fire period (29.3 m).

Secchi transparency is a difficult measurement to make at Waldo Lake because wind often creates waves that interfere with viewing the disk during mid-day. In addition, Waldo Lake water clarity is great and viewing a small (20 cm) disk at 30 m can be difficult, even under good conditions. The long-term record of Secchi transparency in the lake is valuable and measurements should continue, however, characterizing the light field in the lake using irradiance sensors provides more reliable data.

Chemical and Physical Characteristics

In situ profiling of physical and chemical characteristics of Waldo Lake was done with a multiprobe instrument (Hydrolab® Data Sonde III). Measurement of some parameters, particularly pH and specific conductance, was complicated by the extremely low ionic strength of Waldo Lake. An instrument warm-up period of over one hour was used on all sampling dates to allow the probes to acclimate to the low

ionic strength conditions, but profiling protocol varied between and within years. Measurements were recorded in time increments ranging from 5 seconds to 2 minutes. Depth increments were 0.1 to m in the upper 20 m, and 0.5 to 5 m in the lower 100 m of the water column. The varying depths and time increments complicated the analysis of vertical profiles and should be standardized in future monitoring (Quality Assurance/Quality Control Plan).

Grab samples were collected for laboratory analyses of pH, specific conductance, acid neutralizing capacity/alkalinity (ANC), total dissolved solids (TDS), total phosphorus (TP), filtered (1.2 µm) total phosphorus, soluble reactive (SRP), nitrate + nitrite-nitrogen (NO_3+NO_2-N), ammonia-nitrogen (NH_3-N), and silica. The constituents analyzed in laboratory samples differed between years. The Cooperative Chemical Analysis Laboratory at OSU conducted the analyses. The extremely low concentrations of ions and nutrients in Waldo Lake made analyses difficult. Concentrations were typically below the method detection limit. The reliability of reported concentrations that were less than the method detection limit or the minimum standard is unknown. These data were not included in this analysis. Use of lower minimum standards would alleviate some concern over validity of reported values. The laboratory flagged values below method detection limits or below the minimum standard used to develop the standard curve (curve was forced through origin), however, there were inconsistencies in the labeling of these values in the data provided by The Cascade Research Group for analysis. Lack of adequate analytical methods for measuring important nutrient and ion concentrations reinforces the importance of optical and biological tools for monitoring the lake.

Data for grab samples from 1996 through August 2003 were available. There were 211 samples collected from Waldo Lake during the period. Most (166) were collected at depths between 0 and 120 meters at the long-term monitoring station (LTM). Forty-five samples were collected at three locations along the north shore of Waldo Lake (Stations 1-3) and at the North Waldo Lake campground boat ramp and swim area station (NS) to document any changes in chemistry related to the 1996 fire, which covered a substantial portion of the Waldo Lake watershed along the north end of the lake.

Water Temperature and Dissolved Oxygen

Temperature and dissolved oxygen profiles were measured in Waldo Lake on three days in 1998 and on four days each year in 1999, 2001, 2002, and 2003. Waldo Lake exhibited temperature stratification and orthograde dissolved oxygen concentrations typical of middle-latitude, oligotrophic lakes (Figure 35-Figure 37). Maximum surface water temperatures were above 19º C; hypolimnion temperatures never exceeded 5.2 ºC. Onset of thermal stratification was evident as early as late May and stratification persisted into early October.

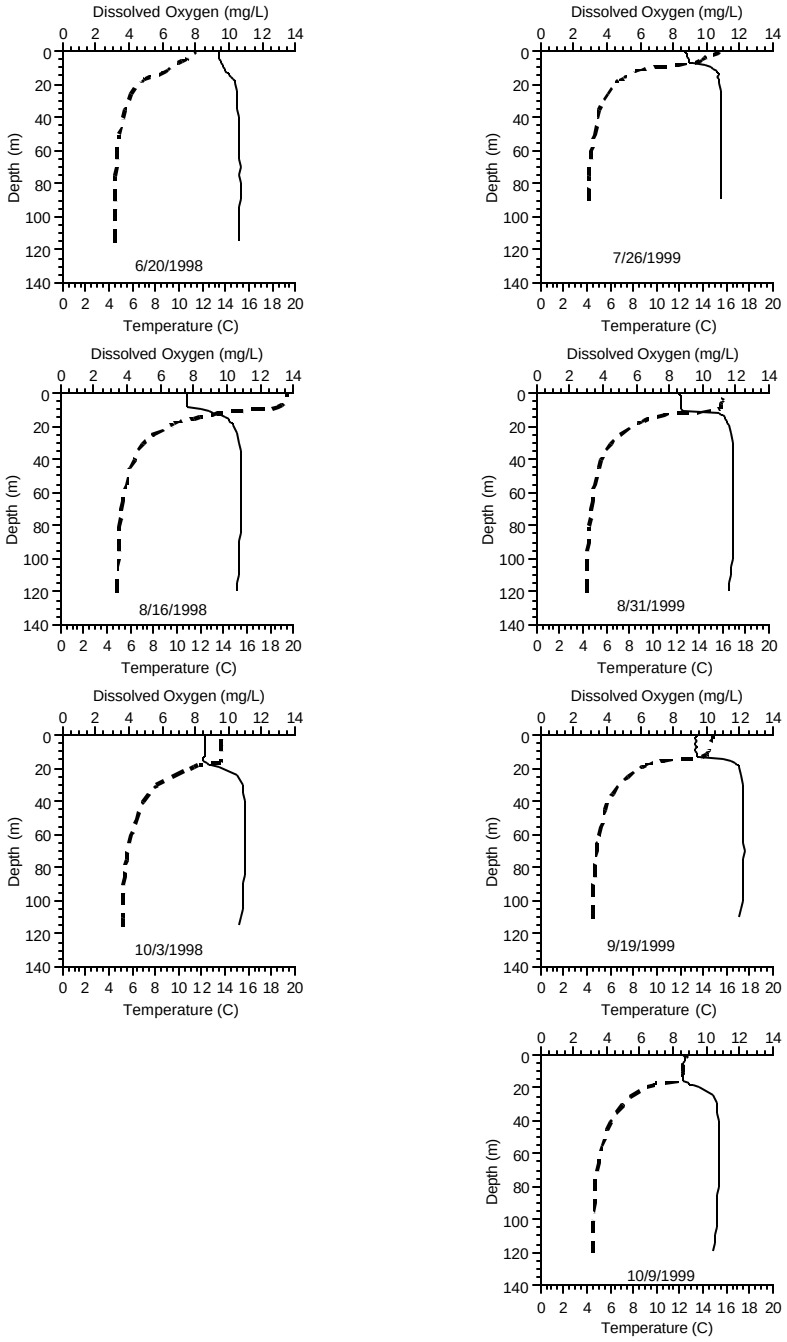


Figure 35: Waldo Lake temperature and dissolved oxygen profiles from 1998-1999. Dashed line indicates temperature. Solid line indicates dissolved oxygen.

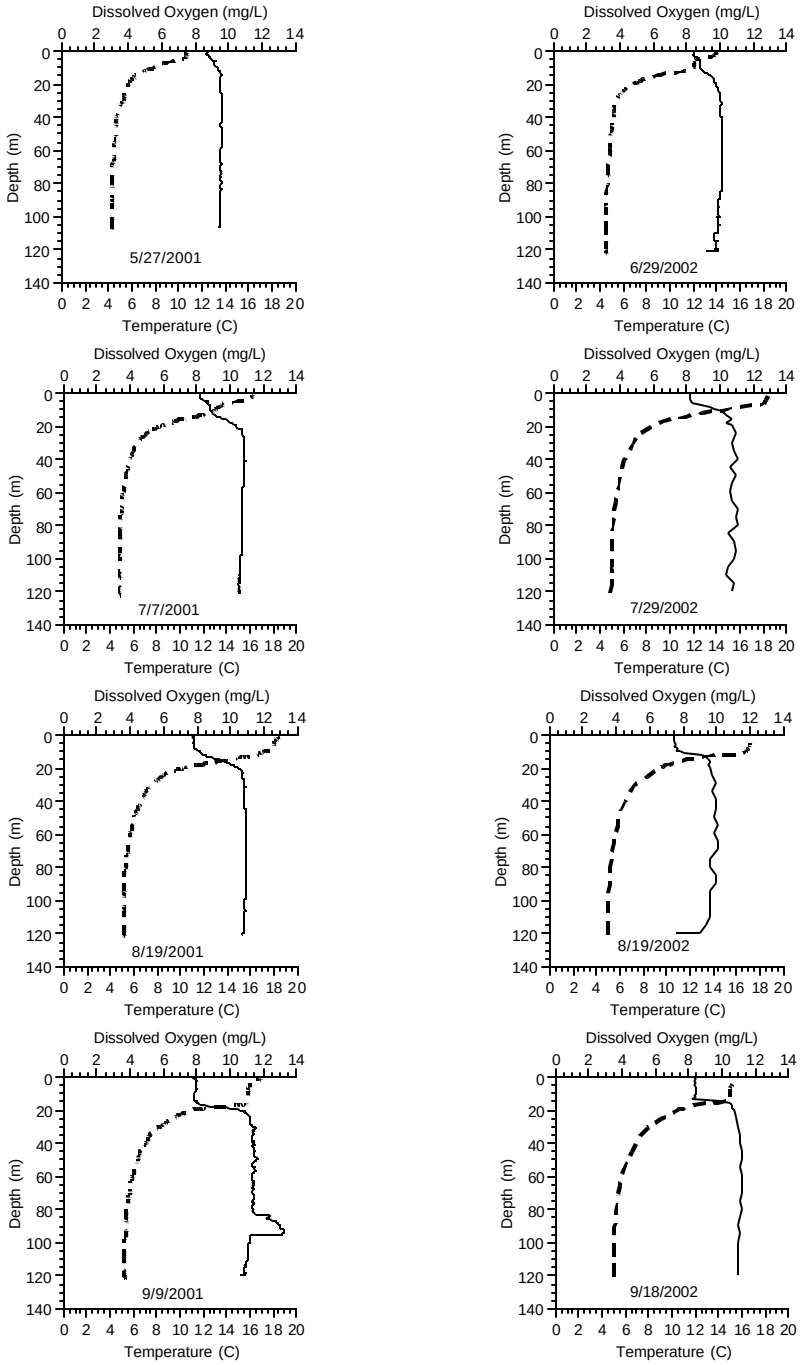


Figure 36: Waldo Lake temperature and dissolved oxygen profiles 2001-2002. Dashed line indicates temperature. Solid line indicates dissolved oxygen.

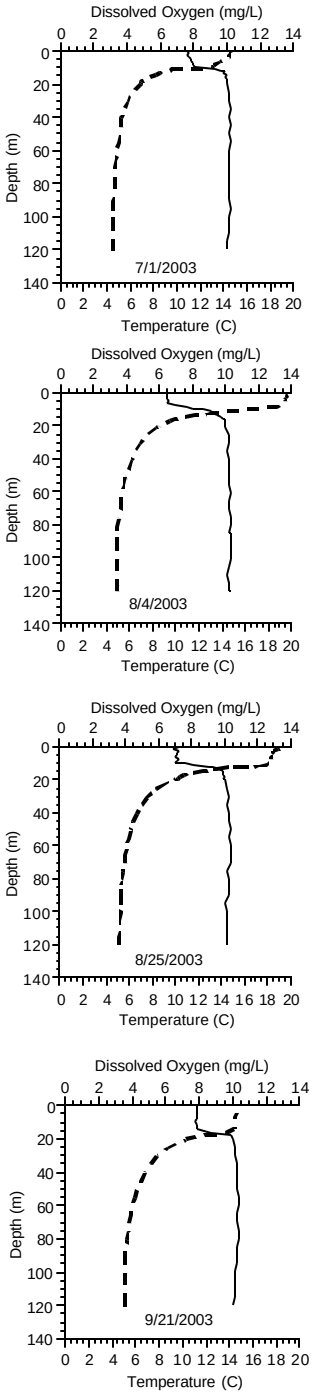


Figure 37: Waldo Lake, 2003 temperature and dissolved oxygen vertical profiles. Dashed line indicates temperature. Solid line indicates dissolved oxygen.

Epilimnion dissolved oxygen concentrations ranged from 6.5 to 9.5 mg/L and saturation ranged from 87.5 to 114.8 percent, averaging 101.0 percent. Lowest percent saturation occurred on 4 August 2002. Hypolimnion dissolved oxygen concentrations ranged from 9.1 to 12 mg/L and saturation ranged from 87 to 113 percent, averaging100 percent. Lowest percent saturation occurred on 27 May 2001. During the 1986 through 1998 period the epilimnion averaged 105 percent saturation, with occasional undersaturation (95 percent) of the near-surface water (1-2 m) of epilimnetic waters; the hypolimnion ranged from 115-120 percent saturation (Salinas, 2000).

There was an anomalous increase in dissolved oxygen concentration between 80 and 95 m on 9 September 2001 (Figure 36). Metadata noted this increase as a "glitch" that did not occur during the more rapid upcast of the instrument through the water column. Winkler titrations for dissolved oxygen at the surface and 120 m coincided with the instrument measurements and instrumental malfunction is not likely. This "glitch" cannot be explained.

Detailed 2003 temperature profiling

Stratification and mixing dynamics are fundamental characteristics of a lake that influence nutrient cycling and the biological community. Water temperature profiles have been regularly collected at the LTM site of Waldo Lake; however, no detailed record of seasonal changes in temperature has been collected. Detailed information on the temperature of the lake is critical to effective modeling of lake behavior.

In July 2003, forty temperature loggers were placed in eight depths at five locations in the lake (Figure 38). Four locations were in deep water (> 60 m), the fifth location, South Lake, was shallower (Table 8). The South Bay location is the most sheltered from the wind and is also the deepest (Figure 38). Temperature loggers were installed on 18 July 2003 and collected data (± 0.5 C°) at 30-minute intervals. Loggers were retrieved and downloaded on 6 October 2003 at the North Lake, South Lake and West Bay locations and on 7 October 2003 at the Mid Lake and South Bay locations. Temperature loggers were then reinstalled at the same depths. One temperature logger was lost between July 2003 and October 2003 (South Lake, 5-meters). The logger was replaced in October.

Table 8: Depth of temperature loggers from July 2003 deployment

Location	Depth of Lake at the Station	Approximate depth of thermistors
West Bay	77 m	5, 10, 15, 20, 25, 35, 45, and 60 m
South Bay	94 m	5, 10, 15, 20, 25, 35, 45, and 60 m
North Lake	65 m	5, 10, 15, 20, 25, 35, 45, and 60 m
Mid Lake	74 m	5, 10, 15, 20, 25, 35, 45, and 60 m
South Lake	47 m	5, 10, 15, 20, 25, 30, 35, and 40 m

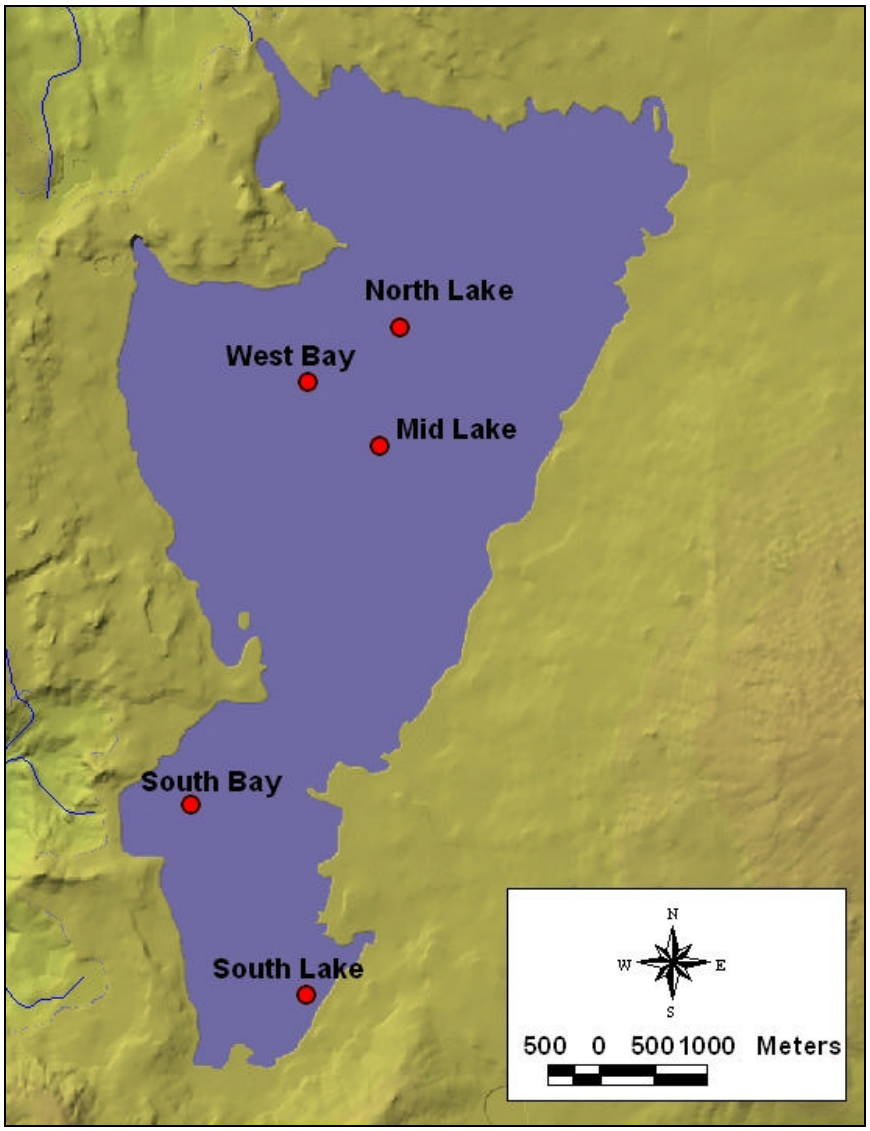


Figure 38: Locations of thermistors

The lake was stratified in July when loggers were installed and remained stratified throughout the deployment period; however, there was a mixing event in mid-September (Figure 39). The mixing event was triggered by a two-day period (16-17 September 2003) of low air temperatures (Figure 40) and high winds (Figure 41). During the mixing event epilimnion temperature declined and the thermocline deepened.

Maximum surface water temperatures (at 5 m) were 20° C on 30 July 2003 and 1 August 2003. Minimum surface water temperatures (at 5 m) were 14°C on 20 September 2003. Lowest hypolimnion temperatures, under 5° C, occurred at the time of installation (19 July 2003). The hypolimnion warmed gradually over the course of the season to 6° C on 30 September 2003.

The thermistors will remain in the lake through 2004. Data collected over winter will allow observation of fall turnover and development of stratification in the spring.

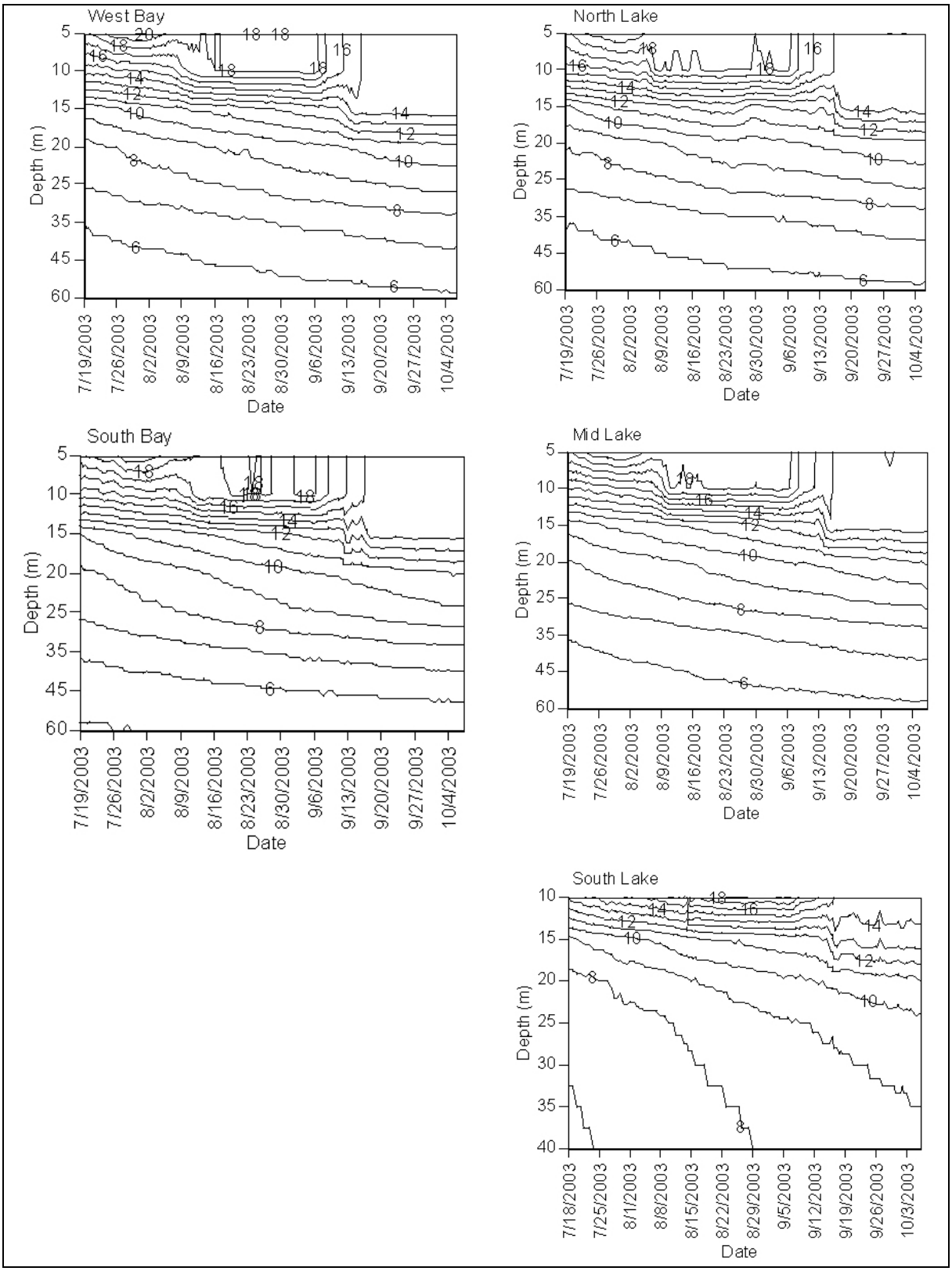


Figure 39: Temperature profiles from five locations in Waldo Lake between July and October 2003.

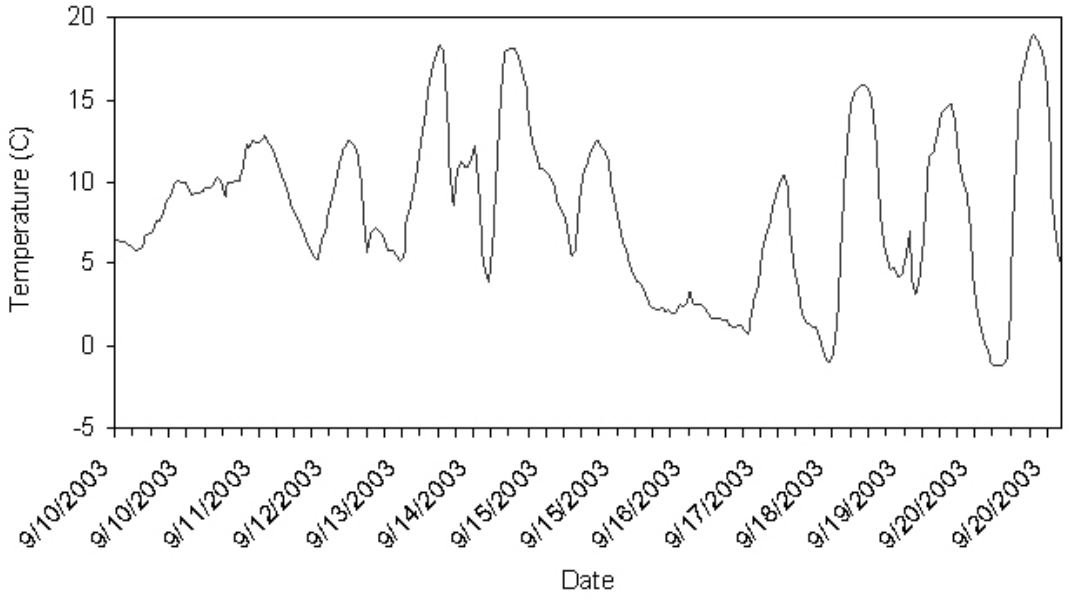


Figure 40: Hourly air temperatures collected at the USFS weather station located at the Islet Campground.

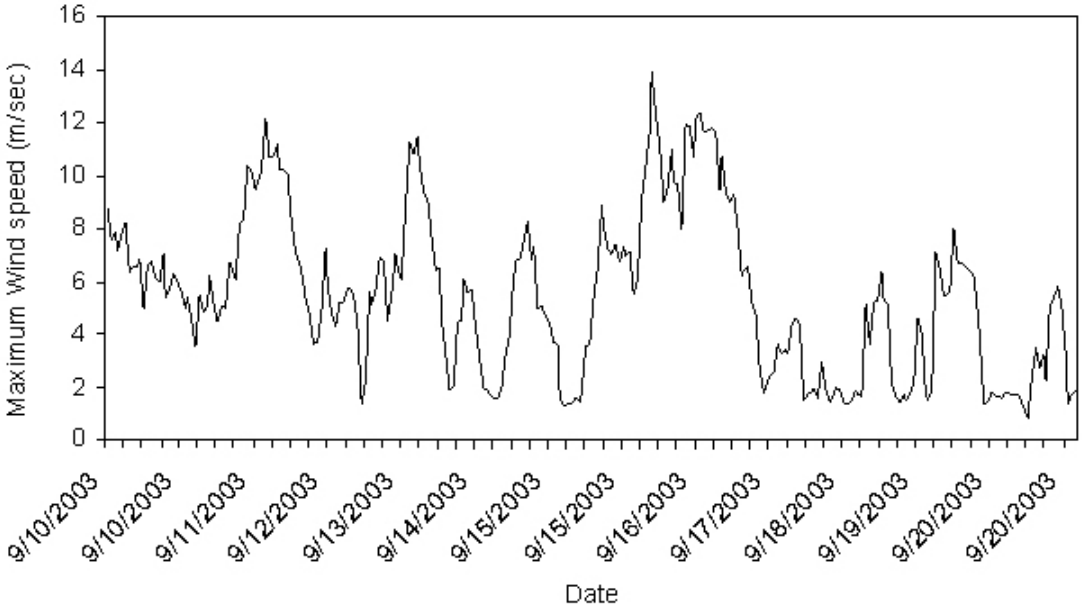


Figure 41: Maximum hourly wind speed (m/sec) recorded at the USFS weather station located at the Islet Campground.

pH

The pH at Waldo Lake was measured in situ and in the laboratory. Measurements were subject to error caused by instrument response or sample handling. The low ionic strength of Waldo Lake requires a long stabilization period for the pH electrode. Erroneous measurements were possible if the electrode was not allowed to stabilize for a long enough time at each depth during in situ measurements. Laboratory measurements may be contaminated by carbon dioxide infusion of the sample during transport or measurement at the laboratory, which is located at an elevation of less than 100 m, much

lower than the lake. Given the low acid neutralizing capacity of Waldo Lake (see below) such contamination could result in biased measurements.

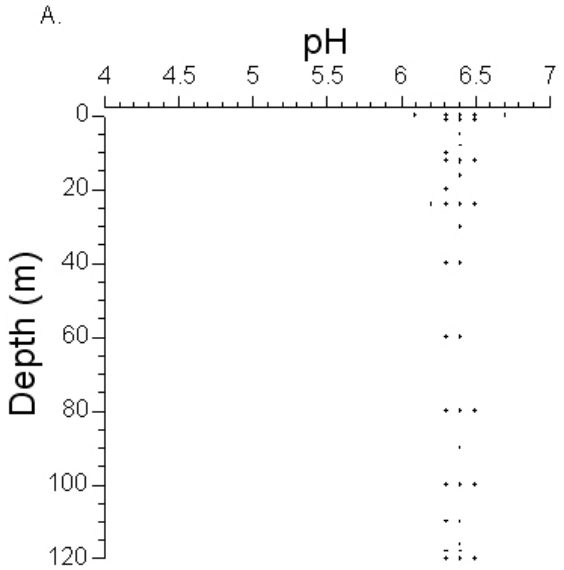
Nineteen in situ vertical profiles of pH were collected between 1998 and 2003 (Table 9). The pH of 214 grab samples collected from Waldo Lake (all depths and locations) from 1996 though 2003 was measured in the laboratory. Eighteen of the 214 samples were repeated during standard laboratory analyses for quality assurance purposes. The relative percent difference of duplicate samples was under two percent.

Table 9: Monthly sampling events between 1998 and 2003 ranged from once in May to six times in August.

Month	Number of Sampling Events
May	1
June	2
July	4
August	6
September	4
October	2

Laboratory pH measurements were less variable than field-measured pH (Figure 42). The pH for all samples collected in Waldo Lake measured in the laboratory ranged from 6.1 to 6.7 and averaged 6.37 ± 0.004 (standard error, n=232) between 1996 and 2002. Field-measured pH from 1998 through 2003 ranged from 4.9 to 6.8 and averaged 5.9. Field-measured pH from 1989 through 1995 ranged between 4.5 and 6.5 (Larson and Salinas, 1995).

In an audit of pH measurements collected in the field on 25 August 2003 a difference of 0.67 and 0.69 pH units occurred between downcast and upcast measurements at 90.5 and 50.4 m, respectively. The relative percent difference between measurements was six percent. A difference greater than 0.5 pH units is ranked as a failure in the Waldo Lake Field Sampling Quality Assurance and Quality Control Project Plan. Given the large variation inherent in field-measurement of pH in Waldo Lake, annual variation in the mean pH observed in field-collected data (Figure 42 and Figure 43) was likely a function of measurement error.



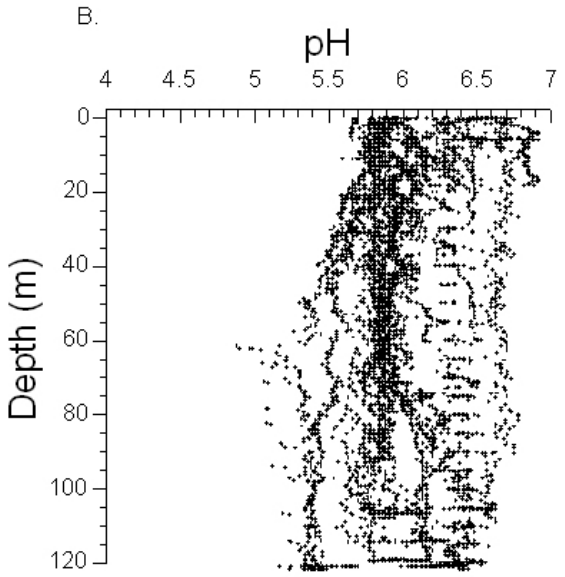


Figure 42: Laboratory (A) and field-measured (B) pH in Waldo Lake from 1996 through 2003 (points overlap in A, n=228)

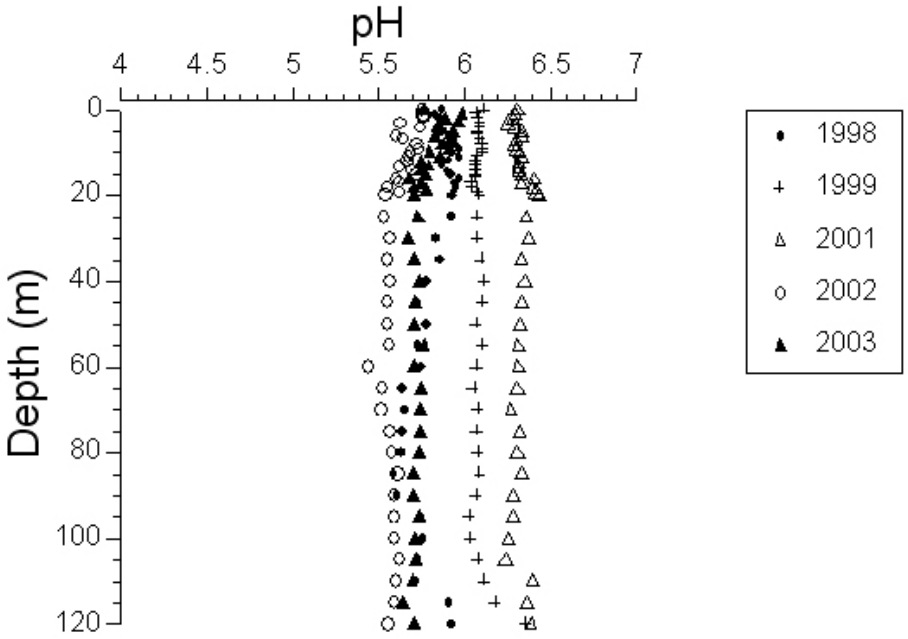


Figure 43: Profiles of mean annual pH with depth in Waldo Lake.

Specific Conductance

Specific conductance in Waldo Lake was extremely low. Specific conductance measured in situ was more variable than measurements conducted in the laboratory. Differences between field and laboratory results could be due to field calibration techniques or instrument response at low conductivity levels, although Hydrolab® specifications indicate a range of 0 to 100 mS/cm with an accuracy of +/- 0.001 mS/cm (1µS/cm). Waldo Lake specific conductance is so low that calibration, especially the zero setting, of the multi-parameter probe instrument requires extreme precision.

Field calibration for specific conductance was done with a 147 µS/cm solution. Dilution of this solution to a lower concentration for calibration in the range of measurement produces unstable measurements in the field due to evaporation and carbon dioxide solubility changes (T.J. Sisson, Hydrolab ® Water Resource Products Representative, personal communication). Therefore, laboratory measurement of specific conductance with a Wheatstone bridge probably provides more reliable and representative results.

Specific conductance measured in situ in 2002 and 2003 ranged from 0.9 to 4.2 µS/cm and averaged 2.9 µS/cm (652 readings on eight sampling days with all depths combined). Specific conductance measured in the laboratory from 1996 through 2003 ranged from 3 to 4.1 µS/cm and averaged of 3.4 µS/cm (194 grab samples). Between 1989 and 1995 in situ measured specific conductance ranged from 4.2 to 5.2 µS/cm; laboratory measurements ranged from 2.9 to 3.8 and averaged 3.3 µS/cm (n=151) (Larson and Salinas, 1995). Thus, the field-measured conductance was substantially more variable than laboratory-measured conductance. The following discussion therefore focuses on the laboratory results.

There was little variation in specific conductance in Waldo Lake with depth, or over time (Figure 44). Samples collected near the north shore, even immediately following the fire, did not have higher specific conductance than the LTM station. In fact, the specific conductance of samples from areas near the north shore was near the lower end of the conductance measured in surface waters. Specific conductance does not indicate that the burn area contributes nutrients to the lake in surface water runoff. In a nutrient poor system such as Waldo, however, dissolved ions may be quickly sequestered in phytoplankton and periphyton biomass and have a very short "half-life" in the water column.

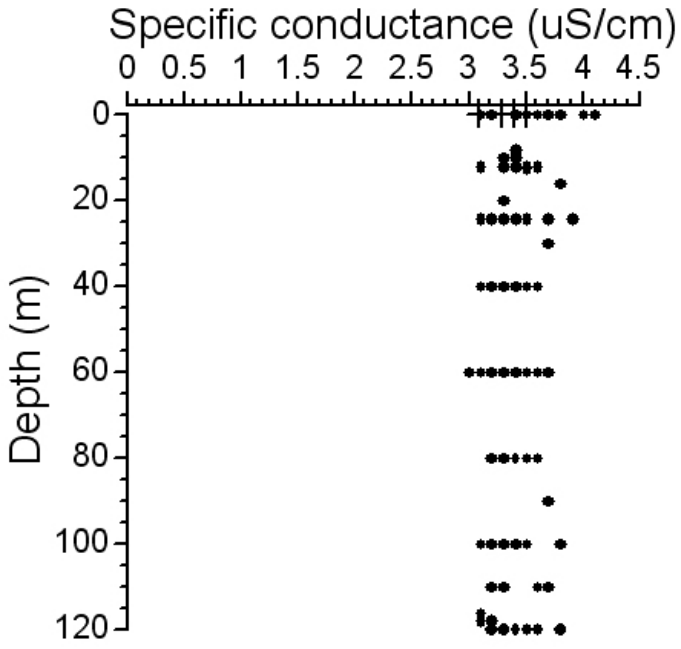


Figure 44: Laboratory-measured specific conductance in grab samples collected at the LTM site from Waldo Lake between 1996 and 2003. + indicates samples from sampling locations along the north shore.

Total Dissolved Solids

Total dissolved solids were measured in 199 samples from the long term monitoring and north shore stations between 1996 and 2003. Additional sampling occurred at Klovdahl Bay and at sites labeled as "WG", "Mouth", "WNI" and "EB". The location of the WB, Mouth, WNI, and EB sites is unknown. The Klovdahl Bay and unknown station samples were not included in this analysis. The method detection limit for TDS was reported as 3 mg/L by Salinas (2000). The detectable limit, as indicated on datasheets from 2002 and 2003 with an asterisk, was 5 mg/L. The 5 mg/L was used as the detection limit for this report.

Between 1996 and 2003 the mean total dissolved solids was slightly higher and had a greater range at the north swim area (8.4± 1.3 mg/L (mean ± standard error, n= 14)) than at the long-term monitoring station (mean=8.1± 0.5 mg/L (mean ± standard error, n= 34) (Table 10). The difference between sites was due to one high concentration (24 mg/L) at the north shore site on 19 September 1997. The high TDS measurement in 1997 was not correlated with a similarly high specific conductance and may be an erroneous measurement.

Table 10: Yearly total dissolved solids concentration (mg/L) from the long-term monitoring site and locations along the north shore.

Long-term Monitoring (LTM)						
Year	Average (mg/L)	Minimum (mg/L)	Maximum (mg/L)	Samples above detection limit	Total Samples analyzed	Percentage w/ Detected concentrations
1996	6.00	6	6	1	10	10.0
1997				0	15	0.0
1998	7.17	6	10	6	28	21.4
1999	6.67	6	9	6	28	21.4
2000	6.25	6	7	4	6	
2001	9.57	6	14	14	29	48.3
2002				0	20	0.0
2003	9.33	8	11	3	15	20.0
Total				34	151	22.5
North Shore (NS)						
Year	Average (mg/L)	Minimum (mg/L)	Maximum (mg/L)	Samples above detection limit	Total Samples analyzed	Percentage w/ Detected concentrations
1996	7.00	7	7	1	2	50.0
1997	24.00	24	24	1	5	20.0
1998	6.25	6	7	4	12	33.3
1999	6.00	6	6	1	10	10.0
2000					0	
2001	8.17	6	13	6	12	50.0
2002	7.00	7	7	1	4	25.0
2003				0	3	0.0
Total				14	48	29.2

Acid Neutralizing Capacity (ANC)/Alkalinity

ANC was measured on 196 samples (151 from the long-term monitoring station and 45 from north shore stations) from 1996 through 2003. The relative percent difference of duplicate samples analyzed in the laboratory was under 6% (n=16). Waldo Lake has a low and unchanging ANC. Annual mean ANC has been relatively constant since 1996 (Table 11). Larson and Salinas (1995) reported that ANC ranged from 1.639 to 2.961 mg $CaCO_3$/L, and averaged 2.448 mg $CaCO_3$/L (n=150) between 1986 and 1995. Between 1996 and 2003 the average alkalinity from the long-term monitoring station was 2.34 mg $CaCO_3$/L (range: 1.75 to 2.71 mg $CaCO_3$/L; n=151). There was no difference in ANC between the NS and LTM stations (Table 12).

Table 11: Average yearly alkalinity in Waldo Lake expressed in mg $CaCO_3$/L.

Year	Average Alkalinity mg $CaCO_3$/L	Minimum Alkalinity mg $CaCO_3$/L	Maximum Alkalinity mg $CaCO_3$/L	n
1996	2.60	0.60	0.65	12
1997	2.43	0.57	0.59	16
1998	2.34	0.53	0.58	39
1999	2.42	0.53	0.64	40
2000	1.82	0.42	0.44	6
2001	2.41	0.54	0.61	41
2002	2.42	0.54	0.62	24
2003	1.93	0.42	0.53	18
1996-2003	2.30	0.42	0.65	196

Table 12: Alkalinity expressed in mg $CaCO_3$/L of the long-term monitoring site and locations along the north shore

Statistic	LTM	NS
Average mg $CaCO_3$/L	2.34	2.39
Minimum mg $CaCO_3$/L	1.75	1.88
Maximum mg $CaCO_3$/L	2.71	2.59
n	151	45

Nutrients

Phosphorous

A total of 235 samples were analyzed for TP between 1996 and 2003. Duplicate samples were analyzed at the laboratory, but no duplicate samples were collected in the field. Laboratory methods of reporting concentrations at or below the method detection limit (1 µg/L with a precision level of ± 2 µg/L (Salinas, 1999)) were inconsistent. Laboratory reports indicated concentrations at or below detectable limits with an asterisk; however, this reporting method was not properly noted in chemistry data sheets supplied by The Cascade Research Group for all years between 1996 and 2003. (The laboratory report data sheets are required for completion of analyses.) Only concentrations reported greater than 1 µg/L were considered above the method detection limit for this report. Salinas (2000) reported values equal to 1 µg/L. Furthermore, TP samples were sometimes filtered (1.2 µm) to remove zooplankton prior to analysis (Salinas, 2000 and personal communication). This nonstandard procedure should be

eliminated. Original chemistry datasheets and field collection notes are needed to clarify confusion and complete the analysis of phosphates.

Of the 235, 21 were duplicate measurements. Four of the duplicate measurements had different TP concentrations; small differences in very small numbers caused the relative percent difference to range between 50 and 67 percent.

Detectable TP concentrations were measured in 42 of the 235 samples. Detectable concentrations ranged from 3 µg/L to 7 µg/L and averaged 4 µg/L. Total phosphorus ranged from 1-8 µg/L from 1986 to 1998 and averaged 2.9 µg/L (n=78) (Salinas, 2000), however, this included measurements at the detection limit (1 µg/L) in calculating the mean.

SRP was analyzed in 228 samples. Of these, 17 were duplicate measurements. One of the duplicate measurements had a different SRP concentration (RPD 200 %). Detectable concentrations (1 µg/L with a precision level of +/- 2 µg/L (Salinas, 1999)) were measured in 5 of the samples (two percent). When detectable, concentrations ranged from 2 to 3 µg/L. Salinas (2000) reported SRP concentrations ranged from 0.0 (sic) to 7.0 µg/L, and averaged 1.2 µg/L from 1986 to 1998 (n=227).

Three samples were collected at locations indicated as "Boat Dock", "Pontoons South end of cove" and "Pontoons North end of cove" on 28 August 1996. These three samples had higher phosphorus concentrations than samples collected at the LTM and NS stations. Dissolved phosphorus concentrations ranged from 40 to 1245 µg/L and total phosphorus ranged from 97 to 2515 µg/L. These values suggest localized phosphorus inputs could be occurring, but better metadata is needed to interpret these results.

Nitrogen

A total of 236 samples were analyzed for NO_3 + NO_2-N. Duplicate samples were analyzed at the laboratory, but no duplicate samples were collected in the field. Twenty-five duplicate samples were analyzed in the laboratory, of these two had different concentrations (RPD 200%).

Sixteen samples (6.8 percent) had concentrations at the detection limit (1 µg/L with a precision level of +/- 1 µg/L (Salinas, 2000)), and one sample contained concentrations above the method detection limit (2 µg/L collected on 13 September 1997).

Ammonia-nitrogen was analyzed on 49 samples collected in 2002 and 2003. No ammonia-nitrogen analyses were done from 1996 through 2001. Seven of the 49 samples were duplicated in the laboratory; of these, three had concentrations which were different, ranging from 40 to 200 relative percent difference. All samples had ammonia-N concentrations below the method detection limit (10 µg/L with a precision level of +/- 2 µg/L (Salinas, 2000)). Data files received from the laboratory reported concentrations below the method detection limit. Concentrations below the method detection limit were considered unreliable.

Silica

A total of 200 samples were analyzed for silica between 1996 and 2003 at both the long-term monitoring site and at locations along the north shoreline. The silica concentrations were above the method

detection limit (0.2 mg/L) in 138 samples. Concentrations ranged from 0.2 to 0.34 mg/L and averaged 0.24±0.003 mg/L (1 standard error).

Twenty-three of samples were duplicated in the laboratory. Of these, ten had different concentrations, ranging from 3.2 to 18.2 % RPD.

North shore locations had higher concentrations of silica than the long-term monitoring site during all years sampled (Figure 45). Silica concentrations increased from 1996 through 1999 at the north shore site following the 1996 fire, perhaps reflecting mobilization of silica in burned soils, and then declined in 2001 through 2003. The average silica concentration of the long-term monitoring site was 0.23 ± 0.003 mg/L (1 standard error, n= 93); the north shore average concentration was 0.25 ± 0.006 mg/L (1 standard error, n= 45). Both locations had a maximum concentration of 0.34 mg/L on 19 August 2000.

Silica concentrations in the upper 20 m of the water column were elevated in 1999 and 2000 (Figure 46). Concentrations were higher than normal below 100 m in 1997.

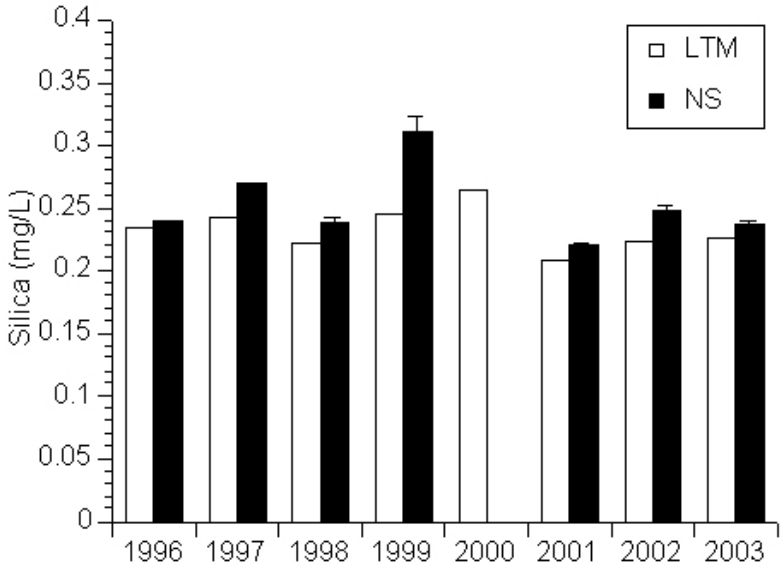


Figure 45: Annual mean (± 1 SE) silica concentration at the long-term monitoring site and along the north shore. No samples were collected at the NS stations in 2000.

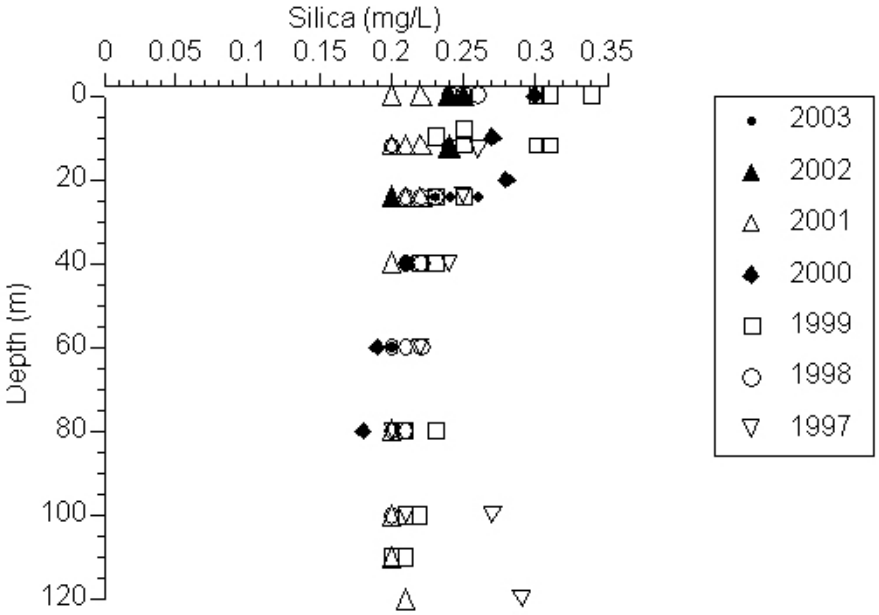


Figure 46: Profiles of silica concentrations at the LTM site in Waldo Lake in 1997-2003.

Biological Characteristics

Phytoplankton Community

A total of 124 phytoplankton samples were collected between 1999 and 2003 (Table 13). No samples were collected in 2000 and data collected from 1997 and 1998 were not made available for this analysis.

Table 13: Samples analyzed between 1999 and 2003. LTM indicates the long-term monitoring site in West Bay and NS indicates the North Waldo Lake Campground swim area and boat launch.

Year	LTM	NS
1999	35	
2001	37	
2002	23	1
2003	28	

Phytoplankton density and biovolume increased during the sampling season in 2002 and 2003 (Figure 47). During 1999 and 2001 phytoplankton populations were very sporadic. In 1993 phytoplankton density decreased from early to late summer.

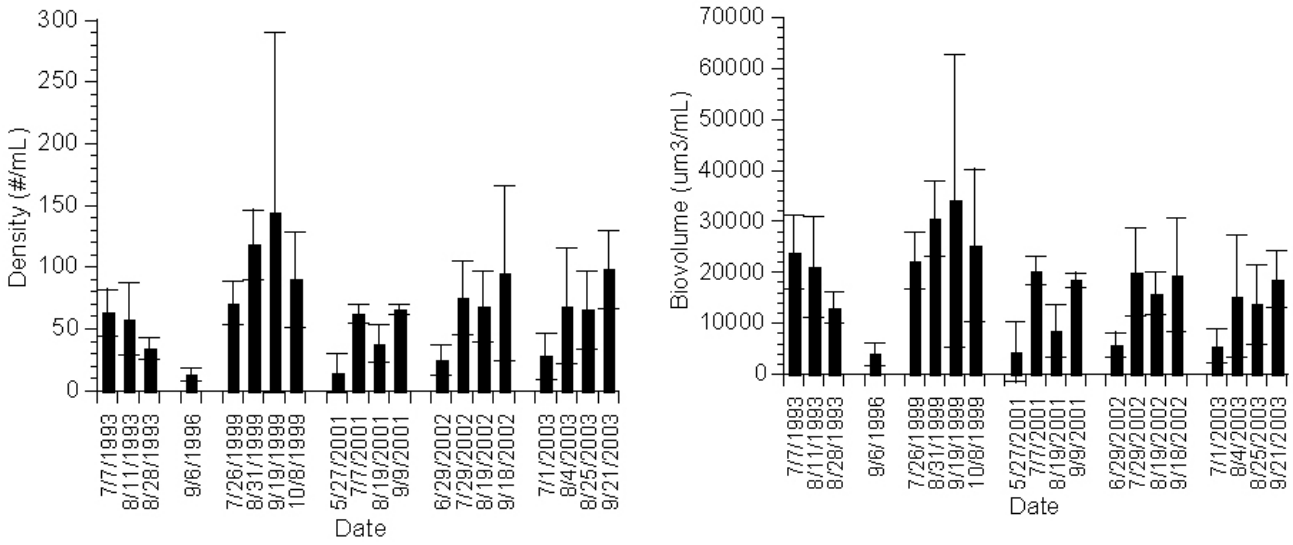


Figure 47: 1993 through 2003 average daily total density (#/mL) and average total biovolume (um3/mL) collected from all samples at all depths at Waldo Lake LTM. Based on all phytoplankton sample information available. Bars indicate 95 percent confidence intervals around the mean.

Phytoplankton densities between 1998 and 2003 were higher than reported in previous studies. Between 1986 and 1995, densities ranged between three and 111 organism/mL, with a mean of 36.3 organisms/mL (n=64) (Larson and Salinas, 1995). Between 1993 and 1998 densities ranged from five to 312 organisms/mL, with an average of 57 organisms/mL (n=112) (Sweet, 2000). From 1998 through 2003 total daily phytoplankton densities from all depths, ranged from seven to 560 organisms/mL, with an average of 71 ± 5.41 S.E. organisms/mL (n=124). Mean phytoplankton densities over the 1999 to

2003 period were generally greater than the mean densities reported by Sweet (2000) for the 1993 to 1998 period at depths greater than 20 m (Figure 48).

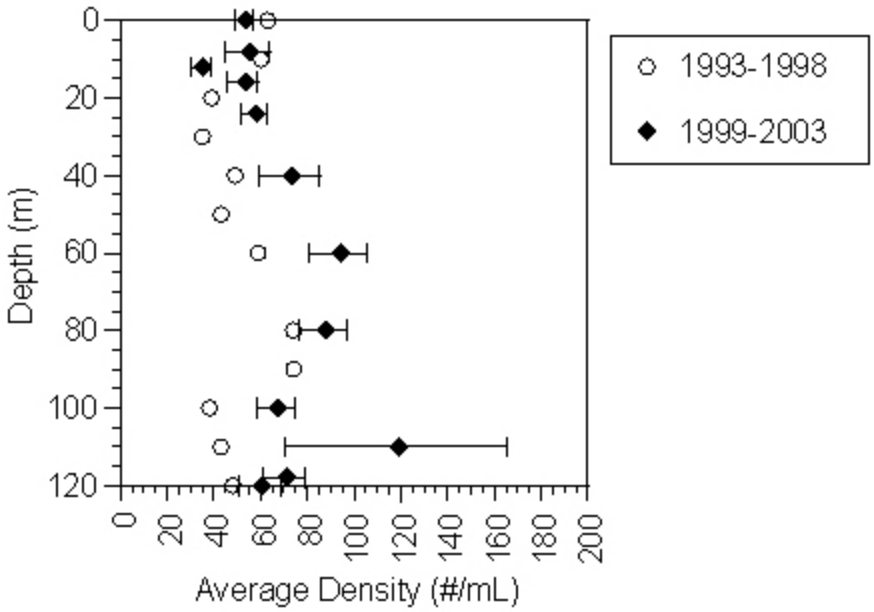


Figure 48: Depth profile of mean (± 95 percent confidence intervals) density of phytoplankton in Waldo Lake over 1993-1998 and the 1999-2003 periods. 1993 to 1998 data from Sweet (2000 p.68).

Phytoplankton biovolume from 1998 to 2003 was very similar to that reported in previous studies. From 1986 to 1995, biovolume ranged from 1,178 to 41,599 μm^3/mL, and averaged 12,744 μm^3/mL (n=64) (Larson and Salinas, 1995). From 1989 to 1998 phytoplankton biovolume ranged from 1,430 to 177,000 μm^3/mL, with an average of 19,000 μm^3/mL (n=112) (Sweet, 2000). During 1999 to 2003 total biovolume collected on each date ranged from 1,400 to 110,529 μm^3/mL, and averaged 18,000 ± 1,251.5 S.E μm^3/mL (n=124).

Seasonal patterns of phytoplankton abundance and biovolume were variable. A seasonal increase in phytoplankton occurred in 2002. In 1999 and 2001, phytoplankton populations were very sporadic (Figure 49 - Figure 51).

On 19 September 1999 biovolume and density of phytoplankton were very high in Waldo Lake. In one sample collected at 110 m, the total density was over 500 organisms/mL and the biovolume over 100,000 μm^3/mL. These values were nearly double the highest numbers of phytoplankton encountered in any other samples (Figure 49).

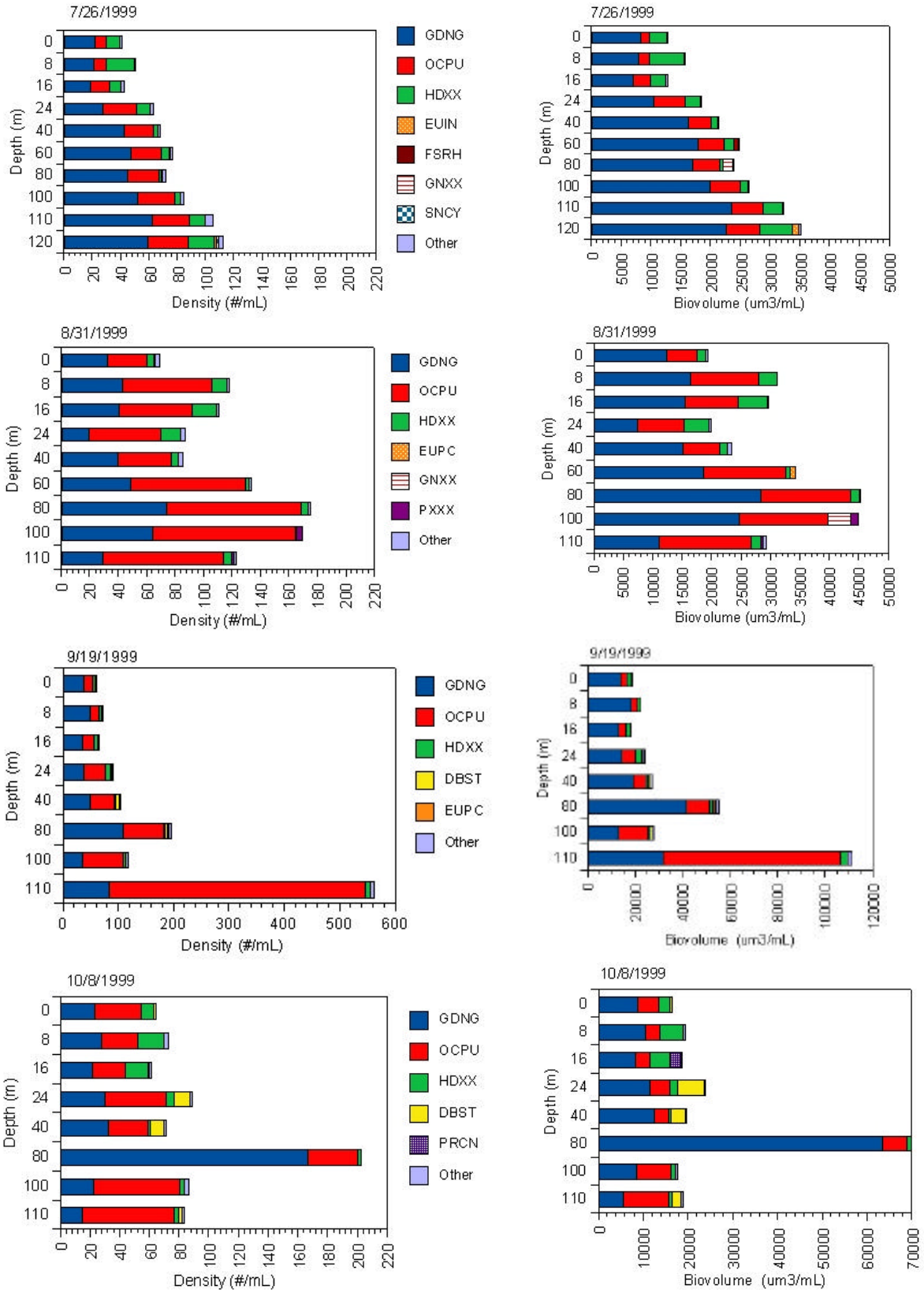


Figure 49: Vertical profiles of phytoplankton density (#/mL) and biovolume (µm3/mL) in Waldo Lake in 1999 (species codes in Table 16). Note the changes in scale on 9/19/1999 and 10/8/1999. "Other" indicates species representing less than 2 % of the total biovolume.

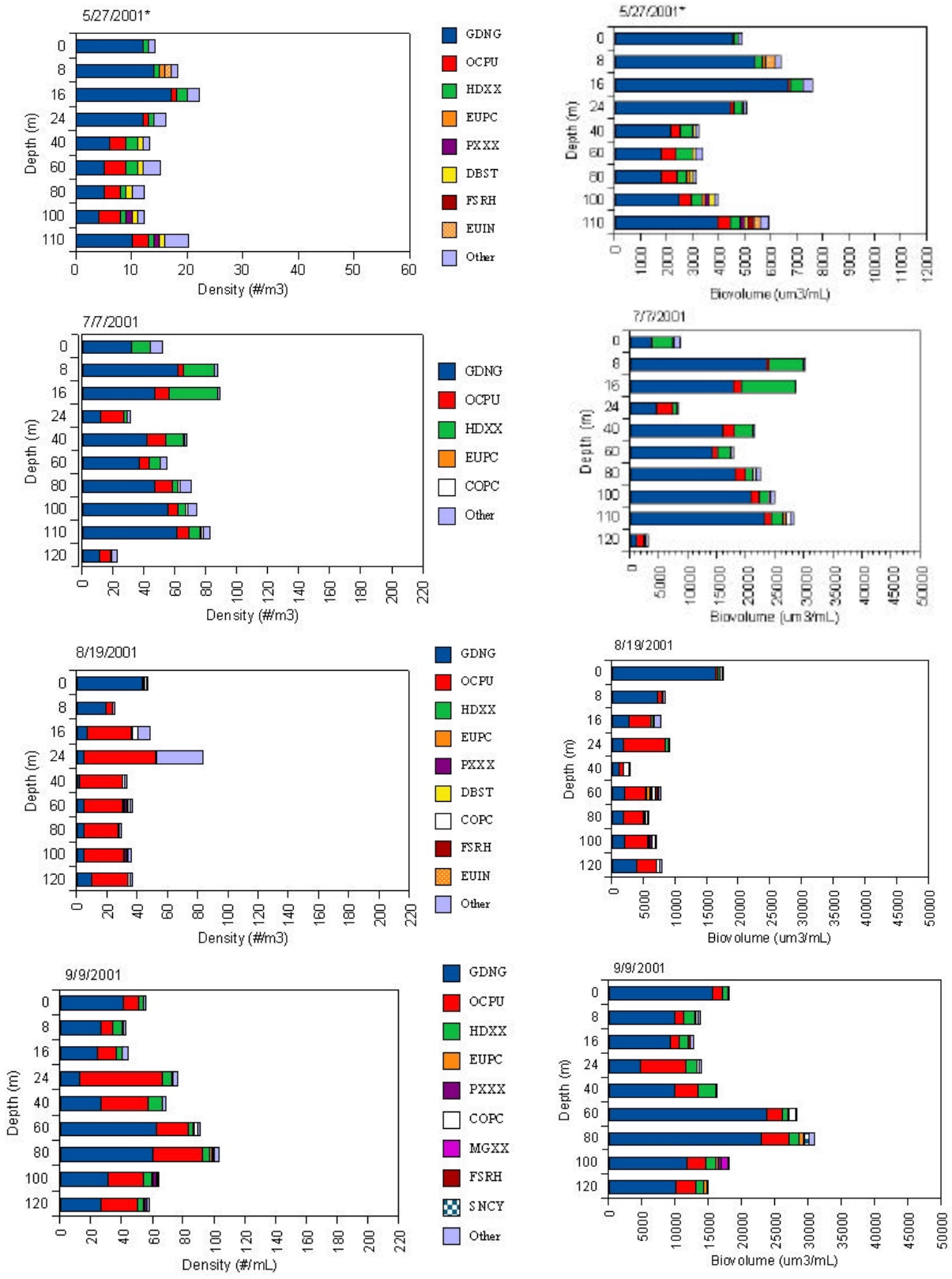


Figure 50: Vertical profiles of phytoplankton density and biovolume in Waldo Lake in 2001 (species codes in Table 16). "Other" indicates species representing less than 2 % of the total biovolume. The asterisk indicates that "Other" species were calculated as species representing less than three percent of the total biovolume. Note the scale on 5/27/2001.

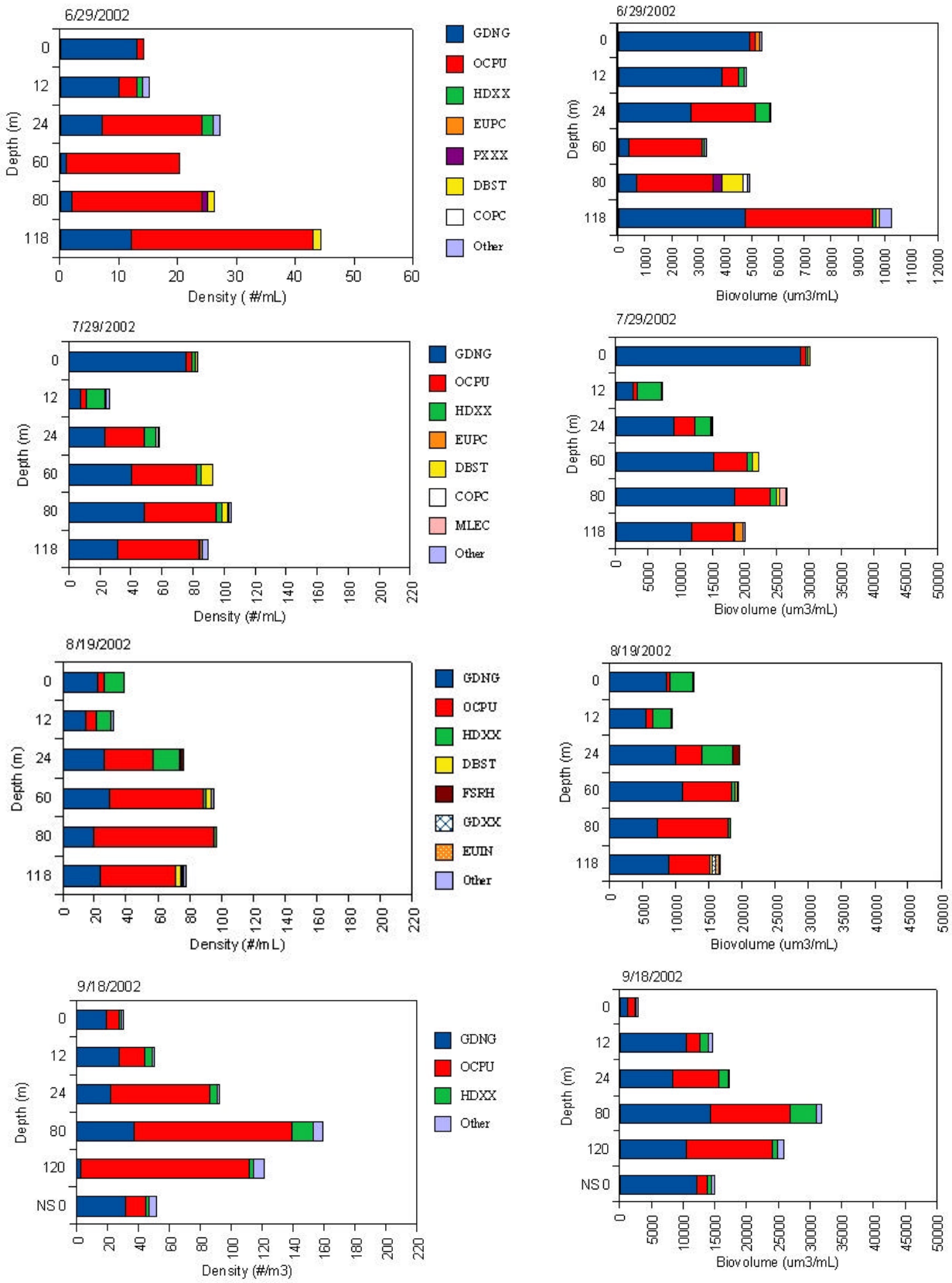


Figure 51: Vertical profiles of phytoplankton density (#/mL) and biovolume (µm3/mL) in Waldo Lake in 2002 (species codes in Table 16). Note change in scale on 6/29/2002. "Other" indicates species representing less than 2 % of the total biovolume.

Major changes occurred in species dominance in the lake. *Oocystis pusilla* was considered a common taxa in previous publications (Sweet, 2000), but no mention was made of its distribution in the water column, suggesting that it was not a major component of the phytoplankton community. However, between 1999 and 2003 its percent occurrence in samples as a common taxa was higher than or equal to that of *Glenodinium neglectum* (Table 14), which once dominated the phytoplankton community at all depths (Sweet, 2000). The increase in phytoplankton density and relatively unchanged biovolume in the 1999 to 2003 period when compared to early reports was primarily due to this change in dominant species. The contribution of *O. pusilla* to biovolume was low compared to its contribution to density.

In 2003, additional phytoplankton species were present in samples in high densities. Diatoms such as *Achnanthes minutissima, Navicula cryptocephala veneta, Crucigenia sp.* were present as common taxa in many of the samples (Table 14). In previous years common taxa were generally only represented by *O. pusilla, G. neglectum* and *Hemidinium sp*. (2003 species distribution has not yet been analyzed in full detail. Species identification was completed in March 2003.)

Table 14: Occurrences of common taxa in samples from 1999 to 2003

Year	Species Name	Percentage[1]
1999	*Oocystis pusilla*	100.0
	Glenodinium neglectum	100.0
	Hemidinium sp.	31.4
	Dinobryon sertularia	5.7
2001	*Glenodinium neglectum*	94.6
	Oocystis pusilla	73.0
	Hemidinium sp.	24.3
	Unidentified flagellate	8.1
	Tetraedron regulare	2.7
2002	*Glenodinium neglectum*	91.7
	Oocystis pusilla	87.5
	Hemidinium sp.	20.8
2003	*Oocystis pusilla*	89.3
	Glenodinium neglectum	64.3
	Hemidinium sp.	14.3
	Achnanthes minutissima	10.7
	Navicula cryptocephala veneta	3.6
	Crucigenia sp.	3.6

1 Percentage of occurrences in samples analyzed each year in which the species density is greater than 10 percent of the total density.

The importance of dinoflagellates in the phytoplankton community structure was less in the 1999 to 2003 period than in the 1986 to 1995 period (Table 15). Between 1986 and 1995 dinoflagellates were comprised almost exclusively of *G. neglectum*. In 28 out of 64 samples analyzed *G. neglectum* was the predominant species, representing 90 percent or more of the phytoplankton population at all depths in the water column (Larson and Salinas, 1995).

In 1999 to 2003, dinoflagellates, in the class Dinophyceae accounted for only between 35 and 55 percent of the phytoplankton density and 52 and 78 percent of the biovolume (this reflects *G. neglectum* and *Hemidinium sp*.) (Table 15). Chlorophyceae comprised between 37 and 51 percent of the total phytoplankton and between 1.5 and 11 percent of the biovolume of phytoplankton in Waldo Lake. The Chlorophyceae were predominantly represented by *O. pusilla*. *Tetraedron regulare* and *Crucigenia sp.*

were represented between 10 and 15 percent of the sample density in some samples; other species were also present, but at less than 10 percent of the total abundance. Together, dinoflagellates and green algae accounted for the majority of phytoplankton in the lake.

Table 15: Average total density and biovolume of phytoplankton classes from all samples collected from Waldo Lake LTM between 1999 and 2003.

Density (#/mL)	Mean ± SE	n	Maximum	Minimum
Dinophyceae	248.17 ± 42.13	16	503.59	29.32
Bacilliarophyceae	21.31 ± 10.98	16	174.36	1.42
Chlorophyceae	266.43 ± 50.09	16	747.80	19.27
Chrysoyphyceae	8.32 ± 1.60	16	22.60	1.06
Chryptophyceae	1.19 ± 0.38	7	3.17	0.41
Unknown	4.30 ± 0.84	14	11.26	0.71
Biovolume (μm^3/mL)	**Mean ± SE**	**n**	**Maximum**	**Minimum**
Dinophyceae	92279.89 ± 15667.05	16	11228.44	184332.71
Bacilliarophyceae	5526.62 ± 2387.44	16	207.74	39255.55
Chlorophyceae	38865.01 ± 7878.21	16	2928.07	117388.52
Chrysoyphyceae	1616.00 ± 679.29	16	48.45	11276.60
Chryptophyceae	120.22 ± 62.11	7	9.40	457.02
Unknown	86.41 ± 17.13	14	14.18	230.29

The mean density of *G. neglectum* in the 1999 through 2003 period was lower than in the 1993-1998 period throughout the water column (Figure 52). The overall distribution of *G. neglectum* exhibited a similar vertical trend, however in 1999-2003 *O. pusilla* was present in highest densities in the lower depths of the water column (Figure 53), where it was previously found only in low densities. The decrease in *G. neglectum* and increase in *O. pusilla* in recent years may account for variation in chlorophyll-a concentrations and spectral changes in the water column noted previously. The cause of the shift in dominance is unknown but may relate to changes in grazing pressure by zooplankton, alteration in nutrient concentrations or ratios, water column mixing events or changes in light attenuation or quality. The sampling intensity of the long-term monitoring program is not sufficient to understand details of phytoplankton community changes which occur on time scales of less than two weeks.

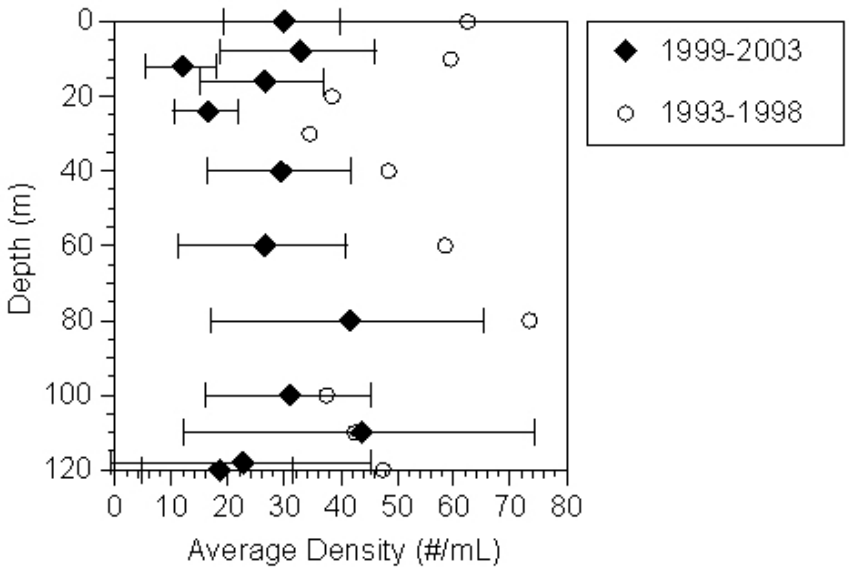


Figure 52: The decrease in density of *Glenodinium neglectum* between 1993-1998 and 1999-2003 at Waldo Lake. Dark circles indicate the average density of samples collected from 1999-2003, collected at that depth. Bars indicate 95 percent confidence interval around the mean. Hollow circles indicate average of density of samples collected between 1993 and 1998 (Sweet, 2000).

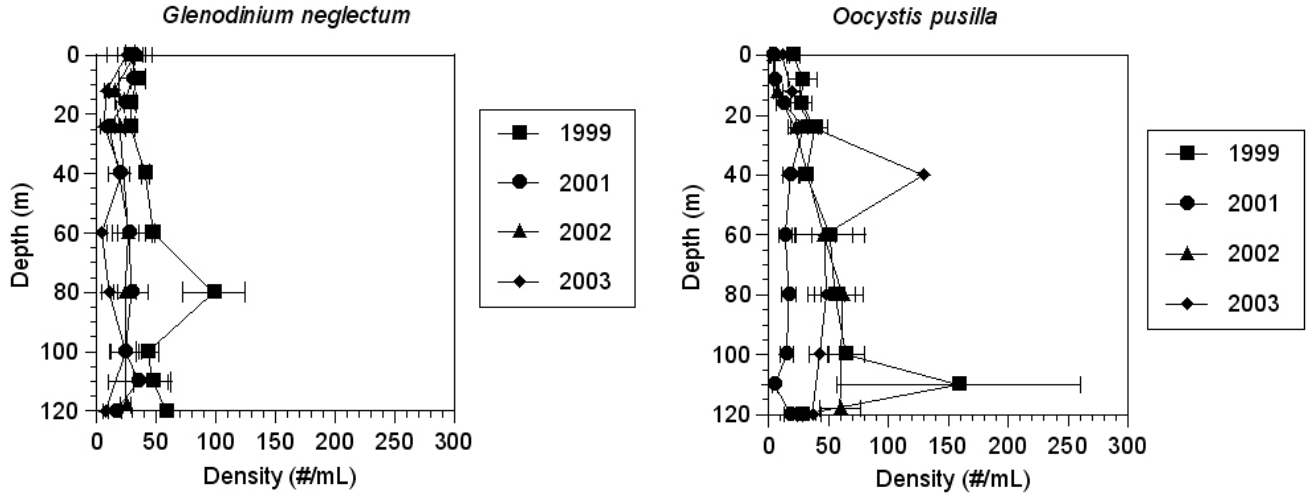


Figure 53: Average yearly density (#/mL) of *Glenodinium neglectum* and *Oocystis pusilla* with depth, points indicate the average density, bars indicate standard error.

O. pusilla and *G. neglectum* differ in size, shape and motility. These differences may influence their ability to utilize low light and low nutrient conditions, escape predation, or offer protection from or avoidance of UV radiation. As a larger species *G. neglectum* may be more pigmented, therefore may be better adapted for conditions in the upper depths of the water column than the smaller species, *O. pusilla.* The distribution and density of *O. pusilla* varied between 1999 and 2003, but the species always occupied depths below 20 m, indicating strong surface avoidance during all years.

Physical adaptations for exposure to UV light can influence an organisms' distribution in the water column. Teubner et al. (2001) reported that larger phytoplankton are better adapted to high light conditions. Plankton over 10 µm have a lower chlorophyll-a to ß-carotene pigment ratio. Smaller size classes of phytoplankton (under 10 µm) are more efficient at utilizing low light conditions and have a

higher chlorophyll-a to ß-carotene pigments. Thus, larger phytoplankton are more able to protect themselves against UV radiation, and smaller phytoplankton are more able to photosynthesize in lower light environments.

Average surface concentrations of chlorophyll-a increased between 1993-1998 and 1996-2003, but surface phytoplankton density, on average, decreased slightly between 1993-1998 and 1999-2003 (Figure 48), offering no apparent explanation or relationship between chlorophyll-a and phytoplankton. The vertical distribution of phytoplankton biovolume in the water column was not previously published, more data is needed to assess if the vertical distribution of phytoplankton biomass has changed since previous publications and if this is a reason for changes in chlorophyll-a in the water column. A more detailed analysis, comparing biovolume and chlorophyll-a concentration is needed to understand the relationship between cell size and chlorophyll-a concentrations.

Phytoplankton sampling methods of the long-term monitoring program fail to capture vertical migration patterns of dinoflagellates. Discrete monthly sampling fails to determine timing and distance of vertical migration patterns of *G. neglectum*. Use of SCUFA to track phytoplankton maxima in the future will provide insight on the migration patterns of dinoflagellates.

In 2003 of the 24 new species recorded, not previously present at Waldo Lake, 21 were of the family Bacillariophyceae (Table 16). In 2003, diatoms have become a more integral part of the phytoplankton community, two species in particular, *Achnanthes minutissima* and *Navicula cryptocephala veneta* are both represented as common taxa in samples collected in 2003 (Table 14).

Clear changes occurred in the phytoplankton community in Waldo Lake in 2003. On 7 July 2003, diatom densities were 68.9/mL. At 0 m densities of *Achnanthes minutissima* (34.31/mL), *Gomphonema angustatum* (6.73/mL), and *Nitzschia dissipata* (4.48/mL) were all greater in density than *Glenodinium neglectum* (3.37/mL). On 4 August 2003 diatom densities were also high (174.4/mL). At 60 and 80 m, many species of diatoms were present. At 60 m *Oocystis pusilla* had the highest density (28.18/mL, 16 percent) *Achnanthes minutissima* represented 15 percent of the phytoplankton density and *Navicula cryptocephala veneta* represented 10.75 percent of the phytoplankton density. At 80 m, *Oocystis pusilla* had the highest density (30.5/mL, 43 percent) and *Achnanthes minutissima* and *Navicula cryptocephala veneta* represented 14.8 and 6.48 percent respectively.

The phytoplankton dataset is among the most complete for Waldo Lake. Changes in the phytoplankton community likely reflect alterations in nutrient ratios, light, and grazing pressure. Therefore, continued monitoring of phytoplankton is critical. The dataset should be subjected to rigorous multivariate analysis to elucidate relationships between changes in the community composition and the physical and chemical characteristics of the lake. Additionally, phytoplankton data from 1997 and 1998 must be incorporated into the dataset for the lake.

Table 16: Species name and associated species code of phytoplankton in Waldo Lake, as indicated in data sheets provided by Aquatic Analysts (Jim Sweet personal communication, 2004), asterisks indicates the species was new in 2003.

Class	Species Name	Species Code
Bacillariophyceae	*Achnanthes hauckiana*	ACHK
	Achnanthes lanceolata	ACLC
	*Achnanthes lewisiana**	ACLW

Class	Species Name	Species Code
	Achnanthes linearis	ACLN
	Achnanthes minutissima	ACMN
	Achnanthes prava	ACPV
	Achnanthes sp.	ACXX
	*Amphora perpusilla**	AMPP
	Anomoeoneis serians	AOSR
	Anomoeoneis vitrea	AOVT
	Asterionella formosa	ASFO
	*Caloneis sp.**	CLXX
	Cocconeis placentula	COPC
	Cyclotella atomus	CCAT
	Cyclotella meneghiniana	CCMG
	Cyclotella ocellata	CCOC
	Cyclotella stelligera	CCST
	Cymbella affinis	CMAF
	Cymbella angustata	CMAN
	Cymbella minuta	CMMN
	Cymbella sinuata	CMSN
	*Diatoma hiemale mesodon**	DIHM
	Diploneis elliptica	DPEL
	Eunotia elegans	EUEL
	Eunotia incisa	EUIN
	Eunotia pectinalis	EUPC
	Eunotia sp.	EUXX
	Fragilaria capucina mesolepta	FRCM
	Fragilaria construens	FRCN
	Fragilaria construens venter	FRCV
	*Fragilaria pinnata**	FRPN
	*Fragilaria vaucheria**	FRVC
	Frustulia rhomboides	FSRH
	Gomphonema angustatum	GFAN
	Gomphonema gracile	GFGC
	*Gomphonema olivaceum**	GFOV
	Gomphonema sp.	GFXX
	*Gomphonema subclavatum**	GFSB
	*Gomphonema tenellum**	GFTN
	*Gomphonema ventricosum**	GFVT
	*Hannaea arcus**	HNAR
	Melosira ambigua	MLAM
	Melosira distans	MLDS
	Melosira excurrens	MLEC
	*Melosira sp.**	MLXX
	*Navicula contenta biceps**	NVCB
	Navicula cryptocephala	NVCR
	Navicula cryptocephala veneta	NVCV

Class	Species Name	Species Code
	Navicula minisculus upsaliensis	NVMU
	Navicula minima	NVMN
	Navicula seminulum	NVSM
	Navicula sp.	NVXX
	Nitzchia communis	NZCM
	Nitzchia paleacea	NZPL
	Nitzschia acicularis	NZAC
	*Nitzschia communis**	NZCM
	Nitzschia dissipata	NZDS
	Nitzschia fonticola	NZFT
	Nitzschia frustulum	NZFR
	Nitzschia innominata	NZIN
	Nitzschia linearis	NZLN
	*Nitzschia paleacea**	NZPC
	Nitzschia sp.	NZXX
	*Nitzschia volcanica**	NZVL
	Peronia sp.	PXXX
	Pinnularia sp.	PLXX
	*Rhoicosphenia curvata**	RHCV
	Synedra cyclopum	SNCY
	*Synedra mazamaensis**	SNMZ
	Synedra radians	SNRD
	*Synedra rumpena**	SNRM
	Synedra rumpens	SNRM
	*Synedra ulna**	SNUL
	Synedra ulna contracta	SNUC
	Tabellaria flocculosa	TBFL
	Unident. pennate diatom	MXPN
Chlorophyceae	*Ankistrodesmus falcatus*	AKFL
	Chlamydomonas sp.	CHXX
	Cosmarium sp.	CSXX
	*Crucigenia quadrata**	CRQD
	*Crucigenia sp.**	CRXX
	Elakatothrix gelatinosa	ELGL
	Golenkinia radiata	GKRD
	Mougeotia sp.	MGXX
	Oocystis lacustris	OCLA
	Oocystis pusilla	OCPU
	Scenedesmus bijuga	SCBJ
	Selenastrum minutum	SLMN
	Sphaerocystis schroeteri	SCSC
	Staurastrum sp.	SMXX
	Stephanodiscus hantzchii	STHN
	Stephanodiscus hantzschii	STHN
	Tetraedron minimum	TEMN

Class	Species Name	Species Code
	Tetraedron regulare	TERG
	Ulothrix sp.	ULXX
Chryptophyceae	*Chroomonas sp.**	CAXX
	Cryptomonas erosa	CXER
	Cryptomonas sp.	CXXX
	Rhodomonas minuta	RDMN
Chrysophyceae	*Chromulina sp.*	KMXX
	Chrysochromulina sp.	KKXX
	Dinobryon sertularia	DBST
	Mallomonas sp.	MMXX
	Pseudopedinella sp.	PZXX
	Surirella sp.	SUXX
	Tribonema sp.	TNXX
Cyanophyceae	*Lyngbya sp. Agardh*	
Dinophyceae	*Glenodinium neglectum*	GDNG
	Glenodinium sp.	GDXX
	Gymnodinium sp.	GNXX
	Hemidinium sp.	HDXX
	Peridinium cinctum	PRCN
Unknown	*Unident. alga*	XXXX
	Unidentified flagellate	MXFG

Phytoplankton Primary Productivity

The availability of data collected from primary productivity incubation experiments is very limited. Only 1999 and 2001 data were available. Productivity experiments took place in 2002 and 2003, but data was not made available. In 1996-1998 field collection notes were not available to determine if incubation experiments were completed in the field during routine lake monitoring events. In 1999, no time periods for incubation, or field conditions were noted. In 2001, cloud conditions were noted, but time periods for incubation were not. Latest communication with The Cascade Research Group has indicated that primary productivity estimates from recent years need to be recalculated and estimates are incorrect. This section represents data currently available, primary productivity estimates will be reassessed for future reports.

Duplication of incubations is needed to quantify the variability inherent in the methodology that allows comparisons between incubations. In 1999 and 2001 one incubation was duplicated. On 7 July 2001 at 12 m the primary productivity was 1.192 mg C/m^3/hour, the duplicate sample was 0.879 mg C/m^3/hour, which is a relative percent difference of 30 percent.

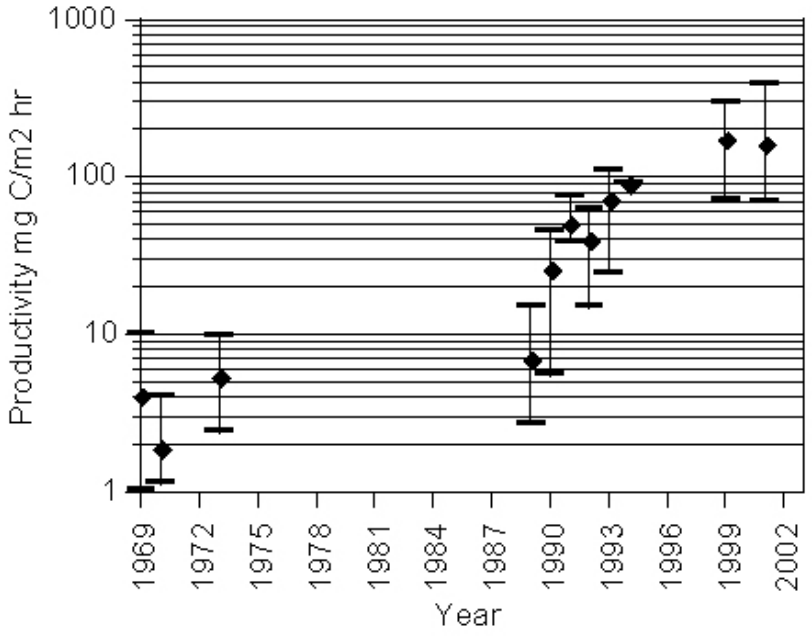


Figure 54: Primary production estimates for Waldo Lake 1969-2001. Data for 1969 -1994 obtained from data summarized in Larson (2000). Average yearly productivity of the entire water column, bars indicate the range.

In 1999 and 2001 productivity increased slightly from productivities previously reported. This increase is not as dramatic as occurred in the 1990's; indicating productivity has recently become more stable. Productivity was highest in August in both 1999 and 2001 at 8 m. In 1999 primary productivity was higher than in 2001, when phytoplankton densities were higher.

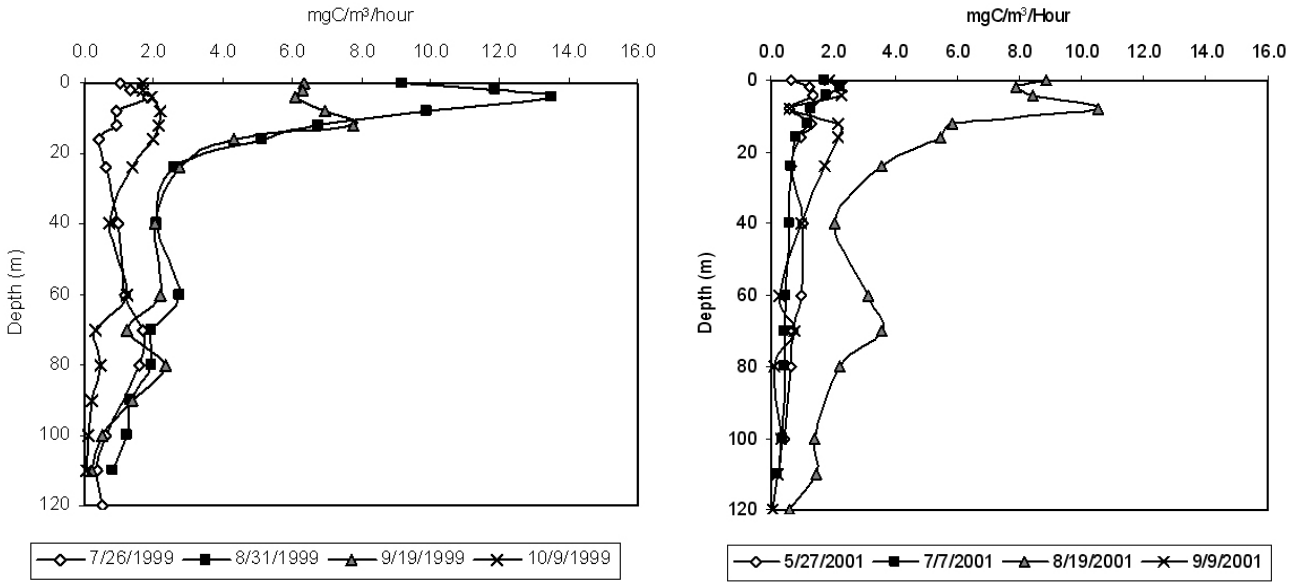


Figure 55: Primary productivity incubation profiles from 1999 and 2001.

Analysis of phytoplankton primary productivity will be completed once a complete and accurate data set is made available.

Chlorophyll-a

Chlorophyll-a samples were collected on 13 dates from 1996 through 2003. There were four sampling dates in 2001 through 2003, and one date in 1996. 1 duplicate sample analyzed on 29 July 2002 from 118 m. Methods for collection of duplicate sample are unknown; there was an 8.7 percent relative difference between the two samples collected on that date.

No samples were collected in 2000 and data from 1997 and 1998 were not available. Sampling depths differed between sampling dates. A total of 113 chlorophyll samples were collected. Most samples (109) were from the LTM site. Four additional samples were collected at the NS site in 2002 and 2003. All samples were filtered through a 0.45-µm filter. On 7 July 2001 additional filtration was performed with a 0.2-µm filter. On three dates in 2003 a Turner SCUFA® Submersible Fluorometer was used for in situ measurement of chlorophyll fluorescence.

Chlorophyll-a concentrations ranged from 0.03 to 1.6 µg/L (Table 17). The maximum concentration was measured at 120 m on 27 May 2001 (Figure 56). The high chlorophyll-a concentration at 120 m was over five times the concentration at 110 m, and the datum may be an error. If that measurement is omitted, the maximum concentration was 0.5 µg/L. Mean annual concentration (all depths and all dates) ranged from 0.085 µg/L in 2002 to 0.163 µg/L in 1996. Chlorophyll-a concentrations from 1996 through 2003 were generally lower than during the 1989 through 1995 period (Table 17).

Table 17: Mean chlorophyll-a concentrations (µg/L) collected at all depths from 1989 through 2003 (0.45-µm filter).

Years	Samples collected (n)	Minimum	Maximum	Mean
1989-1995	unknown	0.007	1.076	0.227
1996	12	0.070	0.478	0.163
2001	40	0.041	1.612	0.175
2002	25	0.033	0.216	0.085
2003	32	0.071	0.484	0.150

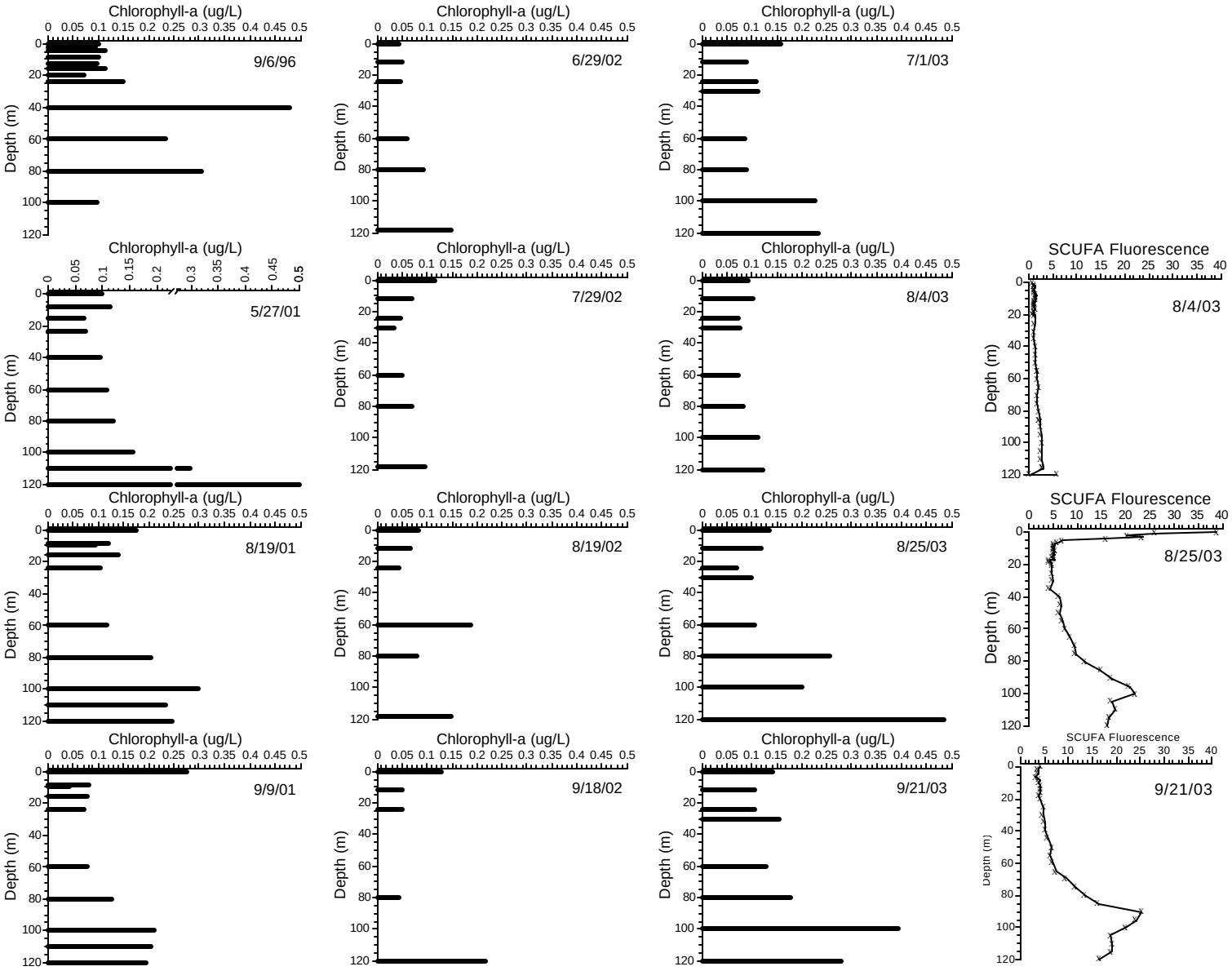


Figure 56: Chlorophyll-a concentration and SCUFA fluorescence in Waldo Lake from 1996 through 2003.

No consistent seasonal trends were evident in the chlorophyll-a data, however, highest concentrations generally were found below 100 meters (Figure 56). Larson and Salinas (1995) also reported chlorophyll-a maxima near the bottom of the lake, below the depth of 1 percent light penetration, from 1989 through 1995.

Larson and Salinas (1995) reported that minimum chlorophyll-a concentrations occurred in the top 30 meters of the water column of Waldo Lake. Chlorophyll-a concentrations in the 0 to 10-m strata from 1996 to 2003 were generally higher than in the 10 to 40-m strata. An increase in surface water chlorophyll-a concentrations may relate to changes in the phytoplankton community in the lake (see phytoplankton section).

Alternatively, high surface water chlorophyll-a may be due to an increase in periphyton density along the shoreline. Scouring of periphyton by waves may result in distribution of periphyton into the surface waters of the pelagic zone. Benthic production may contribute substantially to lake primary production (Johnson and Castenholz, 2000). Anecdotal evidence suggests that production is increasing, particularly along the north shore adjacent to the burn area. Surface chlorophyll-a concentrations at the NS station, however, averaged 0.146 µg/L (range = 0.046 to 0.309 µg/L) in 2002 and 2003; similar to the range and concentration observed at the LTM station. If scouring of near shore periphyton were a significant source of water column chlorophyll-a, concentrations at the NS station should be high although wind sheltering in the boat ramp area could potentially limit periphyton accumulation in the area of collection.

Size fractionation of the phytoplankton contribution to chlorophyll-a in the water column was determined on 7 July 2001. The filtrate that passed through the standard 0.45-µm filter used for chlorophyll analysis was additionally filtered through a 0.2-µm filter to evaluate the contribution of smaller picoplankton to the phytoplankton biomass in Waldo Lake.

Plankton less than 0.45 µm but greater than 0.2 µm represented around 10 percent of the plankton community in the upper 16 m of the water column (Figure 57). The importance of picoplankton decreased with depth; below 20 m chlorophyll-a retained by the 0.20 µm comprised about two percent chlorophyll-a retained by the 0.45 µm filter.

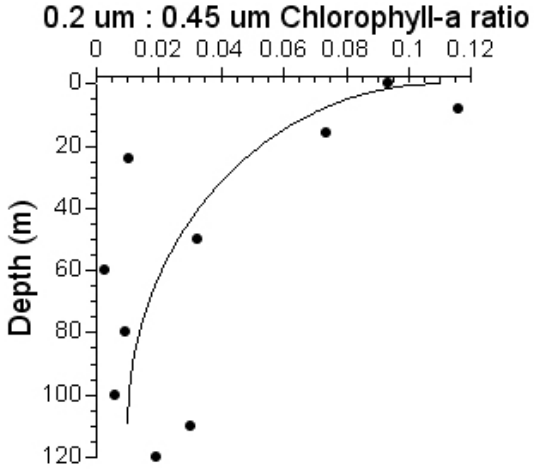


Figure 57: Ratio of chlorophyll-a retained on 0.2 µm filter to that retained on 0.45 µm filter at 10 depths in Waldo Lake on 7 July 2001 (line is hand-drawn).

The importance of picoplankton under 0.45 µm in primary productivity of Waldo Lake is unknown but has been recognized as a potentially significant (Sweet, 2000). Clearly, current methods of measuring chlorophyll-a, using 0.45 µm filters, results in an underestimate when picoplankton under 0.45 µm are abundant. The underestimate appears to be most significant in the surface waters. Additional investigation of the contribution of picoplankton under 0.45 µm to primary production is required.

In situ measurement of chlorophyll fluorescence was correlated with in vitro measurements of chlorophyll-a concentration (Figure 56); however the variability in SCUFA fluorescence was large on some occasions. In general, SCUFA fluorescence increased with depth when chlorophyll-a increased with depth (Figure 56); however, high SCUFA fluorescence was measured in surface waters on 25 August 2003 that was not correlated with water column chlorophyll-a concentration. The high surface fluorescence may be related to lack of warm-up time or some other equipment deployment failure. In addition, however, four repeated measurements at 120 m on 4 August 2003 resulted in SCUFA fluorescence ranging from 0.37 to 8.50. The coefficient of variation in the measurements was 74 percent. Similar variability was not evident in duplicate measurements at 56, 86, and 116 m on 4 August 2003 or on audits conducted during the upcast of the instrument on 25 August 2003. SCUFA may be a valuable tool for tracking phytoplankton populations and its use could enhance understanding of phytoplankton distribution and abundance, however, data quality assurance protocols are needed for effective use of SCUFA in Waldo Lake.

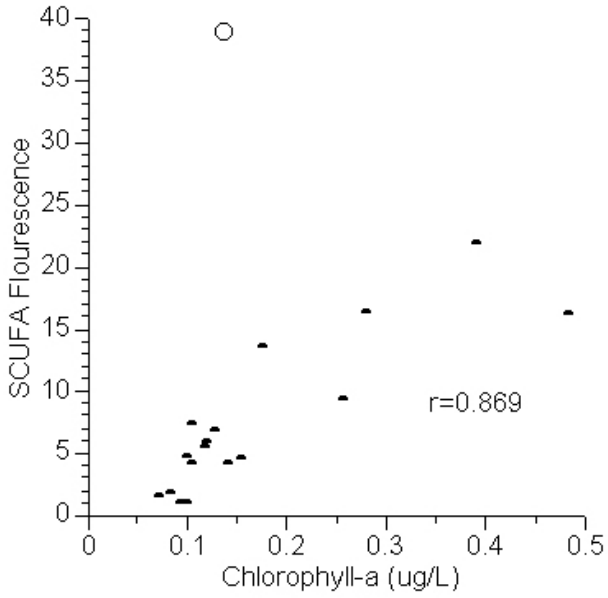


Figure 58: Correlation between chlorophyll-a concentration and SCUFA fluorescence measurements in Waldo Lake in 2003. Only data where SCUFA and chlorophyll-a were collected within 0.5 m of each other were used. SCUFA and chlorophyll-a samples were collected at different times of the same day. The open circle is a surface water measurement made on 25 August 2003 that was excluded from the calculation of the correlation coefficient.

Photosynthetic Efficiency

Introduction

A study of the phytoplankton productivity in Waldo Lake by Salinas and Larson (2000) used in situ incubations of water samples with ^{14}C to estimate primary productivity. In this method, water samples are collected, spiked with ^{14}C, and re-deployed back into the lake in clear and dark bottles for four-hour incubations. The incubation times were usually from 10 am to 2 pm, bracketing noon. The incubation time was important because diel rates of primary production don't always follow the photosynthetically active radiation. Porter (1988) states that "standard mid-day 3-4 hour incubations periods are not yielding realistic or qualitatively sound measurements of pico-and microplankton primary production." Although Salinas and Larson (2000) used standard, accepted techniques, there was a large amount of variability in the productivity measurements. Even with this variability however, a comparison of their recent results to measurements made in 1968 confirmed the hypothesis that there has been an approximate ten-fold increase in productivity over the last three decades (Larson, 2000).

The crucial question is whether the algal population will continue to increase and degrade the clarity that makes Waldo Lake unique. This work explores to what extent the variability in productivity may provide a clue to the future pattern and to what extent the variability is a methodological problem. One should be open to the idea that variability and propagation of variability in natural systems provides important insights. In the words of Carpenter and Kitchell (1988) "The magnitude of temporal variability and the frequency of counterintuitive behavior evidenced by lake communities continue to surprise limnologists and defy prediction." The standard method for measuring primary productivity that was employed by Salinas and Larson (2000) does not usually produce such large variability. Some aquatic systems have characteristics that express high levels of variability during periods in their development. For example, Diamond Lake has been observed to have wild fluctuations in the dissolved oxygen just prior to bloom formation (David Gilbey, Oregon Department of Environmental Quality, 2004, personal communication). The underlying structure of systems that manifest fluctuations can be changing; switching from one quasi-steady state to another.

There are several features of Waldo Lake that may make it particular susceptible to these fluctuations. In particular the lake's high altitude, high proportion of clear days and extremely low levels of dissolved material makes the incident and transmitted ultra-violet light much higher than in other lakes. Natural variations in UV exposure or unintentional variation in UV light conditions during preparation and incubation could lead to large variations in the measured productivity. This sub-project of the overall research plan was designed to address whether UV exposure could account for variability in photosynthetic efficiency. The rationale for this sub-project was to help modify the methods for measuring net primary production and to help understand natural variability in an attempt to determine if these were part of natural fluctuations in community response. The complimentary methods used in this sub-project allow primary productivity estimates to be taken quickly and more frequently

Photosynthesis is often studied and modeled by decomposing the overall reaction into multiple sub-processes that each depend on the function of the cell's molecular machinery. There are four ranges of light where different processes dominate. In the dark and very low light, the respiration processes that consume O_2 and carbohydrate stores dominate. At low to just subsaturating light the relationship between light intensity and production rate at subsaturating light depends on the relative amount of chlorophyll in the light harvesting systems. In the region of saturating light the rate of photosynthesis depends on the ratio of carbon fixation enzymes to the light harvesting systems. Above saturating light intensities there may a decrease in the net photosynthetic rate due to photorespiration, reversible and irreversible photoinhibition. Whereas dark and low light regimes can be considered in cellular steady state, light levels at or above saturating cause cellular damage with a dose response. At higher lights, longer exposures to the same level of light can lead to decreased instantaneous rates of photosynthesis. The model used was based on observed destruction and repair of particular protein components in the

photosystems (Pahl-Wostl and Imboden, 1990). The model however simply fits the dose for destruction as an exponential function parameterized by the time for 50 percent inhibition and an exponential repair rate.

Ultraviolet radiation needs to be considered explicitly at Waldo Lake. The dosages of UV in Waldo Lake are much higher than they would be for other lakes because of the altitude, number of clear days and the extremely low dissolved organic matter. The benthic cyanobacteria in Waldo Lake were shown to produce UV-screening pigment, indicating that even the benthic algae are affected by UV in this environment (Johnson and Castenholz, 2000). Algal cells are exposed to a range of UV light as they are mixed up and down in the water column. The rate of mixing, depth of the surface mixed layer and the attenuation of UV light all contribute to the dose of UV and the inhibition of cells. Franks and Marra (1994) used a Lagrangian model that follows individual cells to show that the particular mixing and light conditions can either protect or exacerbate photoinhibition. Because Lagrangian type models also help visualize the paths of individual cells, they can also help understand the potential variability between water samples that might have originated from a packet of water that had just recently been mixed up or down to the sampling depth.

The main experimental goal of the first year of research was to develop and test potential methods for measuring variations in photosynthetic production so experiments could be designed to address the importance of variability. PAM Fluorometery was employed using the most sensitive model, the Water PAM Fluorometer that has listed detection limits at the same concentrations of chlorophyll-a as seen in Waldo Lake during much of the season. This instrument was used to follow with incubations with different light conditions (both light level and +/- UV). An attempt was also made to do short term ^{14}C incubations in parallel to the PAM Fluorometer incubations.

Methods and Analysis

Sampling times and locations

Experiments were conducted on four different days during August and September of 2003 (Table 18). The experiments were done on the same days when the sampling was conducted.

Table 18: Field Sampling and Incubation

Date	Incubation period, hrs	Time of Incubation	Description
4 August 2003	4	12:08 pm - 4:00 pm	Shore side sample on the east side of North Bay collected at 11:11 am.
24 August 2003	5	9:30 am - 2:30 pm	Sample collected from 30 m depth at a site just beyond North Bay using John Salinas' Van Dorn at 8 am. Shore side incubation site shady until 12:22 pm due to orientation of sun on eastern side of lake
25 August 2003	4	10:25 am - 2:25 pm	Sample collected from 30 m depth at approximately the same area as sample taken 8.24.2003 at 9 am
26 September 2003	4	11:30 am - 3:30 pm	Sample collected from 30 m depth at approximately the same area as samples

Date	Incubation period, hrs	Time of Incubation	Description
			taken 08.24.2003 and 08.25.2003

The bulk water sample was dispensed into Whirl-Pak bags and incubated in incubators that were in kept in the lake to maintain temperature. For ^{14}C incubation the stock $NaH^{14}CO_3$ was added to the bulk water sample and mixed well before dispensing. Individual Whirl-Paks were wrapped in screening to set a range of light. Samples were incubated with and without a Plexiglas filter. The Whirl-Pak bags were used instead of other containers because they allow over 70 percent of UV-B to be transmitted. Plexiglas filters out UV. The combinations of neutral screens and Plexiglas allowed comparing plus and minus UV at a range of light intensities.

Incident light measurements

During the period of the onshore incubations, PAR and UV measurements were recorded every 30 minutes. PAR values were taken with a LICOR meter with sensor positioned next to the incubation chamber. UV measurements were taken with the International Light Meter, Model IL1400A with a model SEL240 probe.

PAM Fluorometer method

In order to understand the photosynthetic efficiency of phytoplankton communities in Waldo Lake, the maximal photochemical yield using a Pulse Amplitude Modulation (PAM) Fluorometer was measured. This device was designed to make highly sensitive chlorophyll fluorescence measurements on small samples of lake water using a saturation pulse given off by LED's in the measuring unit. After samples are dark-adapted (opening all reaction centers of photosystem II), the maximal fluorescence yield (F_m) is measured and variable fluorescence (F_v) is calculated. A measure of the potential quantum yield of PSII is then given by F_v/F_m.

F_m = maximal fluorescence yield
F_o = dark level fluorescence yield (measured before saturation pulse)
$F_v = F_m - F_o$
F_v/F_m = maximal quantum yield

In the field, a 30 m sample of lake water was divided into Whirl-Paks and placed in an incubation tub. The tub was flooded with lake water at the shore to maintain a constant temperature. Samples were divided into four different light schemes: no screen with UV exposure (ns+UV), no screen without UV (ns-UV), three screens with UV (3s+UV), and three screens without UV (3s-UV). The screened samples were in bags made of mesh with three layers. Samples without UV exposure were shaded with a piece of Plexiglas, which blocked 92 percent of wavelengths below 370 nm. After an initial measurement of F_v/F_m (before placing samples in incubator), subsequent samples were taken approximately every 40 to 60 minutes. At each sampling point, three mL of water were measured into the cuvette and allowed the sample to dark-adapt for 5 minutes before measuring fluorescence. Three repetitions of measurements were performed at each sampling point to find an average value.

^{14}C method

Samples were dispensed into 1 L Nalgene dark bottles, to which one ampoule of ^{14}C was added. 50 mL of the inoculated sample were then added to Whirl-Pak bags for incubation. Whirl-Paks were also placed into screen bags to alter light attenuation. Standard incubations were conducted using zero, one, two, three, four and five screens, as well as one sample in the dark. Time-course incubations were conducted using zero and six screen, as well as a sample in the dark. Incubations were conducted in duplicate, with one set of samples exposed to UVR, and one set of samples protected from UVR using a Plexiglas shield.

Incubations were conducted at shore side using a flow-through tank. For time-course incubations, samples were removed every hour and 3 mL of sample were added to triplicate scintillation vials prepared with 200µL of 10 percent HCl. Samples were then placed back into the tank. For standard incubations, the procedure was the same, but all samples were removed at the end of incubation. All samples were kept in the dark upon removal from the tank and during processing. Upon return to the lab, 21 mL of Beckman Ready-Safe scintillation cocktail was added and samples were counted using a Beckman scintillation counter to get raw disintegrations per minute (DPM) data.

Chlorophyll-a

Chlorophyll-a was measured by filter fluorometry on acetone extracts of filter samples. Filters are gently but completely macerated in a glass mortar with a Teflon pestle. Ten mL of 90 percent acetone are used in the grinding and rinsing process. The ground sample was extracted for at least 24 hours, refrigerated in the dark. These sample tubes are spun at low speed to remove glass fiber fragments from the liquid phase and then measured in a Turner Model 10 Fluorometer. This fluorometer was calibrated using chlorophyll samples that simultaneously measured spectrophotometrically.

Results

Time course incubations with PAM Fluorometry

Incubations and intensive sampling for PAM fluorometer measurements demonstrate a definite inhibition of the efficiency of photosynthesis within the first hour of exposure to full light and UV. Incubation under 3 neutral density screens (which provides about 10 percent of incident light). With 3 screens there was little difference in the fluorescence yield between +UV and -UV incubations (Figure 59). There was a large difference however when cells were exposed to full sun (Figure 60). The fluorescent yield of both +UV and -UV decreased with time, indicating an inhibition of photosynthetic efficiency. The +UV incubations decreased dramatically by over 50 percent in only an hour.

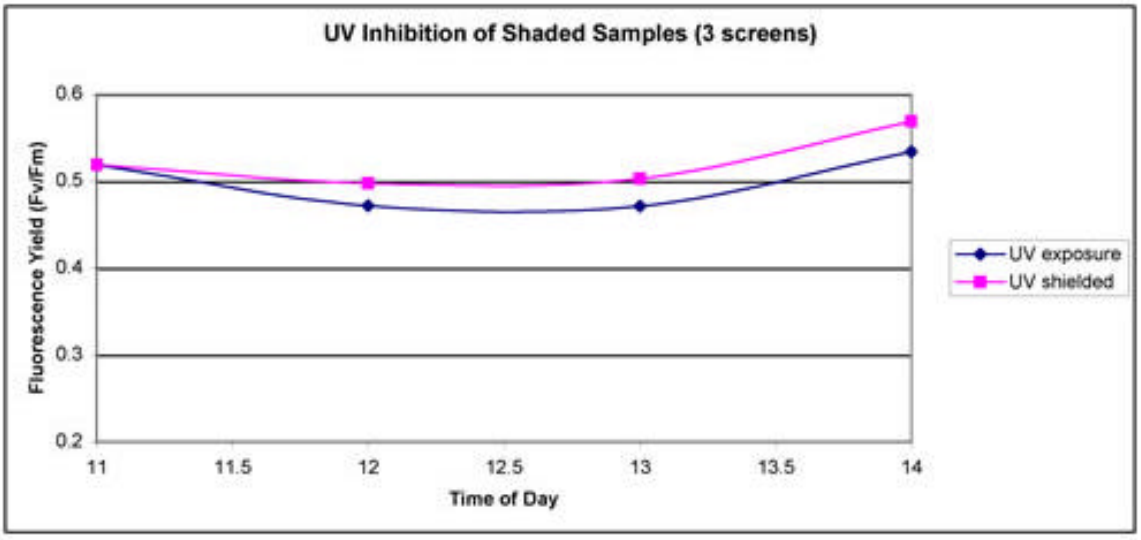


Figure 59: Time course of incubation with 3 screens comparing with and without UV exposure. This data was collected on 25 September 2003.

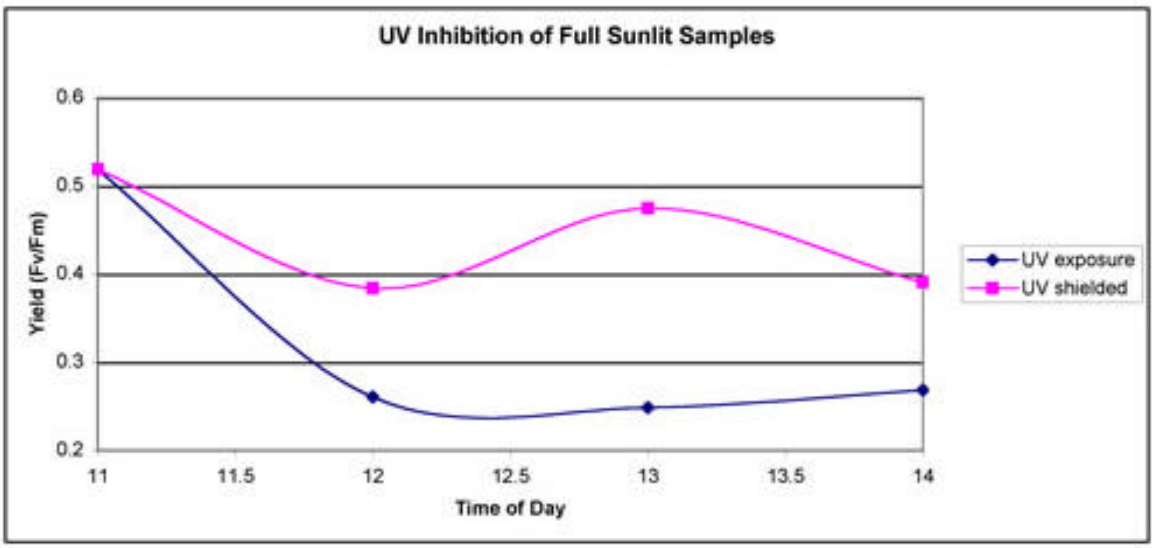


Figure 60: Time course of incubation with full sunlight exposure comparing with and without UV exposure. This data was collected on 25 September 2003.

Time course productivity studies

The standard method for primary productivity measurements with ^{14}C examines the net radioactive carbon fixed. A time course incubation was performed on a matrix of conditions for +/- UV and either no screens or 6 screens (which gives approximately 3 percent of incident light) (Figure 61). The 6-screen -UV time course was the only condition that led to continually increasing net carbon fixed. The other conditions had higher fixed carbon after only two hours and then actually lost net carbon fixed. This was not a decreased rate but a decrease in the total amount fixed, meaning that cells in these three conditions were actually loosing fixed carbon during the last two hours of the incubation. Because the method measured both dissolved and particular organic carbon (as opposed to the standard method which only measures particulate carbon), these results indicate that the cells were respiring fixed carbon

back to CO_2. A similar drop in total fixed particulates could include a loss to dissolve organic carbon. These results indicate that the incubation time is a particularly important parameter at high light or samples that are exposed to UV.

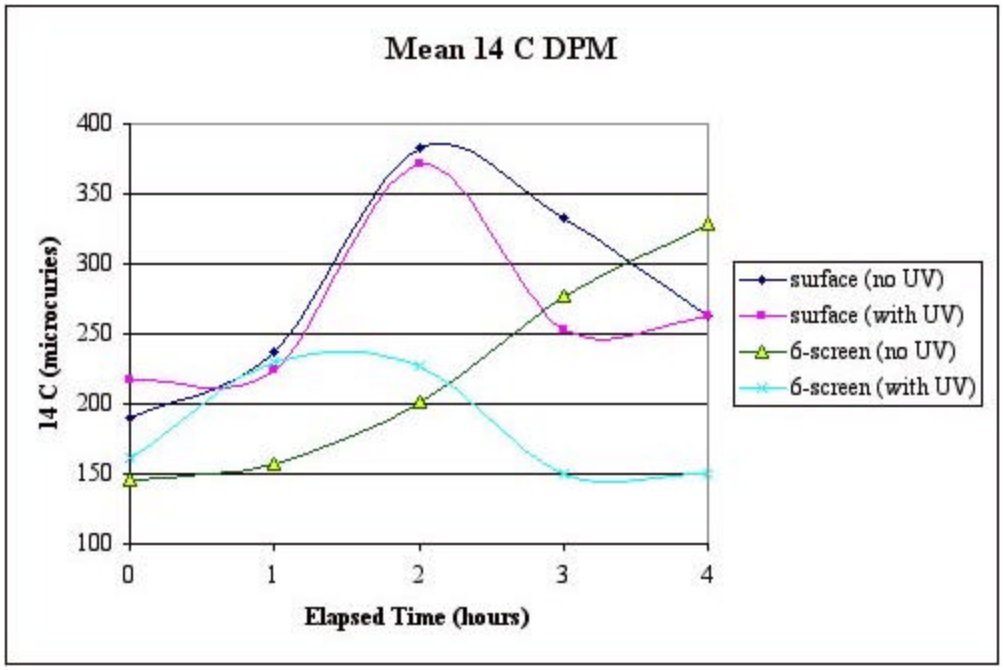


Figure 61: Incubation of multiple samples over a total period of four hours. Some samples were pulled from each incubation condition each hour. The 6-screens provide approximately 3 percent of incident light. This example experiment was conducted on 25 August 2003.

Chlorophyll transect

Samples for chlorophyll were taken along the north shore of the lake on 25 September 2003. The samples were taken in several of the bays, near shore, about half way out the bay and at the mouth of the bay as judged from the shore line. The individual values were compared to the average of the deep water portion of the lake. Even the three samples taken from blue water had a high sample-to-sample variability. The cove that is west of the burn and has a sand beach had much higher average chlorophyll content (over 60 percent higher than the average blue water samples). Because just the variability in these samples was being investigated, transects like this should be redone this year with real time *in vivo* fluorescence. This transect was performed because a colleague had flown over the lake several times and mentioned that he thought the lake looked greener near the burned section. The observed color could also be from benthic plants and should be further investigated.

Discussion

The purpose of this research project was to explore conditions that could be leading to a general increase in productivity in Waldo Lake. Understanding the dimensions of this problem will hopefully facilitate management decisions. Although measurements were made at the shortest time scale (minutes to tens of minutes) and smallest spatial scales (single samples of a liter), there is an attempt to try to put these into a context that addresses the long term trend in productivity that has happened over decades. This

analysis looks at three aspects of how a fluctuating environment may suppress or increase community productivity. First, variations in mixing from day to day could cause changes in productivity due to UV exposure regimes. Second, there may be fluctuations in the capacity of the environment to support growth. An example of this could be weekly patterns of clear and cloudy days that might change during a drought periods. Third, fluctuations in environmental conditions may cross a slow changing threshold and lead to a regime changes (such as higher productivity).

Model of UV inhibition and water mixing

Photoinhibition, and in particular enhanced UV inhibition, is a function of accumulated exposure of cells to the light environment. Phytoplankton cells that are mixed throughout the water column are exposed to a range of PAR and UV depending on the surface irradiance, attenuation coefficients for PAR and UV, the cell's depth at any time and the mixing velocities that also change with depth. These processes can be modeled using a Lagrangian type model that follows an individual cell through time. The model was similar to the one used by Franks and Marra (1994) and was used to model the inhibition as it related to the dose of UV light. What was apparent from this model was how rapidly a particular cell can be inhibited in the morning (Figure 62). In the particular example shown here (only one particular path chosen for illustration purposes), a cell that started at 5 meters at dawn was seriously photoinhibited by a brief exposure to high UV near the surface three hours later. Many of the trajectories share two features; early morning inhibition by UV exposure and a recovery in the afternoon as the incident irradiation decreases. Although no one trajectory was representative of the net processes, Figure 62 illustrates that the actual productivity of this cell was inhibited during mid-day, just during the time when the standard incubation method with ^{14}C would be performed.

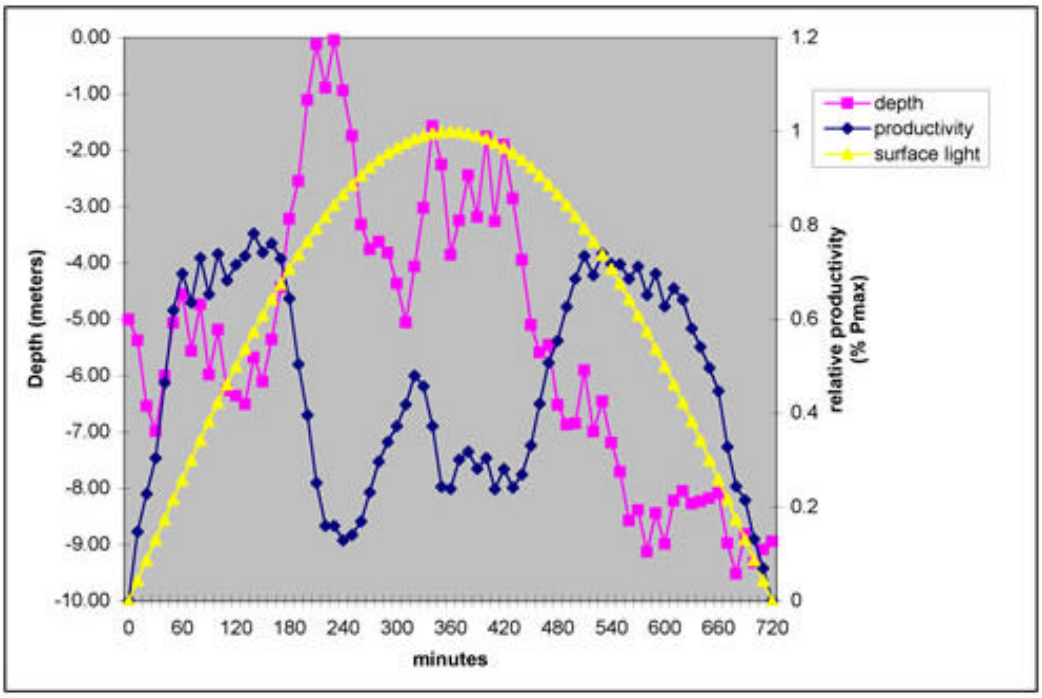


Figure 62: A Lagrangian type model of predicted productivity for a single cell in a variable light environment. For the example shown the UV attenuation was given at 0.5 m^{-1} (Carrillo et al., 2002) and the PAR attenuation was 0.20 m^{-1}. Photoinhibition accumulated at a rate of 0.005 times the normalized surface, noon, full-sun UV dose. The photoinhibition factor decreased exponentially with a half-time of 20 minutes. These inhibition and decay factors were estimated from the PAM Fluorometer experiments on photoinhibition and recovery. The surface water velocity was 0.2 m/min and the turbulent decay of velocity with depth was 0.1 m^{-1} (as estimated from the mixed layer). This example tracks a single particle that started at 5 meters.

Many runs of the particle model were used to get a composite picture of the degree of inhibition due to UV light exposure. A summary of these findings has heuristic value for focusing future studies. Cells that started at the surface moved over greater range of depths and had a wider range of photoinhibition. Cells that were trapped at the surface were strongly photoinhibited. Cells that started deeper in the water column experienced less UV dose and moved less (due to the decrease in velocity). These cells had lower productivities but were not affected by inhibition. Cells that started at depths between 2 and 4 meters below the surface had the widest range in movement and thus inhibition effect. These results indicate that daily productivity estimates need to examine the entire day (from dawn to dusk) and to be put in a context of the surface layer mixing rates.

Fluctuating capacity

Although many community ecology models are based on the concept of a constant carrying capacity, external forcing conditions may lead to fluctuations in the capacity. The degree of variation can repress or promote community productivity and can effect the populations and community structure (Reynolds, 1997). In low productivity systems such as Waldo Lake, fluctuations in conditions and resources may present a set of stresses that suppresses productivity. For example, given the same annual average nutrient and light conditions, changes in the resources or conditions can either lead to a community that increases in size, self-organizes to increase productivity, or communities that are stuck in a perpetual state where their production just equals their maintenance costs. There is no physical structure or

infrastructure that develops in pelagic environments in the way that it does in other ecosystems. The community must be adapted to changing and fluid organizational structure.

Climate changes that result in fewer windy and cloudy days could change the capacity for potential productivity. The combination of wind mixing and cloud cover can decrease the total daily irradiance that is intercepted by the phytoplankton. Reynolds (1997) has shown with plausible ranges of wind, cloud cover and phytoplankton absorption of light in the water column that windy, cloudy days may have about 25 fold less productivity. This could mean that the number of days with higher productivity could increase with climate conditions that are drier and calmer, such as drought. Variations in weather patterns could have accounted for surpassing a critical threshold of productivity (where productivity just equals maintenance) and allowed the positive feedback increase in phytoplankton populations.

Different fluctuation regimes are thought to favor different broad classifications of phytoplankton strategies. Reynolds (1988) describes three types of strategies; "competitor" types that are favored in stable conditions with adequate resources, "ruderal" type species are favored in high frequency disturbed environments, and "stress" types are favored in environments in which low nutrient or high light stresses dominate. When the fluctuation frequency moves toward the rate of cell division it favors ruderal types. Classification of the dominant species in an environment into these three types can also be used to infer what the major selective pressures may be operating. For example, a predominance of ruderal types would indicate the importance of continual disturbance in the system. Table 19 lists the observed taxa in Waldo Lake as compared to similar species that Reynolds has classified. At Waldo Lake, phytoplankton taxa are predominately of the competitor types which infers that important features of the environment may be low temperatures, stability and high light and nutrient availability.

Table 19: Comparison of species identified by Jim Sweet in Waldo Lake to similar species that have been classified by Reynolds (1988) into the three categories of "C" competitors, "R" ruderal or "S" stress.

Sweet (2000)	Reynolds (1988)	Classification
Chlamydomonas	Chlamydomonas reinhardi	C
Ulothrix		
Ankistrodesmus falcatus	Ankistrodesmus braunii	C
Oocystis		
Glenodinium neglectum (most common species)		
Hemidinium sp.		
Chromulina	Chromulina sp.	C
Rhodomonas minuta	Rhodomonas minuta	C
Nitzschia paleacea		
	Dinobryon (maybe like Glenodinium?)	R
	Chlorella pyrendoidosa (maybe like Oocystis?)	C

The community composition and structure are very sensitive indicators of natural and human perturbations. Of course the relative composition of algal species should be expected to change with large shifts in the overall productivity of the system but more subtle shifts in species composition might indicate shifts in underlying conditions that will lead to increased community productivity. For example, Sweet (2000) observed an increase in the dinoflagellate *Hemidinium sp.* during the period from 1993 to 1998 may be interpreted as a shift away from simple nutrient limited conditions (in which competitor

species dominate) to a more varied system that includes "stress" and "ruderal" species. Kitchell et al. (1988) recommend monitoring community structure as after planned and natural perturbations and to examine the variation associated with the different components.

Fluctuations and a changing threshold

Carpenter and others have created a useful framework to address long term trends and thresholds for regime change in lakes. There are processes at work on lakes that function at long time scales, such as multiple year accumulation of biomass or nutrient reserves into sediment. There are also processes that happen much faster, such as the growth of phytoplankton and even the seasonal cycle of community composition. The combination of fast processes, which respond and relax, on top of a background of slow accumulating processes can lead to conditions in which the community will undergo a sudden regime shift. The shift can be dramatic and can happen at concentrations or conditions that previously would have not had a dramatic effect. Figure 63 illustrates how the slow change of the underlying threshold can result in regime changes.

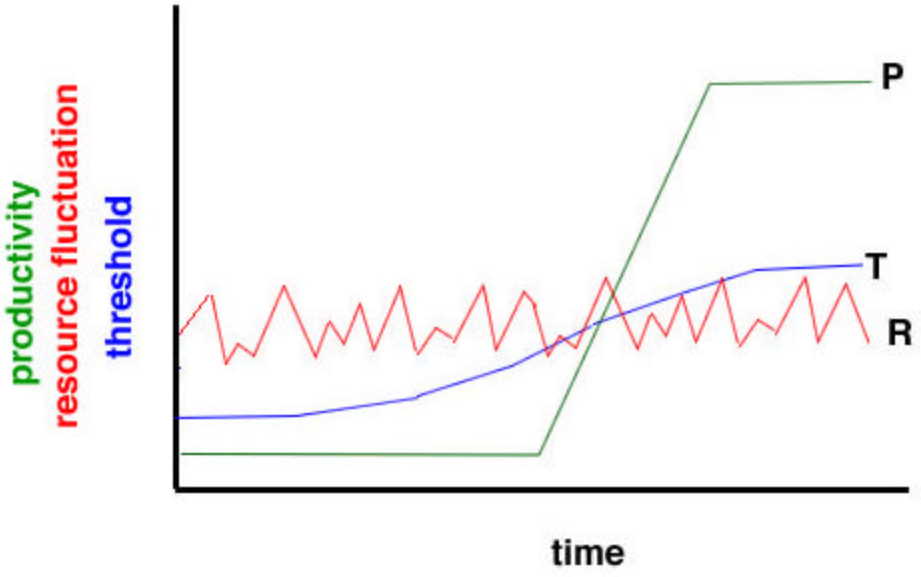


Figure 63: A slow change in the underlying threshold eventually leads to a dramatic change in the community at a value that would have previously not been a problem. Adapted from Carpenter (in press).

From a management perspective, it is important to realize that these slow changes of thresholds can be essentially undetected until it is crossed. There is no method for detecting the exact threshold for change on an individual lake prior to crossing it. It is also important to realize that once a threshold has been crossed, and the community shifts to another regime, it is not as easily reversed as simply reducing the conditions to below the threshold. The threshold to reverse the change in community structure can often be much lower. For example, once lakes undergo eutrophication from accumulated phosphorus input, the community develops mechanisms for exploitation and recycling of phosphorus that are resilient to all but the most extreme reductions in the total phosphorus available.

Conclusions and Recommendations

General recommendations

Although this part of the overall project uses very rapid and small spatial scale methods the results were integrated into larger and longer scales. The problem of productivity in Waldo Lake needs to be addressed in terms of the full range of scales and resiliency cycles that connect these scales (Gunderson and Hollings, 2002). Kitchell et al. (1988) recommends an ensemble of approaches that include studying multiple lakes, small scale manipulation studies and support facilities for multiple investigators studies. The larger framework is an exciting project that would meet the call by Levin (1992, page 1944) to relate "processes that occur at different scales of space, time, and organizational complexity. Understanding patterns in terms of the processes that produce them is the essence of science, and is the key to the development of principles for management."

Specific recommendations for sampling and analysis

The results from the first year of sampling and assaying for fluctuations in productivity indicate that this method can be employed more broadly to address questions of spatial and temporal heterogeneity in Waldo Lake.

Daily patterns of productivity and inhibition should be continued. These should be supported with vertical profiles of PAR, UVA and UVB attenuation in the water column using a spectroradiometer. These diel studies could also focus on the potential uncoupling of photosynthesis and growth that can occur with UV inhibition. This uncoupling can lead to the production of dissolved organic carbon that can accelerate bacterial productivity and feed the mixotrophic portion of the food web. The combination of PAM fluorometry studies with counts of heterotrophic bacteria and the known mixotroph, Glenodinium could address the potential importance of mixotrophy in the overall food web dynamics.

Longer term temporal patterns could be explored by sampling the lake over multiple consecutive days during periods of varying weather (wind and cloud cover). PAM fluorometer studies on water collected from several depths over these time periods could be used to study the daily pattern of photosynthesis and inhibition. It is expected that these daily patterns would vary significantly between quiet days (with full sun and little wind) and windy and cloudy days. It is suggested that sampling be planned for periods in August and September that historically have stretches of quiet days.

PAM fluorometry techniques should be combined with *in vivo* chlorophyll techniques (such as SCUFA) to look spatial heterogeneity. Discrete samples could be taken at locations or depths that are found (with SCUFA) to have distinct signatures. In particular, this combination of PAM fluorometry and SCUFA should be used to look for spatial heterogeneity in the bays or hydrodynamically defined regions of the lake and to examine the productivity of vertically migrating algae.

Zooplankton Community

Between 1996 and 2003 112 zooplankton tows were collected at Waldo Lake (Table 20). All vertical tows between 1996 and 2003 were collected in the daytime. Length of tow was usually approximately 20 meters. No tows were collected in 2000. Zooplankton data from 1998 and 2003 were not available for analysis.

Table 20: Number of vertical tows collected between 1996 and 2002.

Year	LTM	NS
1996	7	1
1997	11	
1998	*	
1999	22	
2000	0	
2001	23	
2002	24	
2003	24*	
* Samples were collected in 1998 and 2003, but were not made available for this analysis.		

Substantial, long-term changes in zooplankton abundance occurred in Waldo Lake from 1996 through 2002 (Figure 64). Vogel and Li (2000) reported similar fluctuations prior to 1996 and attributed the changes to recovery from the effects of fish and mysid stocking. During the 1999 to 2002 period zooplankton density increased from around 2,000 organisms/m^3 to approximately 9,000 organisms/m^3. Most of the increase in abundance was due to an increase in the density of *Bosmina longirostris*. The amazing increase in *B. longirostris* in Waldo Lake since 1989 was described by Vogel and Li (2000).

A seasonal increase of zooplankton densities occurred in 2001 and 2002; this trend was not present in 1999, when densities were much lower overall (Figure 64). In 1996 and 1997 infrequent sampling occurred and seasonal trends could not be assessed. Although in 1997 zooplankton densities decreased from 30 June to 13 September.

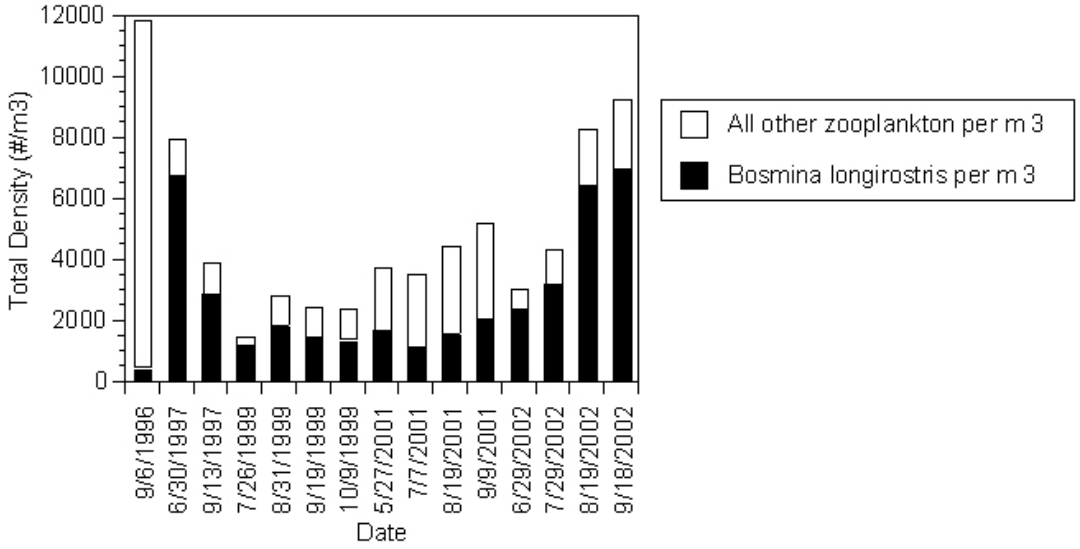


Figure 64: Waldo Lake zooplankton density between 1996 and 2002. Columns indicate total zooplankton density for all vertical tows combined, on a given date. Zooplankton populations have increased between 1999 and 2002. Zooplankton populations continue to be strongly represented by *B. longirostris*.

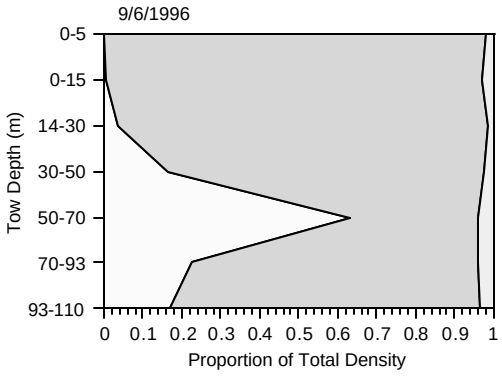
Total zooplankton densities in 2001-2002 were not as high as in 1998 (Vogel and Li, 2000). For example, in August 1998, between 40 and 60 m, *B. longirostris* densities were over 5,000/m^3 (Vogel and Li, 2000). In August 2002, between 40 and 60 m, *B. longirostris* densities were 3,284 /m^3.

Cladocerans tend to occupy mid to lower depths in the water column and copepods occupy the surface waters. Rotifers occupy the entire water column, in very low densities (Figure 65 - Figure 68).

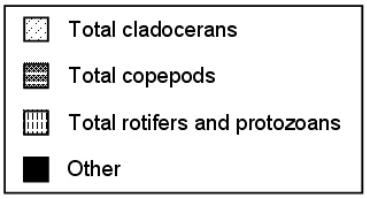
Copepod populations have been reported to have developed pigmentation as an adaptation for UV protection. Daytime surface avoidance by *B. longirostris* was also evident in the 1998 to 2002 zooplankton data (Figure 65 - Figure 68). Cladocerans, specifically *B. longirostris*, do not possess this pigmentation in Waldo Lake. They exhibit daytime surface avoidance and migrate into the surface waters at night to graze on phytoplankton that are more abundant at the surface (Vogel and Li, 2000).

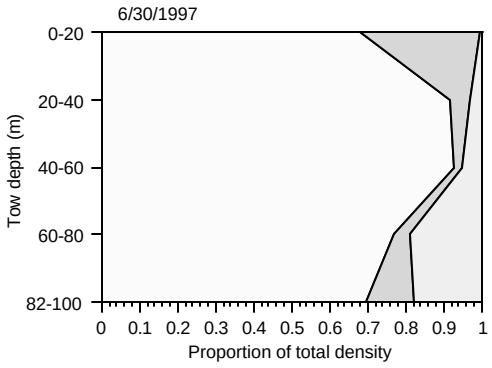
Zooplankton distribution in the water column may be monitored using depth sounding equipment (Bob McClure, Biosonics, Inc., 2003, personal communication). Use of sonar techniques could be used to document migration rates and if nighttime migration to the surface still occurs despite the decrease in surface concentrations of phytoplankton occurring since the time of last sampling, specifically Glenodinium neglectum (see Phytoplankton Community section). Sonar techniques also have the capability of tracking movement of dinoflagellates in the water column.

In 1999, "other" species (other than cladocerans, rotifers, and copepods) represented a significant portion of the zooplankton in the water column (over 20 percent) at 82-100 m. On 19 September 1999, "other" was mainly *Difflugia sp*. On 31 August 1999 tardigarde (water bears) were 7.8 percent of the total zooplankton density collected from the 105 to 110 m tow (Figure 65 - Figure 68).

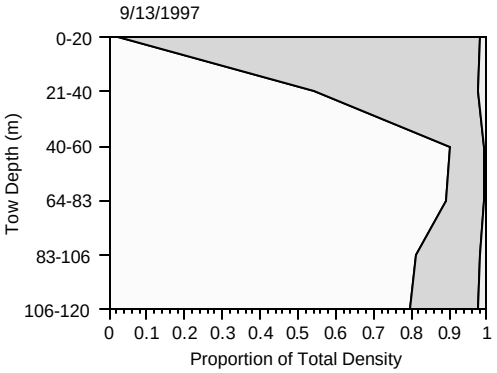


Tow Depth	Total Density (#/m^3)
0-5 m	6421.202
0-15 m	2093.319
14-30 m	1948.057
30-50 m	875.989
50-70 m	353.112
70-93 m	104.073
93-110 m	42.541



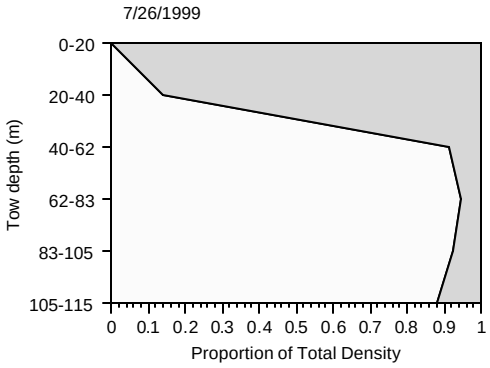


Tow Depth	Total Density (#/m^3)
0-20 m	1195.7
20-40 m	2289.8
40-60 m	2855.2
60-80 m	788.3
82-100 m	852.2

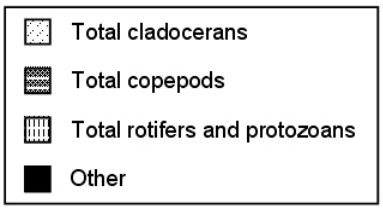


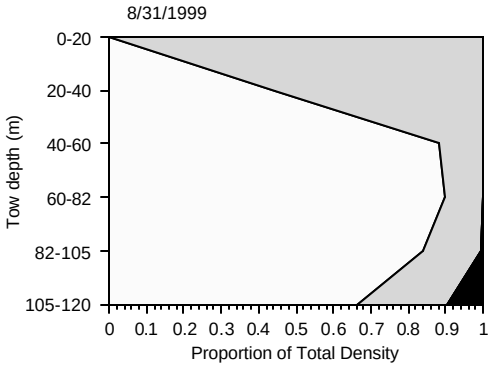
Tow Depth	Total Density (#/m^3)
0-20 m	389.4
21-40 m	550.1
40-60 m	1568.6
64-83 m	706.7
83-106 m	345.4
106-120 m	336.8

Figure 65: 1996 and 1997 proportion of zooplankton groups at Waldo Lake, collected in each 20 m tow.

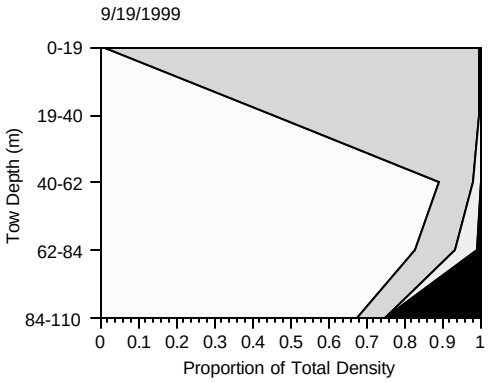


Tow Depth	Total Density (#/m^3)
0-20 m	90.4
20-40 m	80.2
40-62 m	222
62-83 m	228.5
83-105 m	256.3
105-115 m	593.3

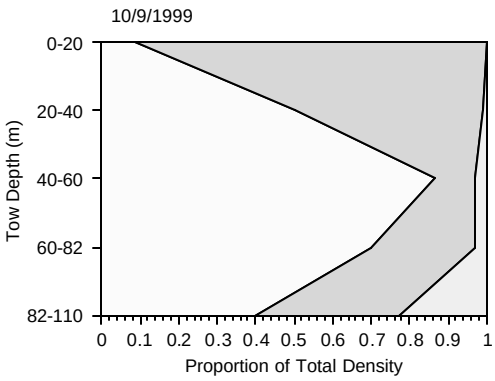




Tow Depth	Total Density (#/m^3)
0-20 m	413.1
20-40 m	350
40-60 m	583.1
60-82 m	644.8
82-105 m	389.8
105-120 m	439.5

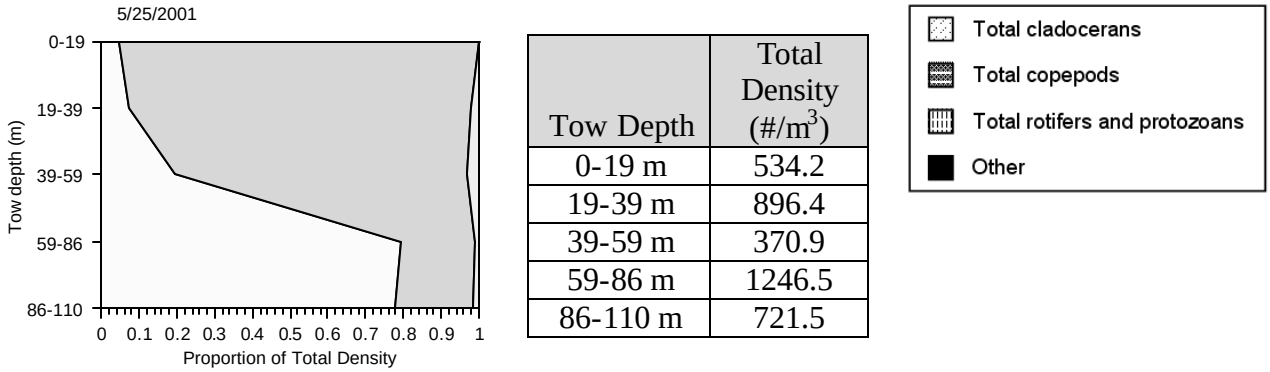


Tow Depth	Total Density (#/m^3)
0-19 m	426.5
19-40 m	581.9
40-62 m	911.7
62-84 m	288
84-110 m	217.6

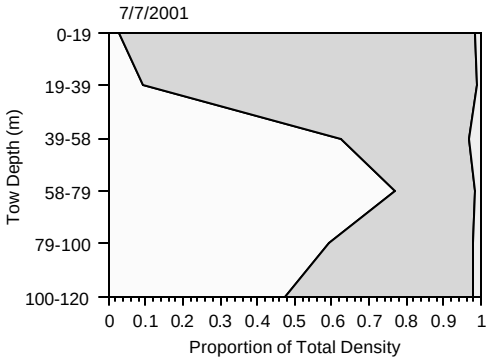


Tow Depth	Total Density (#/m^3)
0-20 m	449.2
20-40 m	597.9
40-60 m	880.1
60-82 m	344.5
82-110 m	134.2

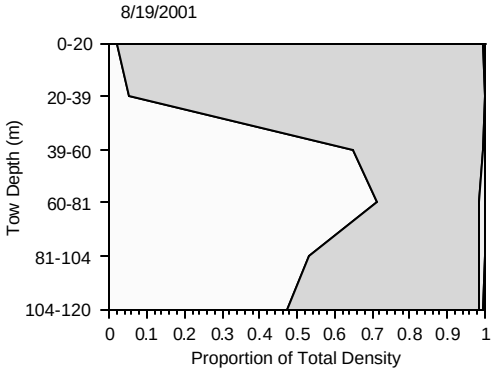
Figure 66: 1999 proportion of zooplankton groups collected at Waldo Lake, in each 20 m tow.



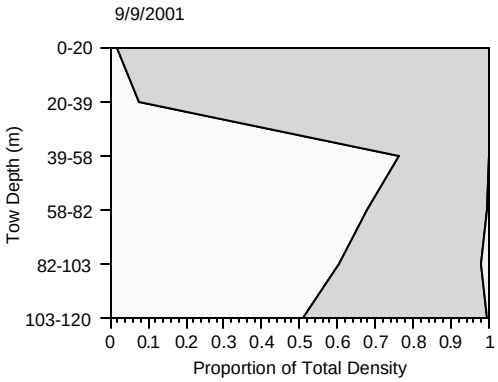
Tow Depth	Total Density (#/m^3)
0-19 m	534.2
19-39 m	896.4
39-59 m	370.9
59-86 m	1246.5
86-110 m	721.5



Tow Depth	Total Density (#/m^3)
0-19 m	273.5
19-39 m	1621.6
39-58 m	528.6
58-79 m	455
79-100 m	213.9
100-120 m	423.7

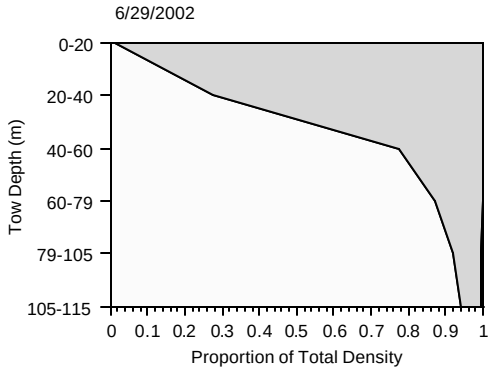


Tow Depth	Total Density (#/m^3)
0-20 m	929
20-39 m	977.8
39-60 m	906.1
60-81 m	615.7
81-104 m	404.8
104-120 m	626.4

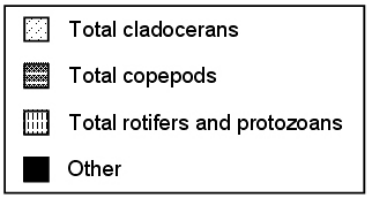


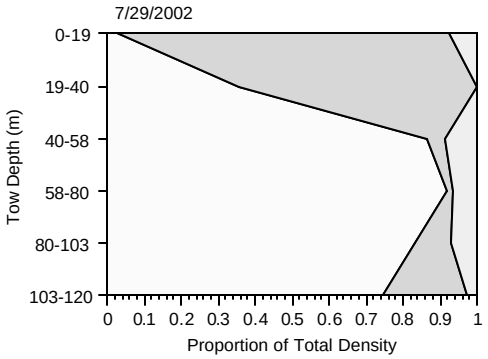
Tow Depth	Total Density (#/m^3)
0-20 m	1222.3
20-39 m	1087.3
39-58 m	1198.8
58-82 m	740.2
82-103 m	480.2
103-120 m	491.6

Figure 67: 2001 proportion of zooplankton groups collected at Waldo Lake, in each 20 m tow.

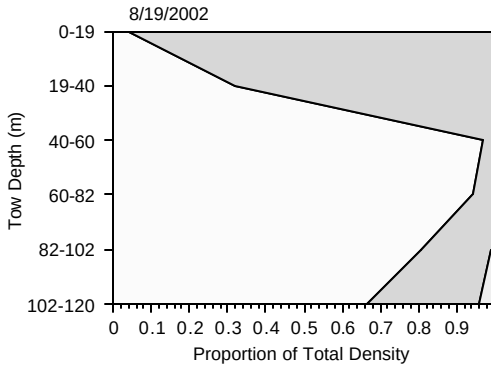


Tow Depth	Total Density (#/m^3)
0-20 m	212.9
20-40 m	218.5
40-60 m	402.3
60-79 m	472.8
79-105 m	622.1
105-115 m	1126.6

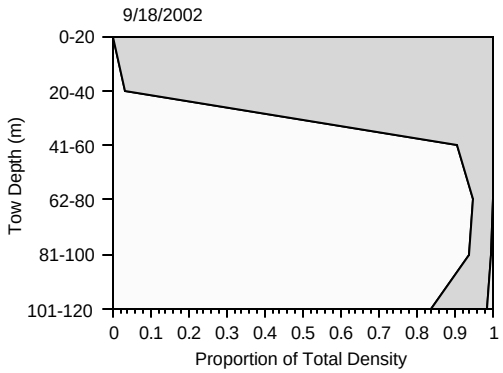




Tow Depth	Total Density (#/m^3)
0-19 m	418.2
19-40 m	448
40-58 m	1328.7
58-80 m	1563.1
80-103 m	281.8
103-120 m	285.5



Tow Depth	Total Density (#/m^3)
0-19	684.8
19-40	877
40-60	3385.8
60-82	1803.8
82-102	900.4
102-120	657.9



Tow Depth	Total Density (#/m^3)
0-20 m	411.5
20-40 m	1339.1
41-60 m	1343.8
62-80 m	3229.3
81-100 m	1801.3
101-120 m	1155.8

Figure 68: 2002 proportion of zooplankton groups collected at Waldo Lake, in each 20 m tow.

Water Quality Modeling

Introduction

The application of a hydrodynamic and water quality model to the Waldo Lake ecosystem will summarize and synthesize the physical, chemical, and biological characteristics of the lake into a tool which can be used to look at management strategies to improve water quality. A model represents the Waldo Lake ecosystem and responds to both meteorological and hydrological forcing processes (Figure 69). Temperature monitoring, water quality sample collection, phytoplankton photosynthetic efficiency and hydrologic analyses are necessary work tasks for the construction of a water quality model of Waldo Lake.

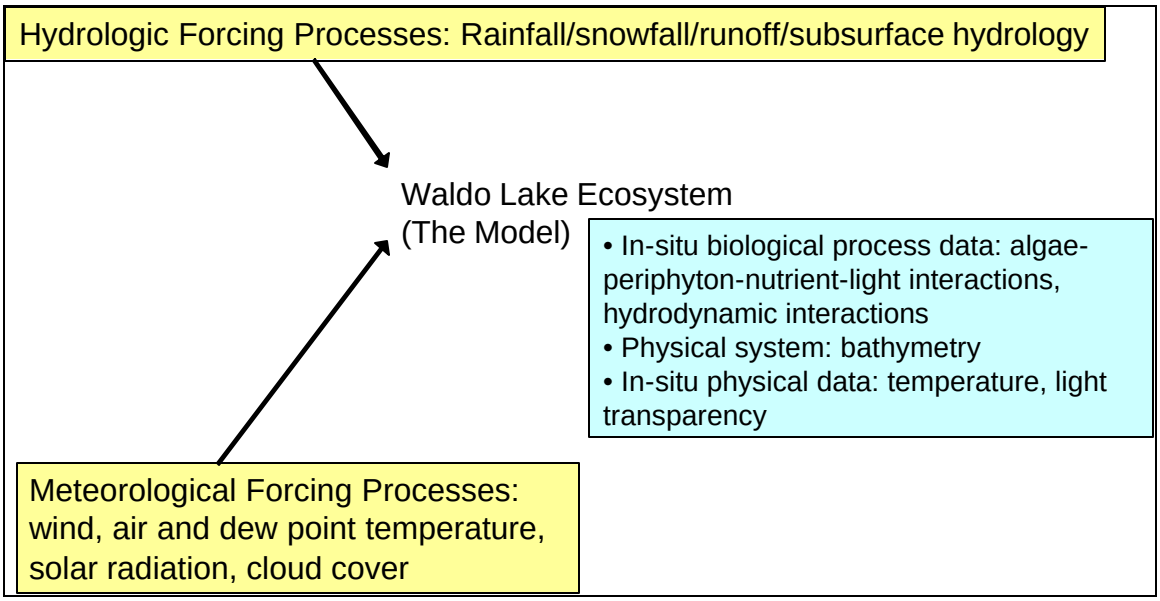


Figure 69: The response of the Waldo Lake ecosystem, the model, to external forcings.

Once the model is constructed, the model is a tool that can be used to manage the water quality of this pristine resource. The model must replicate important processes in Waldo Lake and then be able to estimate the impact of various scenarios on water quality as shown in Figure 70. The modeling effort will also help identify possible future monitoring in the lake by identifying areas where the lake ecosystem is less understood.

This section provides the following background material on modeling Waldo Lake:

- water quality model selection process
- water quality and hydrodynamic models which are available
- choice of a modeling framework for the next phase of the Waldo Lake project

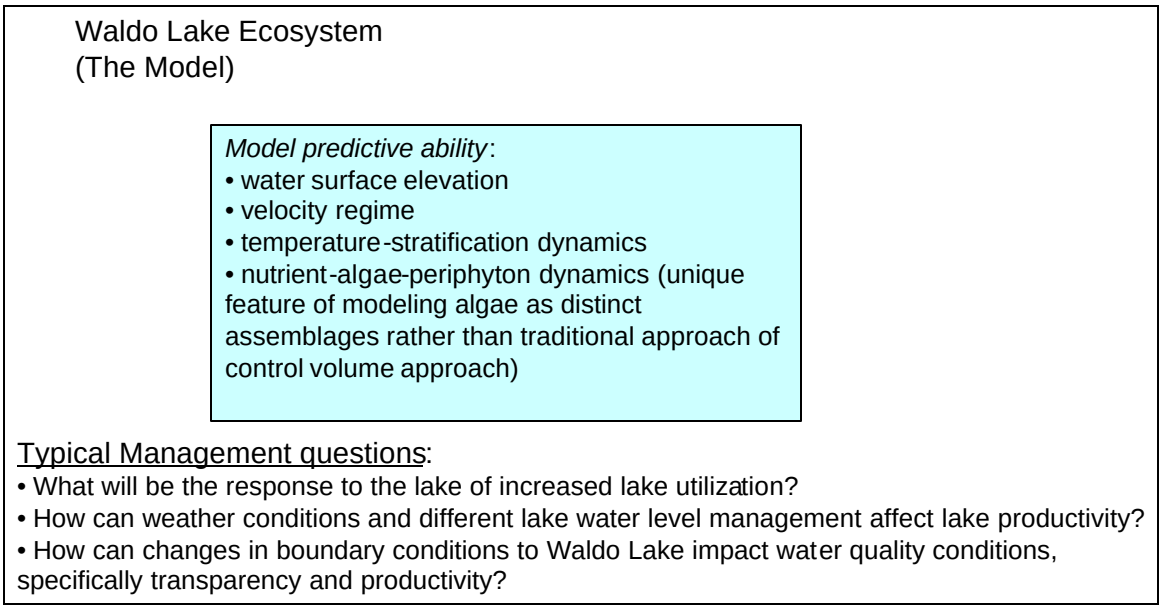


Figure 70: Model predictive ability coupled with water quality management issues.

Water Quality Model Selection

Selection of the appropriate water quality model is a function of properly identifying the water quality problem ("conceptualization") and selecting a model which appropriately describes the water quality changes in the water body, is theoretically valid, and can be easily adapted to site-specific physical characteristics of the water body.

The performance of a mathematical model in predicting the existing and future water quality dynamics of a system is dependent on the following steps:

1. identification of the problem
2. selection of model type and relationship of model to the problem
3. computational representation
4. model response studies or model sensitivity to parameter choices
5. model calibration/verification
6. application of model to evaluate management strategies

Because there are many water quality models available, a choice of the appropriate model would be made after considering the following questions: What physical processes are represented in the model and which are ignored? How are physical processes included in the model? What processes are represented by model coefficients? What kind of model should be used? For example in defining the problem, the following questions could be asked:

1. What are the dominant physical processes at work and can the chosen model represent those processes? (such as, how does the water move? Is there stratification, wind-driven currents, and/or selective withdrawal?)
2. What are the spatial and temporal scales of these processes and can the model represent them? (such as, is steady-state representation adequate, is 1-D, 2-D, or 3-D spatial discretization necessary?)

The choice of the proper model is also based on answering (1) site specific questions (physical characteristics of the each system component - river or reservoir reach, water quality cycles, algal types), (2) management objectives (required accuracy, use for future studies), (3) project resources (data availability, staff constraints, time limitations).

Models Available

Table 21 shows a list of several water quality models that are being used for water quality management of lakes and reservoirs. Models which were not in the public domain were not included in this list of models since the research group feels strongly that for the model to be of the value to later users must be in the public domain. Table 22 lists additional features of these water quality models.

Table 21: List of selected water quality and hydraulic models used for river/reservoir water quality studies.

Model name	Model description	Comments	Reference
WASP	one, two, or three dimensional water quality model, dynamic	no hydraulic computations, hydraulics specified by the user, often linked with 1-D hydraulic model DYNHYD; nutrients-algae and toxics	Ambrose, Wool, Conolly, and Schanz (1988)
DYNHYD	one-dimensional (longitudinal), dynamic hydraulic model	no water quality components, linked with WASP, assumes cross-sectional homogeneity	Ambrose, Wool, Conolly, and Schanz (1988)
EFDC	three-dimensional, sigma-z grid	hydrodynamics and temperature only, coupled with WASP for water quality	Hamrick (1996)
POM	three-dimensional, sigma-z grid	hydrodynamics and temperature only	Blumberg and Mellor (1987)
CE-QUAL-R1	one-dimensional (vertical), dynamic reservoir water quality model	nutrient-algae-zooplankton-macrophyte interactions modeled, assumes horizontal homogeneity	Corps of Engineers (1986)
WQRSS	one-dimensional longitudinal river section and one-dimensional vertical reservoir section, dynamic	water quality and hydraulic modeling in 1-D, assumes horizontal homogeneity in reservoir section and cross-sectional homogeneity in river sections	Corps of Engineers (1978)
CE-QUAL-W2 Version 3	two-dimensional hydrodynamic and water quality river basin model, able to model 2-D river, reservoir, lake, estuary dynamics	assumes lateral homogeneity, nutrient-algae-zooplankton-oxygen-pH interactions, fully 2-D hydrodynamics, enhanced water quality modeling features	Cole and Wells (2003)

Table 22: Basic model features of several water quality models

Model	Time Scale	Spatial Dimension	Hydrodynamics	Solution Technique
WASP5: Stand Alone with DYNHYD4	 Q D	 B xx	 I S	 FD FD
EFDC	D	xyz	S	FE
POM	D	xyz	S	FD
CE-QUAL-W2	D	xz	S	FD
WQRSS or HEC5Q	D	x (longitudinal for river vertical for reservoir)	S (no momentum equation solution for reservoir)	FD
CE-QUAL-R1	D	x (vertical only)	S (no momentum equation solution for reservoir)	FD

D - dynamic Q - quasi-dynamic (tidal-averaged) SS - steady state	x - 1 dimensional xy-3 dimensional, longitudinal-lateral xz-2 dimensional, longitudinal-vertical xyz-3-dimensional B-compartment or box 3D xx-link node branching 2D	I-hydrodynamics input S-hydrodynamics simulated	A-analytical solution FD-finite difference solution FE-finite element solution

WASP5

WASP5 is a general, multi-dimensional model that utilizes compartment modeling techniques (Ambrose et al., 1988). Operated in either the quasi-dynamic or steady state mode, the user must supply initial segment volumes, network flow fields, and inflow time functions. The user also must calibrate dispersion coefficients between compartments since there are no hydrodynamics with this model. Depending on the process model with which it is linked, WASP5 has the capability of simulating a range of conventional and toxic pollutants. Problems that have been studied using WASP5 include BOD, DO dynamics, nutrients and eutrophication, bacterial contamination, and toxic chemical movement. WASP5, along with the associated programs TOXI4, EUTRO4, and DYNHYD4, can be obtained from the Center for Exposure Assessment Modeling, Athens, Georgia.

TOXI4

TOXI4 is a version of WASP5 that is designed to simulate organic chemicals and heavy metals (Ambrose et al., 1988). TOXI4 was created by adapting the kinetic structure of EXAMS-II to the transport framework of WASP5 and adding sediment balance algorithms. It can simulate up to three chemicals and three sediment classes. In addition to segment volumes, flows, and dispersive exchanges,

the user must supply sediment deposition and scour rates, bed sediment velocity, water column/sediment exchange coefficients, and sediment/pore water exchange coefficients.

In TOXI4 the total transformation rate of an organic chemical is based on the simple addition of the rate constants for individual photolysis, hydrolysis, biolysis, and oxidation reactions. These rate constants may either be specified by the user or calculated internally from second order rate constants and such environmental conditions as light intensity, pH, bacteria, oxidants, depth, velocity, and wind speed. Internal transport and export of organic chemicals occur via advective and dispersive movement of dissolved, sediment-sorbed, and biosorbed materials, and by volatilization losses at the air-water interface. Internal transport and export of heavy metals occur via advective and dispersive movement of dissolved, sediment-sorbed, and biosorbed materials. Sorption of both organic chemicals and heavy metals on sediments and biomass is calculated assuming local equilibrium using a constant partition coefficient and spatially varying environmental organic carbon fractions. TOXI4 has the capability of simulating up to two daughter products of organic chemical transformations. Exchange between the water column and the bed can occur by settling or re-suspension of particulates, diffusion of dissolved pollutants between the water column and pore water, direct adsorption/desorption between the water column and bed, and percolation or infiltration. Within the bed, a pollutant can move vertically by diffusion, turnover, percolation and burial, and horizontally with bed load transport.

EUTRO4

EUTRO4 is a version of WASP5 that is designed to simulate conventional pollutants. EUTRO4 combines a kinetic structure adapted from the Potomac Eutrophication Model and the WASP transport structure. EUTRO4 predicts DO, carbonaceous BOD, phytoplankton carbon and chlorophyll a, ammonia, nitrate, organic nitrogen, organic phosphorus, and orthophosphate in the water column and, if specified, the underlying bed. In addition to segment volumes, flows, and dispersive exchanges, the use must supply deposition and re-suspension velocities for organic solids, inorganic solids, and phytoplankton. The fraction of each water quality variable associated with these solids also must be given. Rate constants and half-saturation coefficients for the various biochemical transformation reactions must be specified by the user. Finally, the time and/or space variable environmental forcing functions, such as light intensity, light extinction, wind speed, cloud cover, temperature, and benthic fluxes must be input.

EFDC

This 3-D hydrodynamic model has been used in conjunction with WASP for 3-D model water quality studies usually in estuary systems, even though it has been applied in reservoirs. The model was applied to the Sammamish Lake in Washington but was rejected by King County because of spurious currents developed as a result of the sigma-z coordinate system used in the model. The sigma-z coordinate system has variable thickness vertical layers based on the overall depth of the water, but a constant number of vertical layers throughout the domain.

POM

POM is the Princeton Ocean Model used often in coastal and oceanic studies. This model has been used to predict 3-D circulation. It predicts water levels and the x-y-z velocities, as well as salinity and temperature. It is not a water quality model and the model user has to build his/her own water quality model. The sigma-z vertical coordinate grid can cause spurious currents in enclosed lakes and reservoirs,

such as a recent example in the Dead Sea by researchers with the Israeli Geologic Survey. There is a z-coordinate version of this model, but it has not undergone extensive testing.

CE-QUAL-R1

This is a Corps of Engineers' model maintained by the Waterways Experiments Station in Vicksburg, MS. CE-QUAL-R1 is a one-dimensional model of water quality for reservoir or lake systems. It does not solve the momentum equations nor does it predict lake or reservoir circulation. It assumes horizontal homogeneity (lateral and longitudinal). This model does solve for many water quality parameters – such as eutrophication parameters, several algae types, and zooplankton. CE-QUAL-R1 also has a simple sediment diagenesis model.

HEC5Q or WQRSS

These models are maintained by the Hydrologic Engineering Center, Corps of Engineers, in Davis, Ca. This is a dynamic, eutrophication model. The HEC-5Q (similar to WQRSS) model incorporates a one-dimensional longitudinal river model with a one-dimensional vertical reservoir model (only one-dimensional in temperature and water quality and zero dimensional in hydrodynamics). The modeler must choose the location of the transition from 1-D longitudinal to 1-D vertical. Besides the limitation of not solving for the velocity field in the stratified, reservoir system (no solution of the momentum equation), any point source inputs to the reservoir section are spread over the entire longitudinal distribution of the reservoir layer.

CE-QUAL-W2

CE-QUAL-W2 is a dynamic 2-D (x-z) model developed for stratified water bodies (Cole and Wells, 2003). This is a Corps of Engineers modification of the Laterally Averaged Reservoir Model (Edinger and Buchak, 1978). CE-QUAL-W2 consists of directly coupled hydrodynamic and water quality transport models. The model grid is shown in Figure 71. Hydrodynamic computations are influenced by variable water density caused by temperature, salinity, and dissolved and suspended solids. Developed for reservoirs and narrow, stratified estuaries, CE-QUAL-W2 can handle a branched and/or looped system with flow and/or head boundary conditions. The current version is able to simulate river, lake, estuary and reservoir systems. The current version allows for full river basin simulation capability. With two dimensions depicted, point and non-point loading can be spatially distributed. Relative to other 2-D models, CE-QUAL-W2 is efficient and cost effective to use. This model allows the user to use the Ultimate-Quickest numerical scheme for constituent transport rather than upwinding.

In addition to temperature, CE-QUAL-W2 simulates a user-defined number of water quality variables. Primary physical processes included are surface heat transfer, short-wave and long-wave radiation and penetration, convective mixing, wind and flow induced mixing, entrainment of ambient water by pumped-storage inflows, inflow density stratification as impacted by temperature and dissolved and suspended solids. Major chemical and biological processes in CE-QUAL-W2 include: the effects of DO of atmospheric exchange, photosynthesis, respiration, organic matter decomposition, nitrification, and chemical oxidation of reduced substances; uptake, excretion, and regeneration of phosphorus and nitrogen and nitrification-denitrification under aerobic and anaerobic conditions; carbon cycling and alkalinity-pH-CO_2 interactions; trophic relationships for total phytoplankton; accumulation and

decomposition of detritus and organic sediment; and coliform bacteria mortality; multiple algal groups and algal succession; dissolved and particulate silica for diatom growth; epiphyton and periphyton growth/decay; macrophytes; multiple BOD groups with links to nutrients.

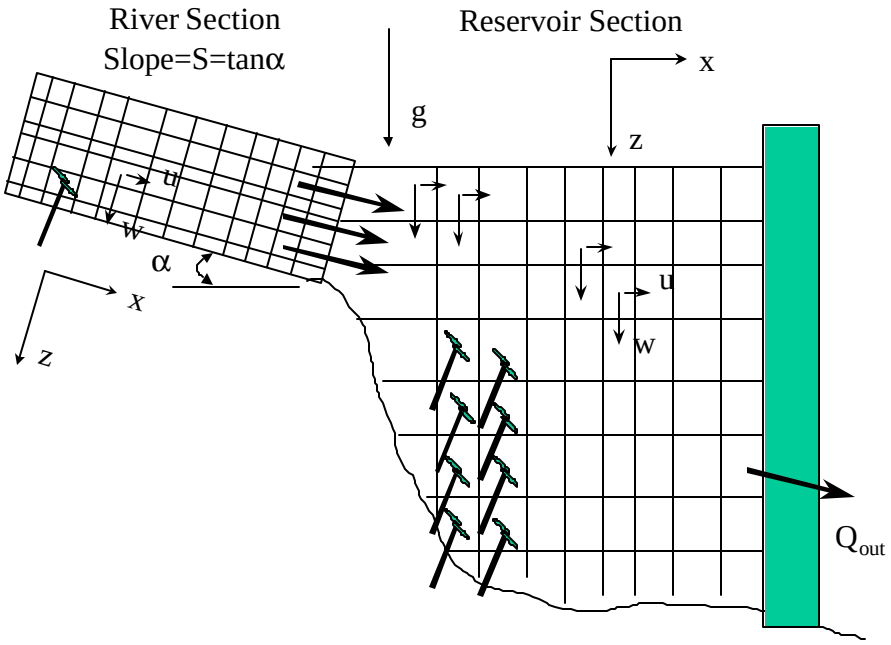


Figure 71: Coordinate system for CE-QUAL-W2 with and without channel slope.

The model also has these additional capabilities:

- Ability to specify the channel slope and model sloping river channels in 2-D and use a sloping channel grid (Figure 72)
- Implicit Solution of Vertical Momentum Transfer allowing for water surface solutions in river channels
- Conservation of Longitudinal Momentum at all branch intersections
- Ability to add dams and reservoirs in series with rivers and estuaries
- Ability to output numerous model derived variables such as TKN, TSS, TOC that can be compared directly to field data
- Choice of model reaeration coefficients and evaporation formulae based on water body type
- Model kinetic coefficients are now variable as a function of water body
- Ability to add hydraulic structures between model branches such as weirs, spillways, pipes, and gates

Model Selection

One-dimensional reservoir models, such as the HEC WQRRS (Water Quality River-Reservoir Simulation) model and the Corps's CE-QUAL-R1, are also not adequate to compute 2-D circulation within lake systems. These models conceptualize a lake as well mixed in each horizontal slab, i.e., over the length and the width of the system. By making this assumption, the vertical and longitudinal circulation patterns within a lake cannot be resolved.

Other hydraulic and water quality models in common use for unsteady flow, include the 1-D dynamic EPA model DYNHYD (Ambrose et al., 1988), used together with the multidimensional water quality model WASP. WASP relies on DYNHYD for 1-D hydrodynamic predictions. If WASP is used in a multi-dimensional schematization, the modeler must specify dispersion coefficients to allow transport in the vertical and/or lateral directions or use another hydrodynamic model that explicitly includes these effects deeper lake systems that stratify. This is non-predictive since the DYNHYD link only computes longitudinal velocities and cannot predict the wind induced circulation patterns which often govern lake behavior.

Three-dimensional models may ultimately be necessary for Waldo Lake. But sigma-stretched z-coordinate models have problems in enclosed lake/reservoir systems with spurious currents. Many 3-D models used in lake modeling are too cumbersome computationally and are not useful for long-term simulations. An example of such an application is Lake Kinneret in Israel where a 3-D model has been applied to run for a period of a month at a time, whereas a 1-D model (DYRESM) is used for calibration and long-term management strategies. For example, Boegmam et al. (2001) applied a 2-D model (CE-QUAL-W2) to Lake Erie and compared it to a 3-D model (POM). They reported that the 2-D model, albeit with the limitations of laterally averaging, represented the vertical structure better than the POM 3-D model.

Hence, for Waldo Lake, the CE-QUAL-W2 Model is proposed as the most appropriate for modeling the Waldo Lake system since it contains the following elements:

- Two-dimensional, dynamic hydrodynamics and water quality capable of replicating the density stratified environment that may exist in the deeper sections of Waldo Lake and predicting wind induced circulation and seiching along the main axis of the wind
- Ability to model attached algae and phytoplankton
- The model is a state-of-the-art tool with features not found in other models

Recognizing the limitations of a 2-D model, the CE-QUAL-W2 model will be tested extensively to evaluate the need at a later time for a 3-D model. The advantage of this approach in 2-D is that the field sampling program completed to date is reasonably applied to a model that has both vertical and longitudinal resolution.

CE-QUAL W2 Model Description

CE-QUAL-W2 is a dynamic two-dimensional, longitudinal-vertical (x-z) model developed for stratified water bodies. The governing equations for this model are shown in Table 23. A cross section of the CE-QUAL-W2 grid is shown in Figure 71 and consists of directly coupled hydrodynamic and water quality transport models. Hydrodynamic computations are influenced by variable water density caused by temperature, salinity, and dissolved and suspended solids.

Table 23: Governing Equations for CE-QUAL-W2.

Equation	Version 3 governing equations
x- momentum	$$\frac{\partial UB}{\partial t}+\frac{\partial UUB}{\partial x}+\frac{\partial WUB}{\partial z}= gB\sin a+g\cos aB\frac{\P h}{\P x}- \frac{g\cos aB}{r}\int_h^z\frac{\P r}{\P x}dz+ \frac{1}{r}\frac{\partial Bt_{xx}}{\partial x}+\frac{1}{r}\frac{\partial Bt_{xz}}{\partial z}+qBU_x$$
z-momentum	$$0=g\cos a-\frac{1}{r}\frac{\P P}{\P z}$$
free surface equation	$$B_h\frac{\P h}{\P t}=\frac{\P}{\P x}\int_h^h UBdz-\int_h^h qBdz$$
Equation of state	$$r = f(T_w,\Phi_{TDS},\Phi_{ss})$$
Conservation of mass/heat	$$\frac{\partial B\Phi}{\partial t}+\frac{\partial UB\Phi}{\partial x}+\frac{\partial WB\Phi}{\partial z} -\frac{\partial\left(BD_x\frac{\partial\Phi}{\partial x}\right)}{\partial x}-\frac{\partial\left(BD_z\frac{\partial\Phi}{\partial z}\right)}{\partial z}= q_\Phi B+S_\Phi B$$

Note: U,W: horizontal and vertical velocity, B: channel width, P: pressure, g: acceleration due to gravity, τ_x,τ_z: lateral average shear stress in x and z, ρ: density, η: water surface, α: channel angle, U_x: x-component of velocity from side branch, q: lateral inflow per unit length, $f(T_w,\Phi_{TDS},\Phi_{ss})$: density function dependent upon temperature, total dissolved solids or salinity, and suspended solids; Φ: laterally averaged constituent concentration, D_x: longitudinal temperature and constituent dispersion coefficient, D_z: vertical temperature and constituent dispersion coefficient, q_Φ: lateral inflow or outflow mass flow rate of constituent per unit volume, S_Φ: laterally averaged source/sink term.

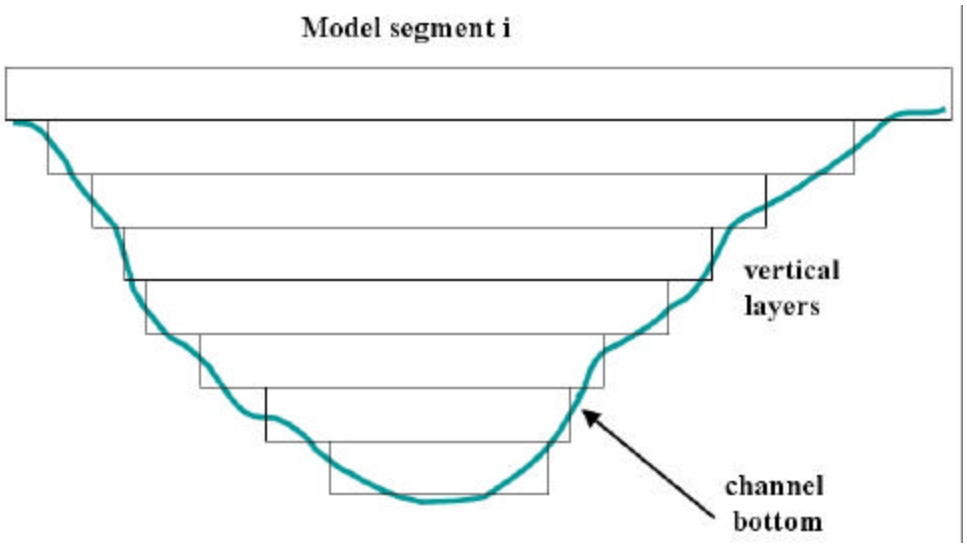


Figure 72: Cross-section of CE-QUAL-W2 model grid

CE-QUAL-W2 also has the capability to model structures and facilities which are useful in evaluating management scenarios. The model capabilities include:

- Multiple Withdrawal Structures for dam facilities
- Water Level Control operations
- Pipes
- Distributed Tributaries
- Tributaries/Diversions/Withdrawals
- Weirs/Spillways/Gates on structures
- Internal Weirs

Additional model capabilities influencing the lake heat budget and water quality dynamics include:

- Incorporating wind sheltering on the lake surface
- Varying light extinction based on Secchi disk depth
- Simulating ice cover
- Multiple evaporation formulations
- Multiple reaeration formulations
- Simulating heat flux through lake bottom

CE-QUAL-W2 simulates a user-defined number of constituents in addition to temperature. Table 24 lists the water quality constituents simulated in CE-QUAL-W2.

Table 24: CE-QUAL-W2 water quality constituents simulated in addition to temperature

Total dissolved solids or salinity	Labile dissolved organic matter
User defined # of generic constituents	Refractory dissolved organic matter
User defined # of Inorganic suspended solids groups	Labile particulate organic matter
User defined # of CBOD groups	Refractory particulate organic matter
User defined # of phytoplankton groups	Total inorganic carbon
User defined # of epiphyton/periphyton groups	Alkalinity

Dissolved oxygen	Dissolved silica
Dissolved inorganic phosphorus	Particulate biogenic silica
Ammonium	Dissolved iron
Nitrate-nitrite	

In addition to the model simulating the various water quality constituents listed in Table 24, the model has the ability to derive additional water quality constituents and fluxes for additional limnological analyses. Table 25 list the water quality constituents derived by CE-QUAL-W2.

Table 25: CE-QUAL-W2 derived water quality constituents

Dissolved organic carbon	Algal production
Particulate organic carbon	Chlorophyll a
Total organic carbon	Total algal biomass
Dissolved organic nitrogen	Dissolved oxygen saturation
Particulate organic nitrogen	Total suspended solids
Total organic nitrogen	Total inorganic suspended solids
Total Kjeldahl nitrogen	Total carbonaceous BOD (ultimate)
Total nitrogen	pH
Dissolved organic phosphorus	Carbon dioxide
Particulate organic phosphorus	Bicarbonate
Total organic phosphorus	Carbonate
Total phosphorus	

Data Requirements

There are three general data requirements for developing a CE-QUAL-W2 model application of a lake system: The bathymetry of the lake, the meteorological conditions, and the boundary conditions for the lake such as inflows and outflows.

The bathymetry of the lake is used to develop the two-dimensional computational model grid. The more refined the lake bathymetry data, the more accurate the model grid. Meteorological conditions for CE-QUAL-W2 consist of air dry-bulb and dew point temperature, wind speed and direction, and cloud cover and/or solar radiation data. Boundary conditions to a surface water system should be characterized as well as the data provides. Higher frequency data collection ensures a better representation of inflows and outflows and any dam or facility operations. Inflows are characterized by flow, temperature and water quality characteristics. Outflows are characterized by flow and location both longitudinally and/or vertically in a lake, reservoir or river.

Application to Waldo Lake Ecosystem

Applying CE-QUAL-W2 to Waldo Lake will incorporate field data collected and analyses conducted which identify model boundary conditions such as hydrological and meteorological processes. The following section describes how the CE-QUAL-W2 would be developed, calibrated and used to investigate various management options for Waldo Lake. The Waldo Lake model will also be helpful in illuminating lake ecosystem dynamics and identifying future field monitoring needs.

Model Development

Bathymetric data was collected in the summer of 2003 and was analyzed extensively as previously discussed. The lake bathymetry will then be used to develop the computation model grid as illustrated in Figure 73 for Reservoir #1 in the Bull Run watershed. The volume-elevation and area-elevation curves for Waldo Lake will also be compared to the volume-elevation and area-elevation curves for the model grid. Figure 74 shows an example for the Reservoir #1 in the Bull Run watershed.

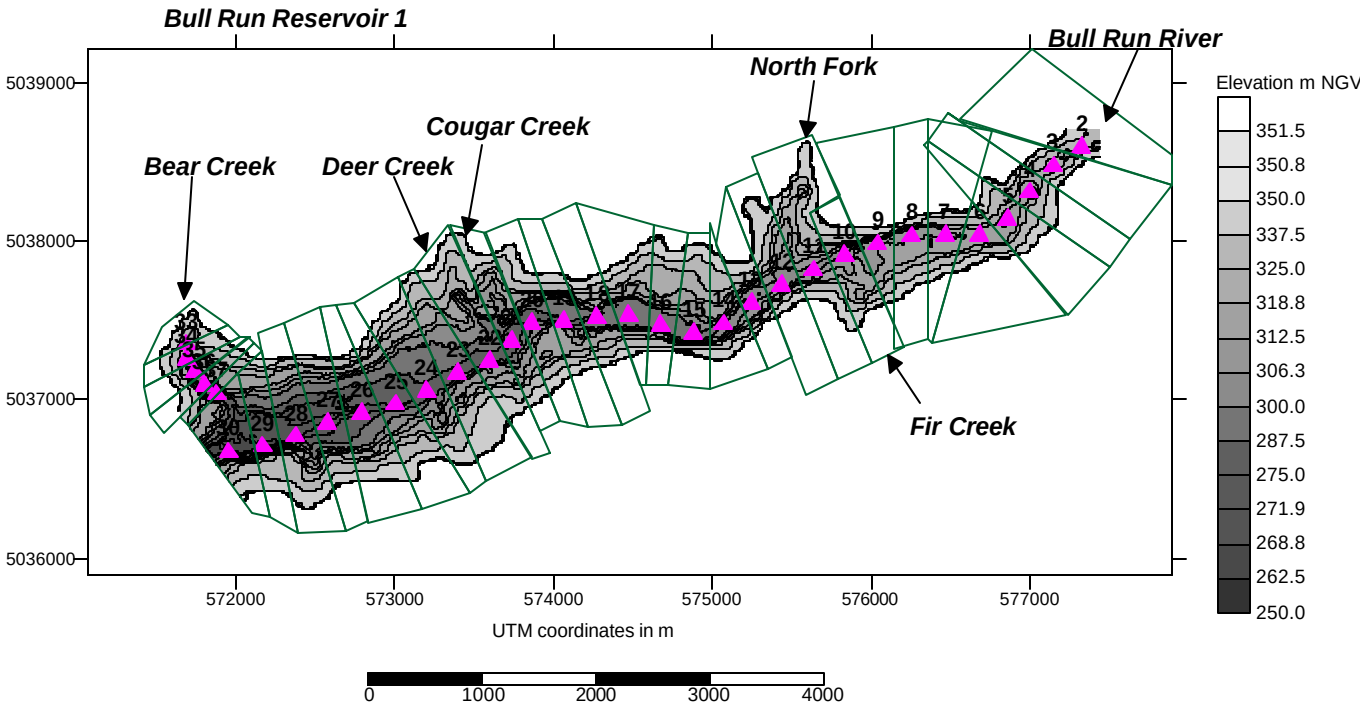


Figure 73: Bull Run Reservoir #1 Model Grid Layout

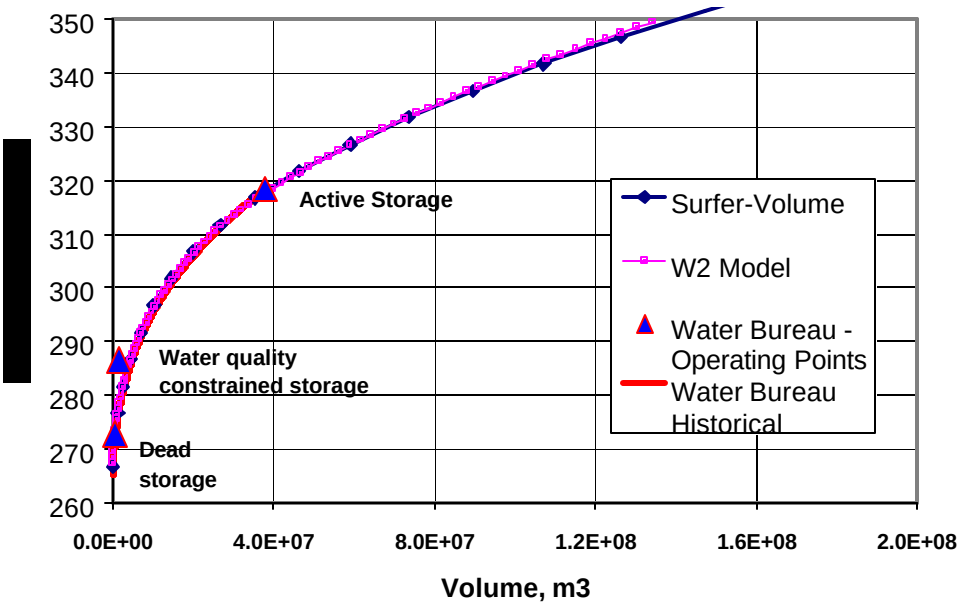


Figure 74: Bull Run Reservoir #1 volume-elevation curve, comparing model grid, bathymetry data, and historical data

Hydrologic and climatic analyses will be used to help develop the inflows to Waldo Lake. The gage station at the Waldo Lake outlet, USGS 14147000, provides the downstream boundary by monitoring the outflow from the lake. The hydrologic analyses will also provide information on the influence of snowfall and snow pack, rainfall, and subsurface hydrology on the lake water budget. Temperature and water quality characteristics for the lake boundary conditions will be developed based on hydrologic analyses conducted and field data from any wells and ephemeral streams.

Meteorological conditions for Waldo Lake will be developed from the meteorological monitoring station on the Northeast end of the lake. The station monitors air temperature, relative humidity, wind speed and direction, and solar radiation. CE-QUAL-W2 uses dew point temperature instead of relative humidity so dew point temperatures will be calculated based on monitored air temperature and relative humidity. The solar radiation data will be compared with calculated theoretical solar radiation for the lake location to determine the influence of cloud cover and atmospheric attenuation.

Model Calibration

The Waldo Lake model will be calibrated in three steps. First, the lake water balance (including hydrodynamics) will be calibrated to ensure the appropriate amount of water is in the lake over time. The water level gage located on the Northeast end of the lake will be compared to the simulated lake level to evaluate the lake water budget and conduct a water balance. The next step is to calibrate the lake temperature regime over the simulation time period. Temperature vertical profiles and temperature thermistor arrays placed in the lake will be used to calibrate the model to ensure the seasonal thermal stratification is captured by the model. Once the hydrodynamics and thermal regime are calibrated, the lake model will be calibrated for water quality. Water quality grab sample collected in the lake will be used to ensure any longitudinal and vertical gradients in productivity are captured as well as the data provides. Grab samples with nutrient concentrations, productivity data, dissolved oxygen, pH, conductivity, and others will be utilized to calibrate the water quality model. Light extinction data and secchi disk data will be utilized to ensure appropriate light transparency in the lake. Historical data will

be utilized to assist in evaluating any season trends captured by the model during the simulation year(s). Phytoplankton efficiency and productivity data will be utilized to assist to refine algae-nutrient-light interactions.

Management Alternative Testing

Once the model has been calibrated for hydrodynamics, temperature and water quality the model can be used to investigate management scenarios for Waldo Lake. The model output results can be post-processed into various statistics plot sand animations to provide managers with tools for interpreting model output. Figure 75 shows a contour plot of water temperature in the Bull Run Reservoirs and represents one frame in time series animation. Vertical profile or contour plot animations can be developed for any simulated hydrodynamic characteristics or water quality constituent to better understand the impacts of individual management scenarios.

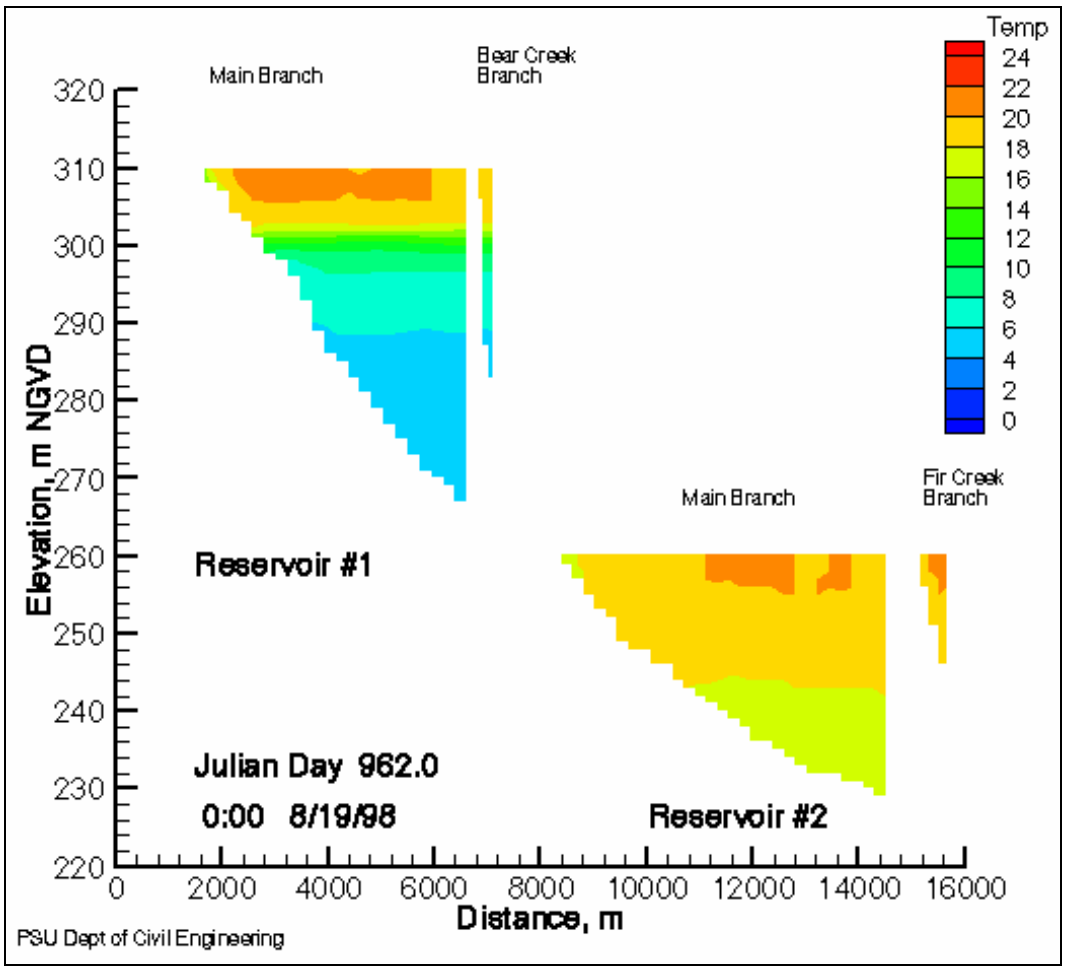


Figure 75: Bull Run reservoir system temperature contour temperature animation frame

Typical management questions that can be investigated with a CE-QUAL-W2 model include:

- What will be the response to the lake of increased lake utilization?
- How can weather conditions and different lake water level management affect lake productivity?

- How can changes in boundary conditions to Waldo Lake impact water quality conditions, specifically transparency and productivity?

Additional questions the model calibration and a sensitivity analysis may include:

- What improvements can made to the field monitoring to better capture the lake ecosystem dynamics? Is any additional data needed?
- What is the sensitivity of the model to changes in the meteorological data or changes to the light extinction coefficient?
- What is the model sensitivity to changes to algae-nutrient interaction coefficients?

Recommendations

Since a model of the lake system – its hydrodynamics and water quality – are essential in postulating impacts of different management strategies, the development of the model is an essential part of tying together the pieces of this project. Besides using the model in a management context, there are many opportunities to use in the model in a research context, such as in evaluating algal assemblages' productivity response to movement through the water column as a result of wind mixing.

The various pieces of this project, all feed into the modeling effort as shown in Figure 76.

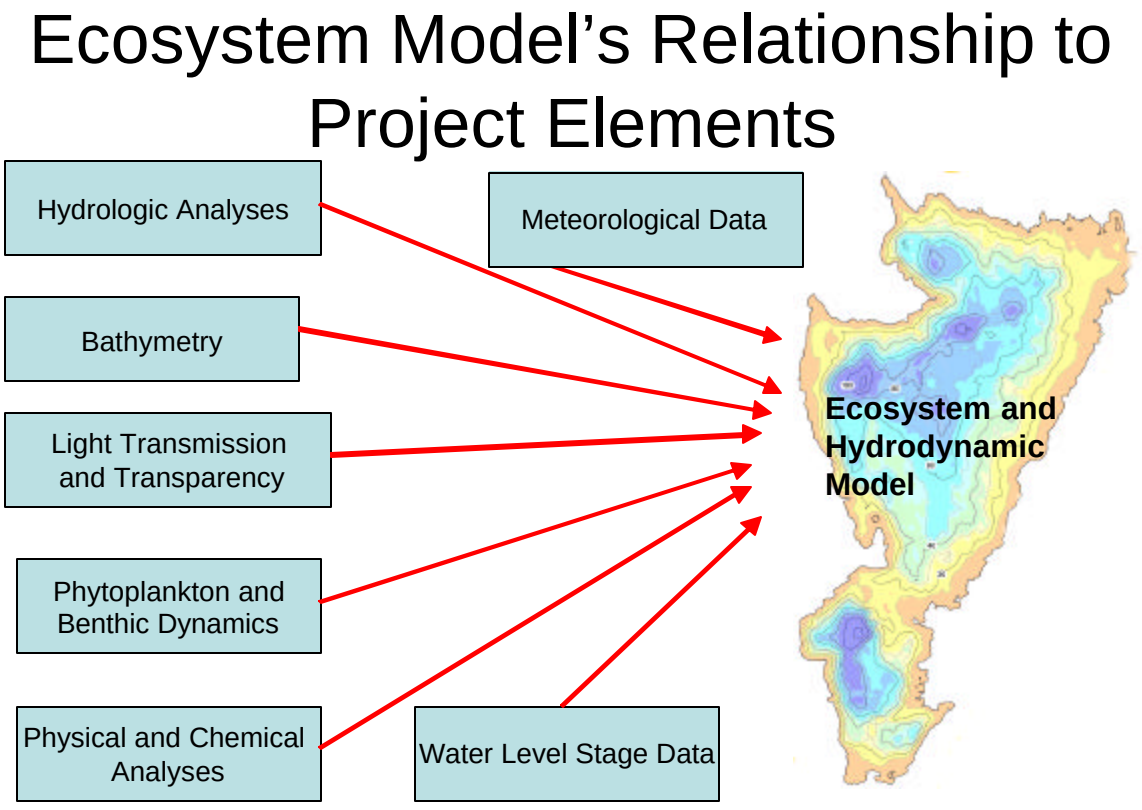


Figure 76: Relationship of ecosystem and hydrodynamic model to project elements.

Since much of these background data have been compiled, the next step is to construct a model of the system.

The recommended list of work items for development of the model of the system are as follows:

- Model construction and set-up
    - Using historical water quality and other field data (such as meteorological data, stage data), determine model years for model calibration
    - Organize data into files for model inputs
    - Construct numerical solution grid of Waldo Lake from the bathymetry data
    - Debug the model development by running the model for test cases
- Model calibration to water level and temperature
    - Calibrate the model to water level and temperature
    - Develop statistical and graphical measures of model calibration
    - Develop animation tools for presentation of model results
- Model calibration to water quality data
    - Calibrate model to nutrient, phytoplankton and benthic algae data
    - Develop statistical and graphical measures of model calibration
    - Develop animation tools for presentation of model results

The model could then be used in the following ways:

- Evaluate and model newly collected data by extending the range of model calibration to other years where high-quality field data have been collected.
- Use the model in a research context.
    - Modeling algal assemblages. The current model is set-up to model algae as a continuum over a model computational segment. The current model does not track the time-history of the algal assemblages in the water column. A particle tracking model for algae assemblages could be developed where the time-history of the algae cells can be determined in response to wind and other mixing events. This would be state-of-the-art research.
    - Add a zooplankton model compartment. The current release version of the model does not include a zooplankton compartment. A zooplankton compartment developed for the Tualatin River by Portland State University could be applied to Waldo Lake.
    - Refine the phytoplankton and periphyton models. As new information becomes available, PSU could re-examine the growth models and evaluate if they are adequate or need to be refined.
- Use the model in a management context
    - Impacts of long-term trends in hydrology and climate
    - Evaluate "what-if" scenarios on the use of increased tourist usage of the lake
    - Evaluate the impacts of forest fires on nutrient increases to the lake

Conclusions

The research conducted in 2003 was successful in further understanding the Waldo Lake ecosystem. Extensive data was collected in the field characterizing the physical, chemical and biological properties. Current research work has led to the need to better understand the benthic communities in the lake. Historical chemistry and biology data collected in the lake are starting to be reviewed in the context of larger time scales to investigate long term trends in lake conditions. Further work is needed in this area to better understand the data and the quality of the data. Meteorological and bathymetric data were collected and the historical climate conditions were analyzed. A preliminary quality assurance plan was developed with a plan to continually refine it as more research is conducted. And finally, preliminary work was started on putting the data together to develop a lake ecosystem model.

Each area of research discussed in this report resulted in some findings and raised new questions about Waldo Lake with some resulting recommendations for more research. The current work and the recommendations for future work, summarized below, are designed to improve our understanding of Waldo Lake from a variety of temporal and spatial scales (Figure 77). As stated at the beginning of the report the objectives of this research are to improve the science conducted on Waldo Lake by building on the historical data collected and developing new science inquiries to better understand the physical and ecological processes that regulate lake trophic status. Additionally, these science inquiries and their results would be used with analytical and computational models to improve the long-term management of Waldo Lake.

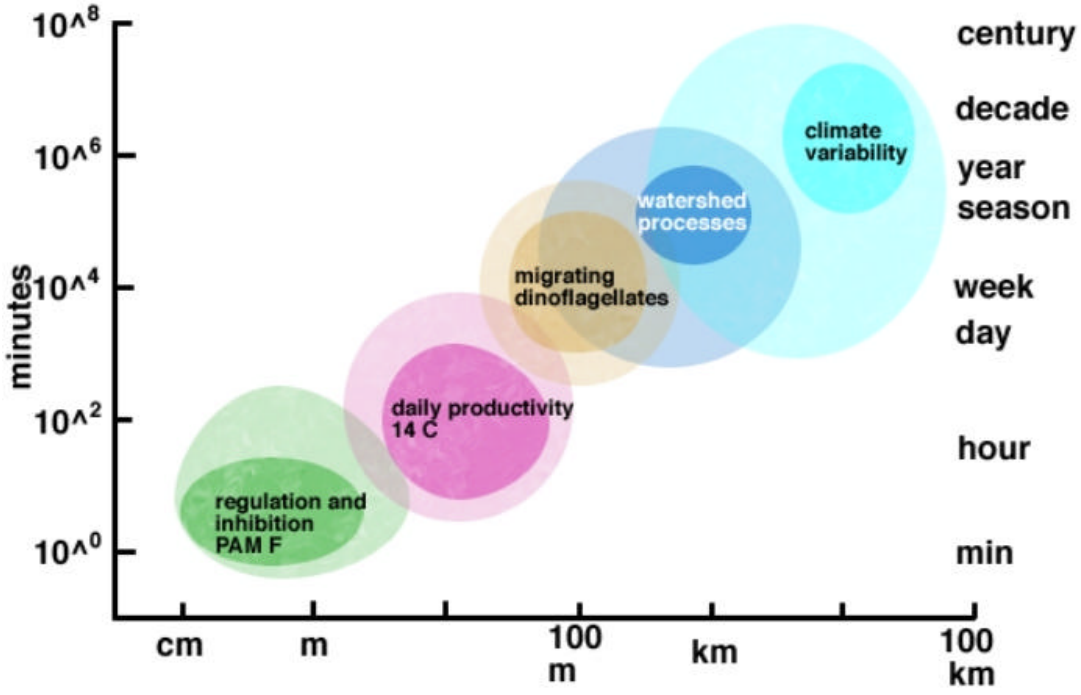


Figure 77: Temporal and spatial scales applicable to the Waldo Lake ecosystem.

The climate analyses presented only begin to elucidate some of the influences long term and large scale climate trends have on the Waldo Lake basin and the lake's physical and ecological processes. These large scale trends then influence the watershed processes such as dictating the water available over inter-

annual periods in the basin's water budget. Additionally meteorological conditions from year to year dictate immediate water resources available in the basin and wind inducing mixing may be influencing biological communities such as migrating dinoflagellates and other phytoplankton in the lake. Field studies over the past year regarding UV inhibition of phytoplankton and daily production of ^{14}C from phytoplankton are influenced by a variety temporal and spatial scales, from wind mixing, nutrient availability on a seasonal basis and climate conditions. In conducting the various pieces of research on Waldo Lake it will be important to put results in the context of the range of overlapping spatial and temporal scales for Waldo Lake. The interrelations between the scales will be studied further when an ecosystem model of Waldo Lake is developed.

Recommendations

The research conducted over the past year on Waldo Lake has resulted in new questions about the lake ecosystem and the need for some further research. The list below summarizes some proposed research and field activities for the coming year. This summary list will be used to develop a more detailed scope of work for the coming year, including budget information for each research and field activity.

- Proper surveying of the Islet Campground benchmark site is necessary to complete the bathymetric analysis.

- The water surface gage station needs to be surveyed in to convert lake stage levels to water surface elevations. This will be valuable in developing and calibrating the water quality model.

- The current stage-flow rating curve used for the lake outlet weir structure where there is a gage station needs to be re-examined to ensure the rating curve is accurate.

- Locate another meteorological station along the western shore of the lake just north of the Klovdahl Bay and south of Rhododendron Island. It is recommended that at a minimum of wind speed and wind direction data should be recorded. If possible the site could serve as a back up meteorological site to the current meteorological monitoring site if air temperature and relative humidity are also recorded. The meteorological data is valuable for climate studies and essential to modeling efforts in Waldo Lake.

- Reanalyze the 2003 sonar data with Biosonics Inc.'s Bottom Typing software to produce a map of substrate type as well as a map of the well-developed mats of liverworts and mosses living in the deeper sections of the lake. This analysis would require the collection of a small number of sediment and benthic mat samples to ground-truth software inferences.

- The optic qualities of Waldo Lake may provide the best indicator of change in the lake. Better characterization of the light field is necessary. The Licor scanning spectroradiometer should be used to measure light quality at depth in the lake.

- Picoplankton under 0.45 µm in diameter may be a significant contributor to primary production in the lake. This size class of picoplankton pass through filters currently used for primary production measurement. Size fractionation in Chl-a and C14 analyses should be implemented.

- There was a good correlation between in situ fluorescence and Chl-a in the water column. Quality assurance protocols for SCUFA and the SCUFA/Chl-a relationship should be developed to allow tracking of phytoplankton assemblages and better characterization of the distribution of phytoplankton with depth.

- The dominant zooplankton in the lake currently exhibits diurnal vertical migration perhaps to exploit phytoplankton in the upper water column where high UV intensity prohibits feeding during the daylight hours. Depth sounding equipment may be useful in tracking zooplankton in the water column. Use of depth sounding for zooplankton detection and SCUFA for

phytoplankton detection may allow development of a clearer picture of trophic dynamics in the lake.

- Benthic bryophytes and algal mats are likely to provide a significant portion of the primary production in the lake. Productivity of these organisms should be quantified. In addition, anecdotal reports suggest that benthic algae are more abundant along the north shore of the lake and may be responding to nutrients in runoff from the burned area. This hypothesis should be investigated using artificial or natural substrates.

- Temperature loggers currently present in the lake provide a detailed description of seasonal mixing in the lake. The loggers should be maintained in the lake.

- The database of Waldo Lake data is incomplete. All laboratory and field datasheets, and accompanying metadata, should be collected, and entered into an Access database for storage and easy retrieval.
    - All data should be checked for data quality and a grade for each parameter for each date added
    - All data below the method detection limit will be flagged.
    - Data that is outside the range of standards used for the analysis should be flagged.
    - The laboratory should be consulted on use of lower minimum standards.
    - Calculate average concentrations, averaging duplicate laboratory measurements
    - Include averaged values and 21 September 2003 in final chemistry summary
    - Corrected phytoplankton productivity estimate calculations needs to be completed and evaluated

- Develop a 2-dimensional hydrodynamic and water quality model of Waldo Lake using CE-QUAL-W2:
    - Model construction and set-up
        1. Using historical water quality and other field data (such as meteorological data, stage data), determine model years for model calibration
        2. Organize data into files for model inputs
        3. Construct numerical solution grid of Waldo Lake from the bathymetry data
        4. Debug the model development by running the model for test cases
    - Model calibration to water level and temperature
        1. Calibrate the model to water level and temperature
        2. Develop statistical and graphical measures of model calibration
        3. Develop animation tools for presentation of model results
    - Model calibration to water quality data
        1. Calibrate model to nutrient, phytoplankton and benthic algae data
        2. Develop statistical and graphical measures of model calibration
        3. Develop animation tools for presentation of model results

- Use the CE-QUAL-W2 model of Waldo Lake to:
    - Evaluate and model newly collected data by extending the range of model calibration to other years where high-quality field data have been collected.
    - Use the model in a research context.
        1. Modeling algae assemblages. The current model is set-up to model algae as a continuum over a model computational segment. The current model does not track the time-history of the algal assemblages in the water column. A particle

tracking model for algae assemblages could be developed where the time-history of the algae cells can be determined in response to wind and other mixing events. This would be state-of-the-art research.

2. Add a zooplankton model compartment. The current release version of the model does not include a zooplankton compartment. A zooplankton compartment developed for the Tualatin River by Portland State University could be applied to Waldo Lake.
3. Refine the phytoplankton and periphyton models. As new information becomes available, PSU could re-examine the growth models and evaluate if they are adequate or need to be refined.

- Use the model in a management context
    1. Impacts of long-term trends in hydrology and climate
    2. Evaluate "what-if" scenarios on the use of increased tourist usage of the lake
    3. Evaluate the impacts of forest fires on nutrient increases to the lake

- Daily pattern of productivity on multiple days
  The pattern of relative primary productivity over the entire light cycle of the day will vary with light levels and wind mixing. It is important to understand how this can vary between days (for example a windy versus calm or cloudy versus clear sky) and over several day sequences that progress from calm to windy or windy to calm. The model shows that these short term weather forcing factors can lead to very different production rates.

- Spatial heterogeneity of chlorophyll and photosynthetic efficiency
  In addition to temporal variations, there could be significant horizontal and vertical variations in the amount and productivity of phytoplankton. Vertical profiles or horizontal transects of in vivo chlorophyll fluorescence can be combined with selected discrete sampling and PAM Fluorometry to give estimates of this variation.

- Characterization of the mixotrophic cycle
  It is possible that the food web has a strong component of dinoflagellates feeding on bacteria and picoplankton, so called "mixotrophy". The flow of nutrients through mixotrophic cycle would compete with autotrophic algae. More mixotrophy can lead to higher lake clarity. The idea of mixotrophy as an important component of Waldo Lake food web dynamics has been proposed before but there is some evidence that it may be shifting now (with the recent decrease in the Glenodinium counts). The productivity and feeding activity of migrating dinoflagellates should be put in the context of vertical water mixing rates and exposure to PAR, UVA, and UVB.

- Survey of benthic plant community, nutrient budget and turnover
  The benthic community consists of plant, algae and cyanobacteria. The biomass of these communities should be surveyed and an attempt made to determine the amount of N, P that they store and how much soluble N, P and dissolved organics they may release in a given year. The benthic community may be a slow acting nutrient reservoir that could help explain the resiliency response of the entire lake ecosystem.

- Refine the annual water balance for Waldo Lake and develop a monthly water balance.
  To determine the importance of the watershed to the hydrology of the lake, the annual water balance must be refined to provide an estimate of the contribution of the watershed to the lake water balance. Two major tasks are required to refine the annual water balance:

- The evapotranspiration for the watershed and the evaporation from the lake must be estimated.
- An estimate of groundwater contribution from the watershed to the lake must be made

- Establish observation wells to determine groundwater levels and quality in the vicinity of Waldo Lake.
  Observation wells would support both the refinement of the water balance and provide information on the quality of the groundwater entering the lake. Installation of at least a few observation wells in the vicinity of the lake would be useful in establishing the direction of groundwater flow between the lake and the watershed. Should it indicate that water is flowing into the lake from the local groundwater system, information on the groundwater geochemistry would be useful in establishing the chemical characteristics of water flowing into the lake.

- Develop more detailed understanding of the relationship of local, short term climate variability to long term, large scale variations (ENSO, PDO).
  The short term variation of local climate in the vicinity of Waldo Lake (precipitation, temperature, solar radiation, etc.) provides the forcing for the dynamics of the lake and its ecosystem. However, this variation occurs in the larger context of patterns governed by global-scale features in the ocean-atmosphere system. In particular, inter-annual variations related to ENSO, superimposed on decadal scale persistence influencing the local climate as a result of the PDO, provide a backdrop against which the variation in ecosystem indicators must be viewed. In particular, the occurrence and persistence of cloudy vs. clear days and its impacts on light, temperature and precipitation are all important to the dynamics of the lake system. Persistent patterns of more or less light or higher or lower temperature related to the large scale persistence in the climate, which is suggested in the preliminary analysis, could explain some of the underlying natural variation in the system.

- Development of climate and hydrologic forcing scenarios for the Waldo Lake hydrodynamic model.
  The 2-D hydrodynamic model can be calibrated using the limited historic data on lake outflow and other data collected over the past summer. However, to use the hydrodynamic model to evaluate various scenarios of lake behavior, it is necessary to develop forcing, in particular sequences of climate variables including precipitation, temperature, solar radiation, etc., that drive the hydrodynamic model. Based on the understanding of the relationship of short term climate fluctuations to larger scale and longer term patterns (Recommendation 3, above) the local data can be used to develop models of the occurrence and variation in these characteristics and, working with other members of the team, various scenarios will be developed to test hypotheses related to the lake ecosystem.

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Appendix A: Phytoplankton class distribution

Table 26: Phytoplankton class distribution for each sampling event 1999-2003.

	7/26/1999	8/31/1999	9/19/1999	10/8/1999	5/27/2001	7/7/2001	8/19/2001	9/9/2001	6/29/2002	7/29/2002	8/19/2002	9/18/2002	7/1/2003	8/4/2003	8/25/2003	9/21/2003
Density (#/mL)																
Dinophyceae	485.6	454.3	469.7	393.4	98.3	503.6	106.4	353.0	48.6	252.9	173.3	159.7	29.3	97.8	135.0	209.7
Bacilliarophyceae	4.1	6.9	9.9	1.5	10.0	14.7	16.5	15.2	3.5	5.1	1.5	3.9	68.9	174.4	3.4	1.4
Chlorophyceae	201.4	592.2	747.8	301.7	19.3	79.6	218.8	219.5	93.6	174.2	225.9	300.2	94.5	203.6	236.3	554.3
Chrysoyphyceae	2.4	5.0	15.5	22.6	5.1	9.6	2.2	3.5	2.3	14.8	8.0	8.0	1.1	3.5	15.8	13.8
Chryptophyceae	3.2			1.9		1.1			0.4				0.6		0.5	0.7
Unknown	8.6	5.1	3.1	2.9	9.1	11.3	2.3	3.8	2.4	3.1	3.0			0.7	0.9	4.0
TOTAL	705.3	1063.4	1246.0	724.0	141.9	619.9	346.2	595.1	150.8	450.1	411.6	471.9	194.3	480.0	391.9	784.0
Biovolume (μm^3/mL)																
Dinophyceae	179516.5	171796.5	176065.7	147761.8	36604.2	184332.7	40199.7	131180.8	18287.6	94251.4	63242.0	58785.6	11228.4	37574.7	49824.8	75825.7
Bacilliarophyceae	2799.0	2594.8	3261.1	207.7	3123.1	4652.8	6463.0	6255.3	939.9	2629.5	1278.5	1181.2	12918.7	39255.5	546.5	319.3
Chlorophyceae	40210.0	100227.6	117388.5	42754.6	2928.1	13601.4	29448.4	27904.2	13909.6	21813.1	29803.9	36776.2	14095.2	29756.2	30159.0	71064.4
Chrysoyphyceae	48.4	504.8	3281.9	11276.6	671.6	295.3	326.9	348.1	896.9	1761.5	837.7	821.5	167.6	672.7	2089.3	1855.1
Chryptophyceae	63.3			37.2		457.0			215.6				11.8		9.4	47.3
Unknown	171.8	101.6	62.1	57.5	182.7	230.3	45.6	75.8	48.1	62.8	59.2			14.2	18.0	80.1
TOTAL	222809.1	275225.4	300059.4	202095.4	43509.7	203569.5	76483.7	165764.2	34297.6	120518.3	95221.2	97564.5	38421.6	107273.2	82647.0	149192.0

Appendix B: Zooplankton classification

Table 27: Zooplankton classifications for sampling events from 1996 to 2002.

Date	Group	Most common species	Percentage of Total of Group	Percentage of Total of all Zooplankton	Group Total per m^3	Total Zooplankton per m^3
9/6/1996	Cladocera				478.7	11838.3
		Bosmina longirostris	99.9	4.0		
		Alona sp.	0.14	0.01		
	Copepoda				11117.6	
		Diaptomus copepodite	49.1	46.1		
		Copepod nauplii	37.7	35.4		
		Diaptomus signicauda	13.2	12.4		
		Diaptomus shoshone *	0.03	0.03		
		Ocyclops. modestus	0.005	0.004		
	Rotifera and Protozoa				242.0	
		Collotheca sp.	94.2	1.9		
		Keratella cochlearis	4.0	0.1		
		Filinia longiseta	1.5	0.031		
		bdelloid rotifer	0.1	0.003		
		Difflugia sp.	0.2	0.004		
9/6/1996 NS						4318.8
	Cladocera				61.115	
		Bosmina longirostris	77.8	1.1		
		Chydorus sphaericus	22.2	0.3		
	Copepoda				3293.446	
		Diaptomus copepodite	54.4	41.5		
		Diaptomus signicauda	26.6	20.3		
		Copepod nauplii	18.8	14.3		
		Harpacticoid	0.2	0.2		
	Rotifera and Protozoa				957.476	
		Collotheca sp.	75.2	16.7		
		Keratella cochlearis	10.6	2.4		
		Lecane(M) cornuta (?)	5.0	1.1		
		Polyarthra dolichoptera	4.3	0.9		
		Brachionus urceolaris (?)	2.1	0.5		
		Lecane (L) sp.	0.7	0.2		
		Filinia longiseta	0.7	0.2		
		Trichocerca cylindrica	0.7	0.2		
		Ploesoma truncatum	0.7	0.2		
	Non-Crustacean Zooplankters					
		Water mites		0.2		
6/30/1997						7981.2
	Cladocera				6765.9	
		Bosmina longirostris	100.0	84.8		
	Copepoda				697.5	
		Copepod nauplii	85.0	7.4		
		Diaptomus kenai x shoshone*	11.7	1.0		
		Large. Diaptomid	3.3	0.3		

Date	Group	Most common species	Percentage of Total of Group	Percentage of Total of all Zooplankton	Group Total per m^3	Total Zooplankton per m^3
		copepodite				
	Rotifera and Protozoa				515.8	
		Collotheca pelagica	85.1	5.5		
		Kellicottia longispina	13.4	0.9		
		Keratella cochlearis	0.4	0.03		
		Difflugia sp.	1.1	0.1		
	Misc. Zooplankters Other than Rotifers and Protozoans					
		Water mites		0.025		
9/13/1997						3897
	Cladocera				2902.8	
		Bosmina longirostris	100.0	74.5		
	Copepoda				939.9	
		Small Diaptomid copepodite	37.5	9.0		
		Large Diaptomid copepodite	24.0	5.8		
		Copepod nauplii	19.8	4.8		
		Diaptomus signicauda	10.0	2.4		
		Diaptomus kenai x shoshone*	8.7	2.1		
	Rotifera and Protozoa				54.4	
		Collotheca pelagica	95.2	1.3		
		Keratella cochlearis	3.5	0.05		
		Kellicottia longispina	1.3	0.02		
7/26/1999						1470.7
	Cladocera				1190.5	
		Bosmina longirostris	100.0	80.9		
	Copepoda				280.4	
		Diaptomus kenai x shoshone *	72.1	13.7		
		Large Diaptomid copepodite *	19.4	3.7		
		Copepod nauplii	6.8	1.3		
		Small Diaptomid copepodite	1.3	0.2		
		Diaptomus signicauda	0.4	0.1		
	Rotifera and Protozoa		none			
8/31/1999						2820.3
	Cladocera				1866.9	
		Bosmina longirostris	99.2	65.7		
		Alona costata	0.8	0.5		
	Copepoda				909.6	
		Copepod nauplii	71.4	23.0		
		Diaptomus kenai x shoshone *	25.1	8.1		
		Small Diaptomid copepodite	1.1	0.4		
		Harpacticoid copepod	0.8	0.3		
		Diaptomus signicauda	0.3	0.1		
		Microcyclops varicans	0.2	0.1		
		Large Diaptomid copepodite *	0.1	0.02		

Date	Group	Most common species	Percentage of Total of Group	Percentage of Total of all Zooplankton	Group Total per m^3	Total Zooplankton per m^3
	Rotifera and Protozoa					
		Collotheca pelagica	none			
	Misc. Zooplankters Other than Rotifers and Protozoans					
		Water mites *		0.04		
		Tardigarde		1.301280006		
		Difflugia sp.		0.234017658		
9/19/1999						2425.7
	Cladocera				1470.2	
		Bosmina longirostris	99.8	60.5		
		Alona costata	0.2	0.1		
		Chydorus sphaericus	0.034	0.021		
	Copepoda				863.7	
		Copepod nauplii	77.5	27.6		
		Diaptomus kenai x shoshone *	19.9	7.1		
		Diaptomus signicauda	1.2	0.4		
		Harpacticoid copepod	0.7	0.3		
		Microcyclops varicans	0.5	0.2		
		Small Diaptomid copepodite	0.1	0.03		
	Rotifera and Protozoa				34.7	
		Collotheca pelagica	98.3	1.4		
		Keratella cochlearis	1.7	0.02		
	Misc. Zooplankters Other than Rotifers and Protozoans					
		Water mites *		0.02		
		Ostracods		0.1		
		Tardigarde		0.1		
		Nematodes		0.02		
		Difflugia sp.		2.2		
10/9/1999						2405.9
	Cladocera				1398.5	
		Bosmina longirostris	100.0	58.1		
		Chydorus sphaericus	0.03	0.02		
	Copepoda				935.6	
		Copepod nauplii	74.8	29.1		
		Diaptomus kenai x shoshone *	24.5	9.5		
		Diaptomus signicauda	0.44	0.17		
		Small Diaptomid copepodite	0.11	0.04		
		Large Diaptomid copepodite *	0.11	0.04		
		Cyclops vernalis	0.04	0.02		
		Cyclopoid copepodite	0.02	0.01		
	Rotifera and Protozoa					
		Collotheca pelagica	99.3	2.9		
		Monostyla lunaris	0.7	0.02		
	Misc. Zooplankters Other than Rotifers and Protozoans					
		Water mites *		0.04		
		Dipteran larvae *		0.01		
5/27/2001						3769.5

Date	Group	Most common species	Percentage of Total of Group	Percentage of Total of all Zooplankton	Group Total per m^3	Total Zooplankton per m^3
	Cladocera				1715.3	
		Bosmina longirostris	100.0	45.5		
	Copepoda				2000.6	
		Diaptomus kenai x shoshone*	46.2	24.5		
		Large. Diaptomid copepodite*	44.7	23.7		
		Copepod nauplii	5.8	3.1		
		Small Diaptomid copepodite	3.2	1.7		
		Diaptomus signicauda	0.1	0.05		
	Rotifera and Protozoa				53.5	
		Collotheca pelagica	99.98	1.42		
		Kellicottia bostonensis	0.02	0.0003		
7/7/2001						3516.3
	Cladocera				1165.8	
		Bosmina longirostris	100.0	33.2		
	Copepoda				2291.8	
		Copepod nauplii	53.4	34.8		
		Diaptomus kenai x shoshone*	39.1	25.5		
		Large Diaptomid copepodite*	4.7	3.0		
		Small Diaptomid copepodite	1.4	0.9		
		Cyclopoid copepodite	0.04	0.03		
	Rotifera and Protozoa				58.8	
		Collotheca pelagica	97.3	1.6		
		Keratella quadrata	1.72	0.03		
		Keratella cochlearis	0.85	0.01		
8/19/2001						4459.8
	Cladocera				1610.8	
		Bosmina longirostris	99.9	36.1		
		Chydorus sphaericus	0.06	0.02		
		Alona costata	0.06	0.02		
	Copepoda				2813.4	
		Copepod nauplii	73.1	46.1		
		Diaptomus kenai x shoshone*	14.2	9.0		
		Small Diaptomid copepodite	11.3	7.1		
		Large Diaptomid copepodite*	0.8	0.5		
		Diaptomus signicauda	0.6	0.4		
		Cyclopoid copepodite	0.05	0.03		
	Rotifera and Protozoa				2813.4	
		Collotheca pelagica	97.3	0.7		
		Trichocerca cylindrica	2.7	0.02		
	Misc. Zooplankters					
		Ostracods (Cyclocypria kincardita?)		0.06		
		Dipteran larvae *		0.02		
9/9/2001						5220.4

Date	Group	Most common species	Percentage of Total of Group	Percentage of Total of all Zooplankton	Group Total per m^3	Total Zooplankton per m^3
	Cladocera				2062.2	
		Bosmina longirostris	99.9	39.5		
		Chydorus sphaericus	0.03	0.01		
		Chydorus gibbus	0.06	0.02		
	Copepoda				3137.9	
		Copepod nauplii	52.4	31.5		
		Sm. Diaptomid copepodite	24.9	15.0		
		Diaptomus kenai x shoshone*	10.2	6.1		
		Lrg. Diaptomid copepodite*	7.2	4.3		
		Diaptomus signicauda	5.2	3.1		
		Cyclopoid copepodite	0.11	0.07		
		Microcyclops varicans	0.01	0.01		
	Rotifera and Protozoa				20.4	
		Collotheca pelagica	66.7	0.3		
		Keratella cochlearis	32.7	0.1		
		Lecane luna	0.05	0.0002		
	Misc. Zooplankters					
		Dipteran larvae *		0.02		
6/29/2002						3055.2
	Cladocera				2417.0	
		Bosmina longirostris	100.0	79.1		
	Copepoda				628.5	
		Diaptomus kenai x shoshone*	56.8	11.7		
		Large Diaptomid copepodite *	28.7	5.9		
		Copepod nauplii	11.7	2.4		
		Small Diaptomid copepodite	2.6	0.5		
		Diaptomus signicauda	0.2	0.05		
	Rotifera and Protozoa				9.7	
		Collotheca pelagica	79.4	0.3		
		Lecane mira	20.6	0.1		
	Misc. Zooplankters Other than Rotifers and Protozoans					
		Water mites		0.02		
		Dipteran larvae *		0.1		
7/29/2002						4325.3
	Cladocera				3206.4	
		Bosmina longirostris	99.99	74.12		
		Alona costata	0.01	0.01		
	Copepoda				839.0	
		Diaptomus kenai x shoshone*	61.78	11.98		
		Copepod nauplii	24.80	4.81		
		Sm. Diaptomid copepodite	7.20	1.40		
		Diaptomus signicauda	2.26	0.44		
		Large Diaptomid copepodite *	3.91	0.76		

Date	Group	Most common species	Percentage of Total of Group	Percentage of Total of all Zooplankton	Group Total per m^3	Total Zooplankton per m^3
		Cyclopoid copepodite	0.11	0.02		
	Rotifera and Protozoa				279.2	
		Keratella cochlearis	91.2	5.9		
		Polyarthra vulgaris	3.8	0.2		
		Collotheca pelagica	2.7	0.2		
		Kellicottia bostonensis	1.4	0.1		
		Trichocerca multicrinis	0.68	0.04		
		Trichotria tetractis	0.18	0.01		
		Difflugia sp.	0.22	0.01		
8/19/2002						8309.7
	Cladocera				6459.9	
		Bosmina longirostris	100.0	77.7		
		Alona costata	0.02	0.02		
	Copepoda				1787.5	
		Copepod nauplii	67.4	14.5		
		Diaptomus kenai x shoshone*	17.2	3.7		
		Small Diaptomid copepodite	8.2	1.8		
		Large Diaptomid copepodite *	4.4	0.9		
		Diaptomus signicauda	2.8	0.6		
	Rotifera and Protozoa				62.3	
		Collotheca pelagica	90.4	0.7		
		Keratella hiemalis	2.4	0.02		
		Keratella cochlearis	4.8	0.04		
		Trichocerca multicrinis	2.25	0.02		
9/18/2002						9280.8
	Cladocera				6980.8	
		Bosmina longirostris	99.97	75.2		
		Chydorus sphaericus	0.03	0.02		
	Copepoda				2267.5	
		Copepod nauplii	56.0	13.7		
		Small Diaptomid copepodite	14.2	3.5		
		Diaptomus signicauda	10.44	2.6		
		Diaptomus kenai x shoshone*	10.42	2.5		
		Large Diaptomid copepodite *	8.9	2.2		
	Rotifera and Protozoa				32.5	
		Collotheca pelagica	73.5	0.3		
		Polyarthra vulgaris	19.7	0.07		
		Kellicottia bostonensis	6.5	0.02		
	Misc. Zooplankters Other than Rotifers and Protozoans					
		Dipteran larvae *		0.02262736		