Barr Lake

Reservoir Water-Quality Assessment
Adams County, Colorado

Prepared for:
The Barr– Milton Watershed Association

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Final Report

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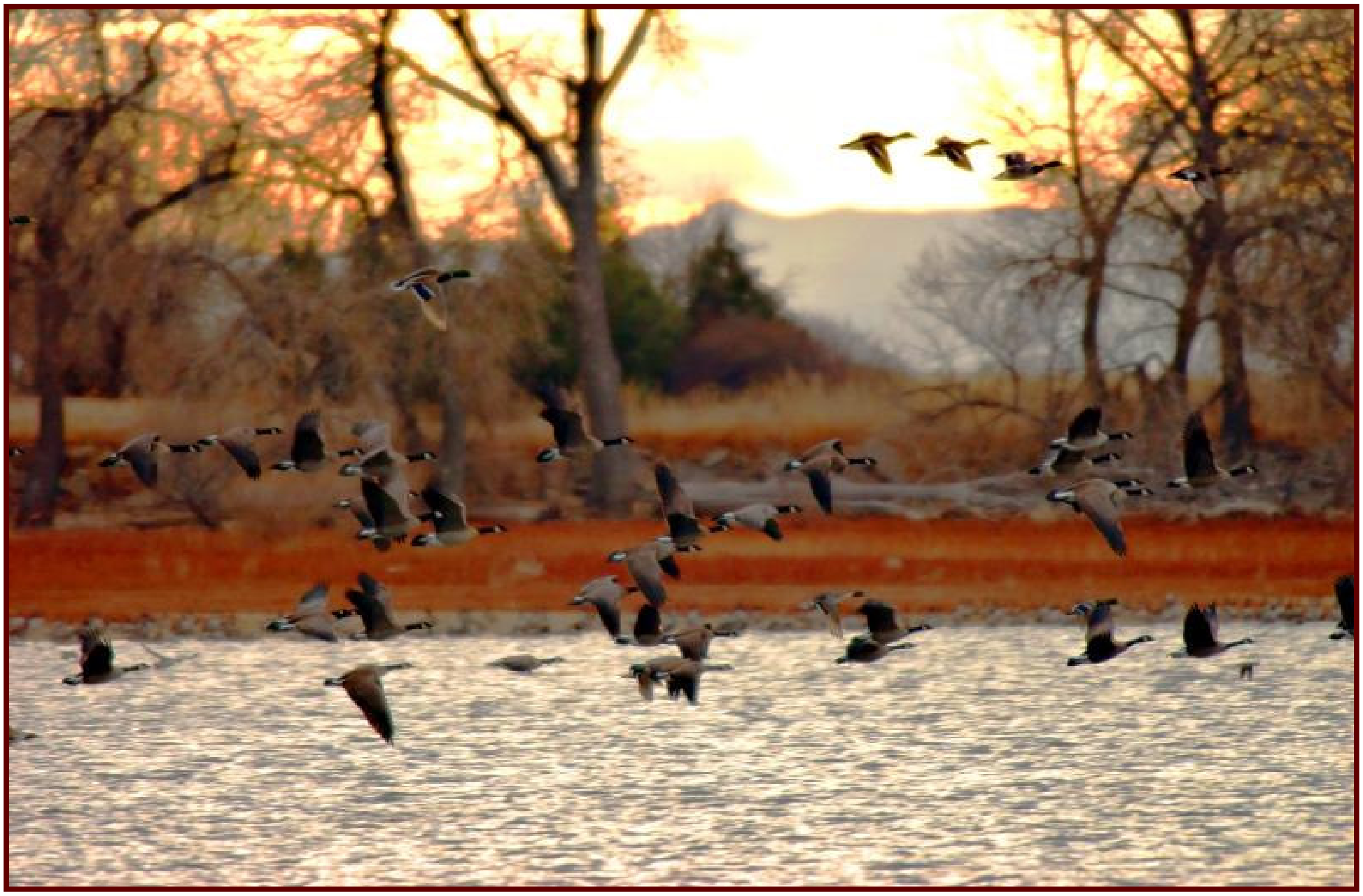

TABLE OF CONTENTS

Figures

Tables

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Abbreviations

AF – acre-foot
EPA - Environmental Protection Agency
FRICO - Farmers Reservoir Irrigation Company
ft – feet
g - gram
HA – hectare
IY – irrigation year
m – meter
mg - milligram
l – liter
lbs - pounds
mg - milligram
MWRD - Metro Wastewater Reclamation District
N – nitrogen
n - number of data points
NA – Not Applicable
NED – Not Enough Data
N:P - Nitrogen to Phosphorus Ratio
P – phosphorus
R^2 – coefficient of determination
SACWSD - South Adams County Water and Sanitation District
SU – standard unit
TKN - Total Kjeldahl Nitrogen
µg – microgram
µS – micro Siemens
USGS - US Geological Survey

INTRODUCTION

Barr Lake is a reservoir located on the high plains of Colorado about 20 miles northeast of Denver (Figure 1). Its elevation is approximately 5,100 feet above mean sea level. Precipitation in the area is approximately 15.8 inches per year. The main source of water to the reservoir is the Burlington-O'Brian canal, which diverts from the South Platte River (Figure 2). Water is released from the reservoir via two outlets - the east outfall and the west outfall. It is owned and managed by the Farmer's Reservoir Irrigation Company (FRICO).

Barr Lake has four designated use classifications: agriculture, aquatic life warm, recreation, and water supply. The reservoir is currently on the State's 303(d) list for exceeding the upper pH limit of 9.0.

This reservoir water-quality assessment includes 1) in-reservoir data analysis, 2) inflow and outflow data analysis, 3) a water balance, 4) a nutrient balance and 5) a comparison with other reservoirs in the same geographic area. Also included is an analysis of water and nutrient budgets for the Burlington-O'Brian canal. A discussion of observed water-quality dynamics within the reservoir is also included.

Figure 1. Barr Lake – Aerial Photograph

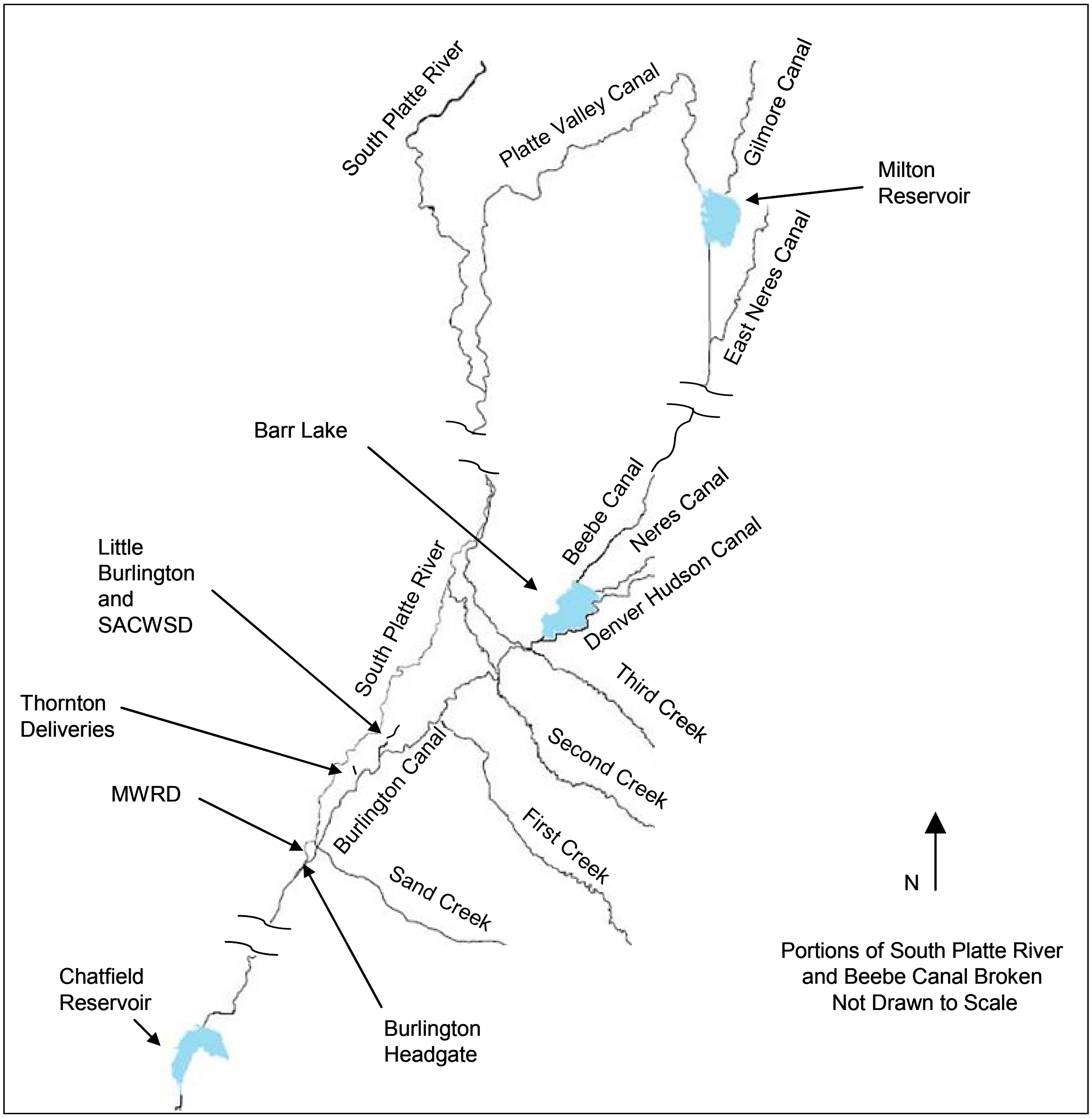

Figure 2. Map of Barr Lake and Environs

DATA – SOURCES AND TREATMENT

Data from several sources were used for this analysis (Table 1). With respect to water-quality data, results reported as being below the detection limit were treated as being at one-half the detection limit. In addition, when data for duplicate samples were available, the average of the sample and the duplicate were used in the analysis.

Table 1. Data Sources

Data Description	Source
Daily Surface Water Flows into Barr Lake (11/84-10/05)	D. Helton Consulting (Rink, 2007a)
Daily Reservoir Release Flows (11/84-10/05)	D. Helton Consulting (Rink, 2007a)
Daily Diversions From the South Platte River to the Burlington-O'Brian Canal (11/84-10/05)	D. Helton Consulting (Rink, 2007a)
Daily Diversions from the Burlington-O'Brian Canal (11/84-10/05)	D. Helton Consulting (Rink, 2007a)
Daily Toe Drain Seepage from Barr Lake (11/84-10/05)	D. Helton Consulting (Rink, 2007a)
Daily Pumping from MWRD to the Burlington-O'Brian Canal (1991-2005)	Lundt, 2006e
Daily Flows from the Waste Gate on the Burlington-O'Brian Canal	Smith, 2004, 2008b
In-Reservoir Water Quality (6/02[1]-10/05)	Lundt, 2006d
Algal Species (2002-2004)	Lundt, 2004
Inflow / Outflow Water Quality (1/95-12/05)	Mountain River Associates (Dorsch, 2004; Lundt, 2006a)
Elevation - Area - Capacity Table	D. Helton Consulting (Rink, 2007a)
Reservoir Contents (11/84-10/05)	D. Helton Consulting (Rink, 2007a)
Sediment Phosphorus Data	Lundt, 2005
Water-Quality for Other Lower South Platte Reservoirs	Sprague, 2002a

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[1] In-reservoir water-quality sampling started in June 2002. Therefore, there are no data for the first seven months of the 2000 irrigation year.

Data Description	Source
Historical In-Reservoir Water Quality (1978-1979)	Lundt, 2003
Historical In-Reservoir Water Quality (1975)	Tri-County District Health Department, 1975
Historical In-Reservoir Water Quality (1975)	EPA, 1975
Historical In-Reservoir Water Quality (1980-89)	Lewis and Saunders, 1990

Most annual computations for this report are based on an irrigation year – November 1 through October 31, and are designated using ‘IY’. For example, IY05 represents November 1, 2004 through October 31, 2005.

Overall trend analyses were conducted for in-reservoir water-quality constituents as well as inflow (Burlington-O’Brian Canal) water quality. The Mann-Kendall Methodology (Gilbert, 1987) was used. Although the Mann-Kendall test for trend can be performed on a small sample (4 <= n < = 10), a larger sample size is suggested (n >= 20) (EPA, 2000). Therefore, data were analyzed for trends only if there were at least 20 data points. Trends are described in the subsequent sections of this report and are reported with a 95% confidence interval (α = 0.05) to determine whether a trend is significant. Only significant trends are reported. Note that trend analyses were conducted using recent available water-quality data (2002-2005 for the in-reservoir data and 1994-2005 for the inflow / outflow data). Data from the 1970’s and 1980’s were not included due to few historical data points and the gap in data between 1990 and 2001.

Daily data for many components of the water balance were developed by D. Helton Consulting (Rink, 2007a). Most of the data values were from FRICO records and in some cases, data were filled in by Mr. Helton to provide a complete daily time series for the water balance (Helton, 2008). In addition, some values (e.g., the Burlington-O’Brian at the Sand Creek Flume) were adjusted to fix suspected errors in the diversion data (Helton, 2008). These data were provided to AMEC Earth & Environmental specifically for the water nutrient balance efforts and it was assumed that the data were the best datasets available to characterize the system. No attempts were made to verify the values received.

Mr. Helton mentioned that he made “adjustments” to the raw data to fix errors he suspected in the diversion data. For example, a change in storage in Barr Lake that wasn’t captured in the flow record (because of some missing data perhaps), the flow data were adjusted to “better balance” the flow.

RESERVOIR DATA ANALYSIS

Comparison of Sampling Sites

Water-quality samples are taken from three locations within Barr Lake (Figure 3). An analysis was completed to determine if the results from the three sites were statistically different from each other. The chi-square test for homogeneity (EPA, 1998) was used at a 95% confidence level (α = 0.05).

The analysis focused on several constituents and compared data at the bottom of the reservoir (hypolimnion) and compared data near the surface (epilimnion) of the reservoir. The results are summarized in Table 2.

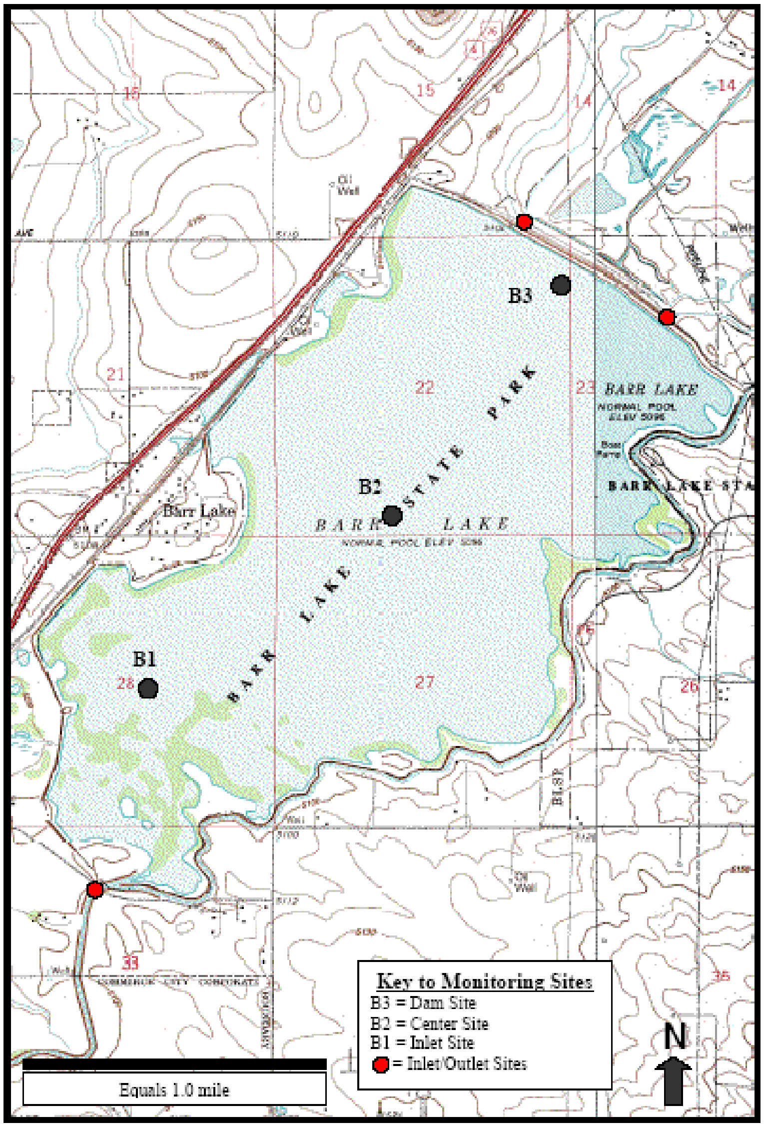

Figure 3. Barr Lake Sampling Sites (Map Credit: S. Lundt, MWRD)

With respect to chlorophyll *a*, total organic carbon, Secchi-disk depth, total suspended solids, total phosphorus, orthophosphate, nitrate + nitrite, and Total Kjeldahl Nitrogen (TKN) in the epilimnion, the analysis indicates that data taken from sampling sites B1, B2, and B3 are not statistically different. Statistical differences were found for ammonia in the epilimnion. This could be due to the abundance of ammonia results that were reported below the detection limit. Making estimates for these results could have affected the results of the statistical analysis for this constituent.

For the hypolimnion, the analysis results indicate no statistical differences with respect to total organic carbon, and all of the nutrient species, with the exception of ammonia. Since the overall analysis indicates that the three sites are statistically homogeneous, data from the site near the dam (B3) were used for the discussion in the rest of this report. This site also had more data records associated with it over sites B1 and B2.

Table 2. Comparison of In-Reservoir Sampling Sites B1, B2, and B3

Constituent	Epilimnion (Surface Layer)	Hypolimnion (Bottom Layer)
Chlorophyll *a*	No Difference	NA
Secchi-Disk Depth	No Difference	No Difference
Total Organic Carbon	No Difference	NED
Total Suspended Solids	No Difference	No Difference
Total Phosphorus	No Difference	No Difference
Orthophosphate	No Difference	No Difference
Total Kjeldahl Nitrogen	No Difference	No Difference
Nitrate + Nitrite	No Difference	No Difference
Ammonia	Difference	Difference

NA = Not Applicable
NED = Not Enough Data

Physical Data

Morphometry

The morphometry of Barr Lake at full pool is summarized in Table 3. The reservoir is relatively shallow. Note that the reservoir is seldom at full pool as noted in Figure 4 and its contents dropped considerably during the dry year of 2002. The relationships between surface water elevation, reservoir surface area, and reservoir contents are shown in Figure 5.

Table 3. Barr Lake Morphometry at Full Pool*

Parameter	Value (British Units)	Value (Metric Units)
Elevation		
Gage Height	34.25 ft	10.4 m
Surface Water Elevation (MSL)	5,095 ft	1,553 m
Depth		
Mean	16.4 ft	5.0 m
Maximum	34.25 ft	10.4 m
Surface Area	1,833 Acres	742 HA
Contents	30,071 AF	37.1×10^6 m^3

* Full Pool defined as maximum contents 1985-2005

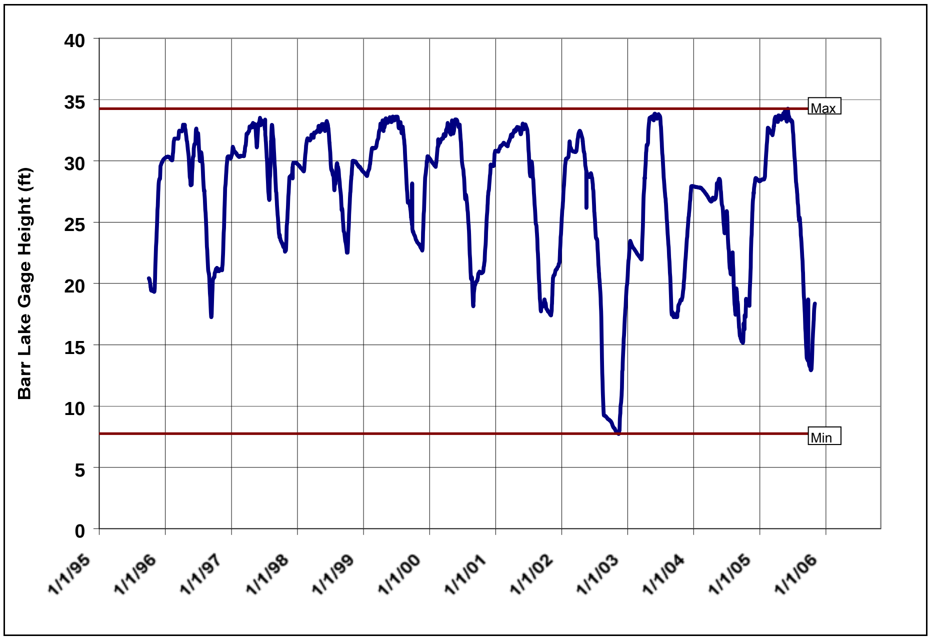

Figure 4. Historical Gage Height for Barr Lake

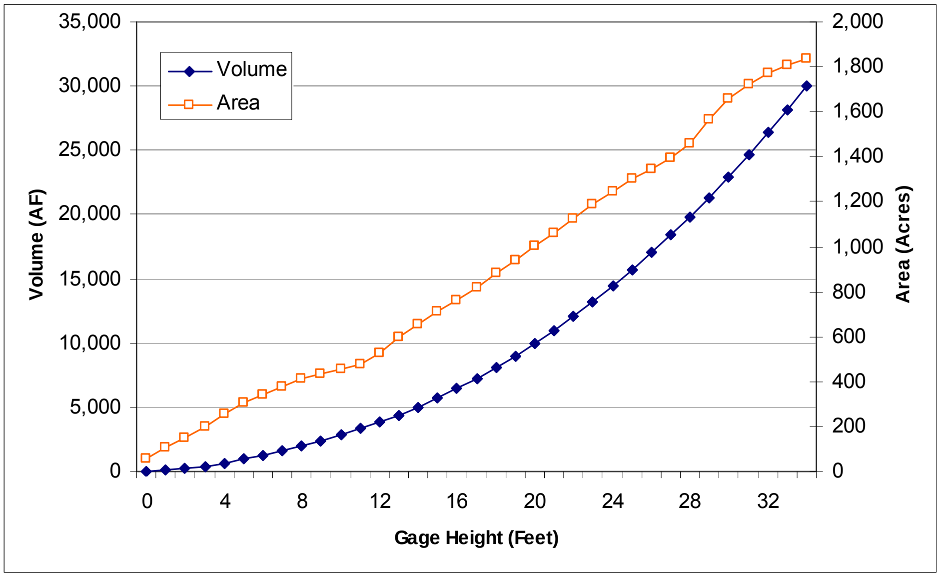

Figure 5. Area and Volume versus Gage Height for Barr Lake

Hydrology

Daily inflow and outflow data were analyzed for patterns and magnitude. Annual inflows and outflows are summarized in Table 4.

Table 4. Barr Lake Hydrology for IY85-IY05 (AF/Year)

	Inflow from Burlington-O'Brian Canal	Reservoir Releases
Average Irrigation Year Flow	45,020	32,034
Maximum Annual Flow / Irrigation Year	71,334 (1985)	44,530 (1998)
Minimum Annual Flow / Irrigation Year	26,861 (2002)	19,559 (2002)

Figure 6 shows the inflow and outflow for a composite year. This plot was developed by averaging daily hydrographs from 1995 through 2004. Although the data are somewhat smoothed by the averaging process, the major features of the reservoir's hydrology can be seen. Inflows are low in January and increase in February to over 150 AF/day and then dropping down at the end of the month. Starting in March, inflows increase steadily until May and then decrease erratically until the end of September. Flows increase starting in October through the beginning of December with peaks in mid-October, mid-November, and early December.

Outflows are minimal between November and March, ramp up starting in April and continue through October. Peak outflows are in July and August. Reservoir contents for a composite year are displayed in Figure 7. Contents generally peak in May and are at lowest levels in October. The hydraulic residence time based on releases and average contents for each irrigation year are shown in Table 5.

Table 5. Hydraulic Residence Times by Irrigation Year

Year	Hydraulic Residence Time (months)
IY00	8.9
IY01	10.3
IY02	9.3
IY03	5.4
IY04	6.6
IY05	6.1
Average (IY00-IY05)	7.5

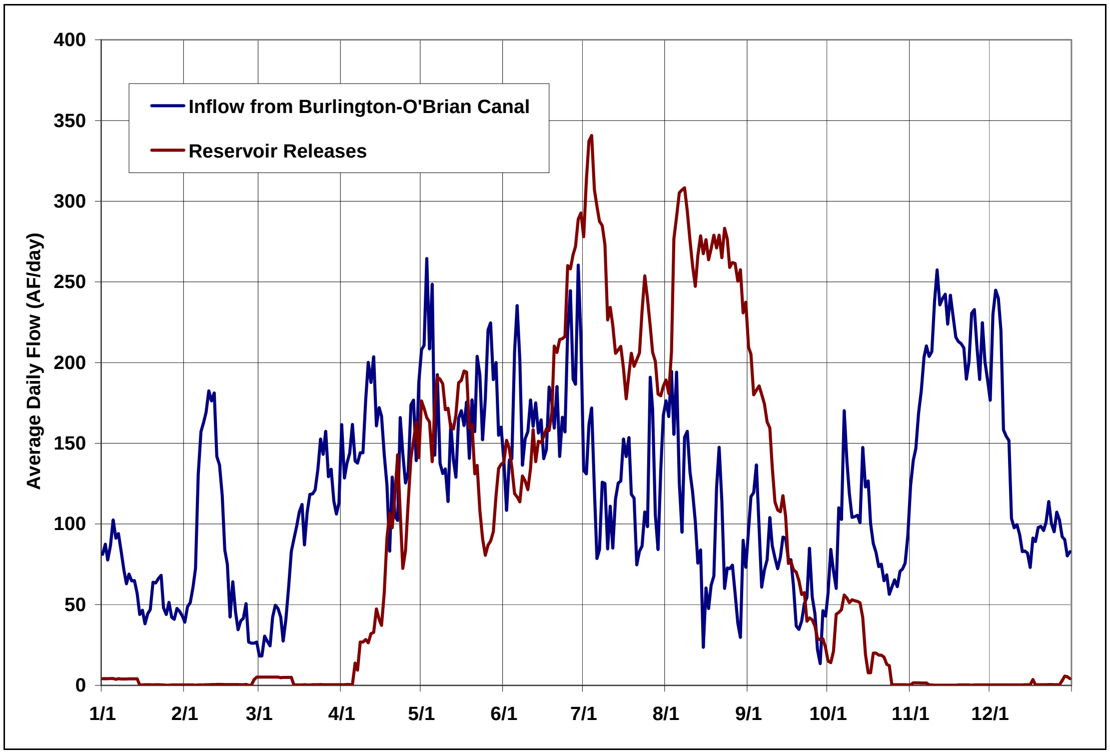

Figure 6. Inflow from the Burlington-O'Brian Canal and Reservoir Releases for Barr Lake for a Composite Year Representing the Average of 1995 through 2004

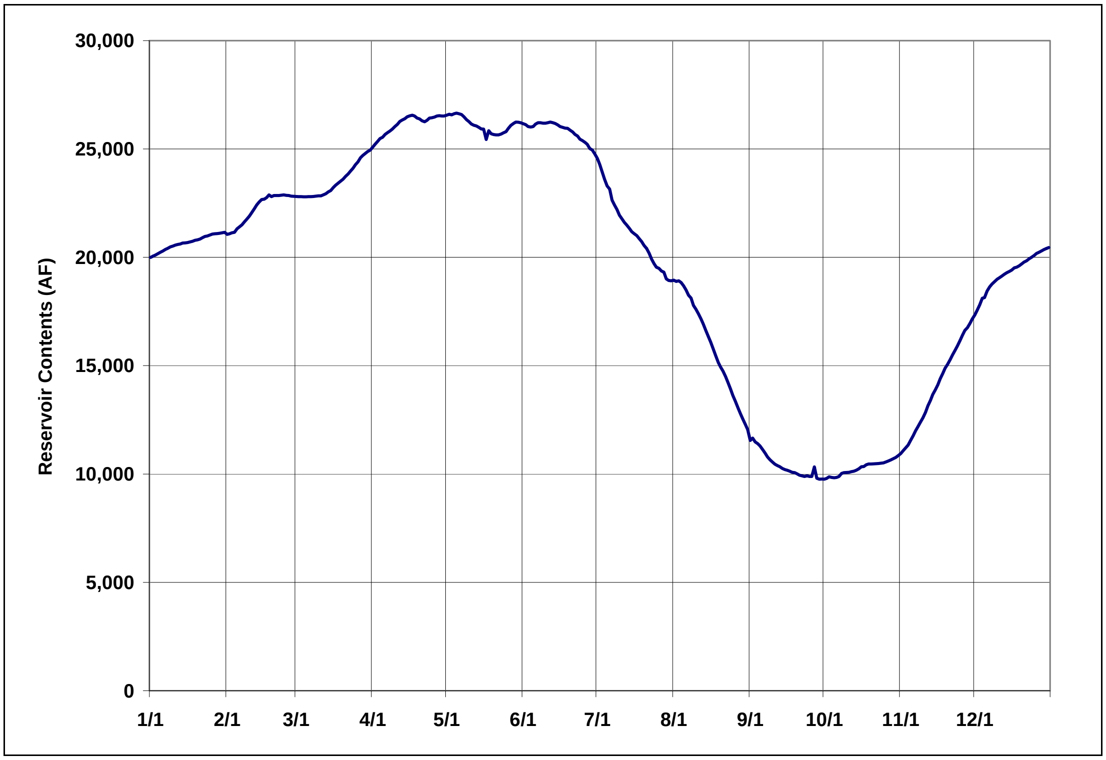

Figure 7. Barr Lake Reservoir Contents for a Composite Year Representing the Average of 1995 through 2004

Field Data

Field data include water temperature, dissolved oxygen, pH, and Secchi-disk depth. The first three constituents are taken every one-half meter throughout the water column.

Water Temperature

Recent surface and bottom temperatures are displayed in Figure 8. Temperatures peak in July of each year at about 24°C. The exception is the drought year of 2002 when peak temperatures exceeded 27°C. Reservoir contents were low during that year (Figure 3). Temperatures at the bottom do not differ greatly from surface temperatures throughout the year, although there can be weak stratification during the spring and early summer and during some winters. In lakes and reservoirs that strongly stratify, the temperature at the bottom does not increase in the summertime. This is not the case with Barr Lake. There is some level of mixing between the upper layer and the bottom layer throughout the year. This is caused by wind mixing when the reservoir is shallow and is also influenced by releasing water from the bottom layer at the dam outlets. Available historical data are displayed in Figure 9. These data appear to follow the same patterns seen in Figure 8.

Trend analysis using recent data (2002-2005) shows no trend over time for water temperature at the surface or at the bottom of the reservoir.

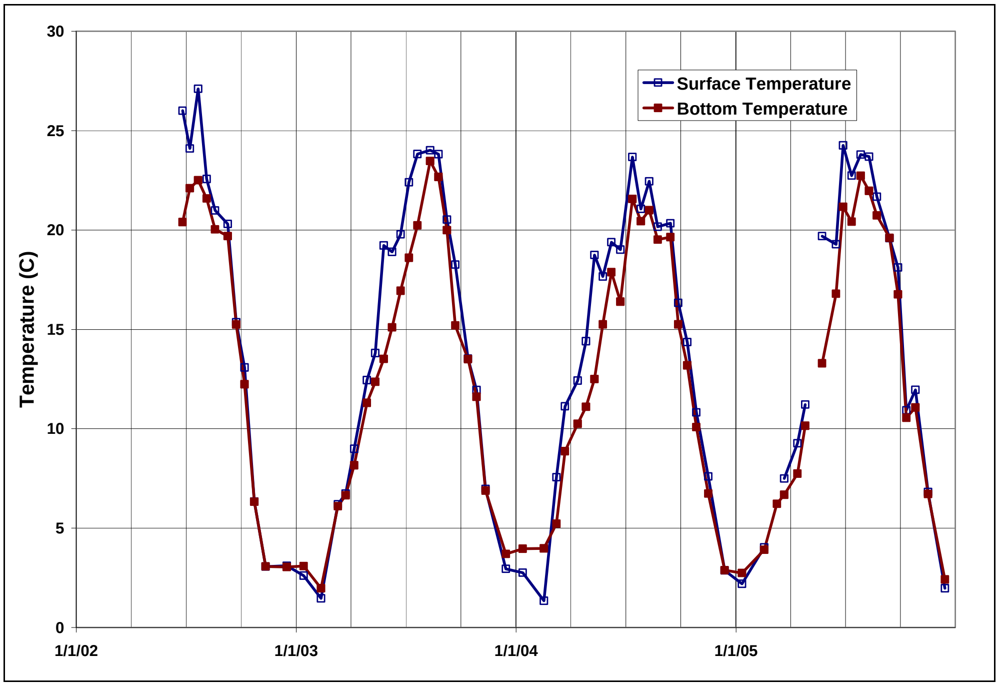

Figure 8. Surface and Bottom Temperatures in Barr Lake (Station B3)

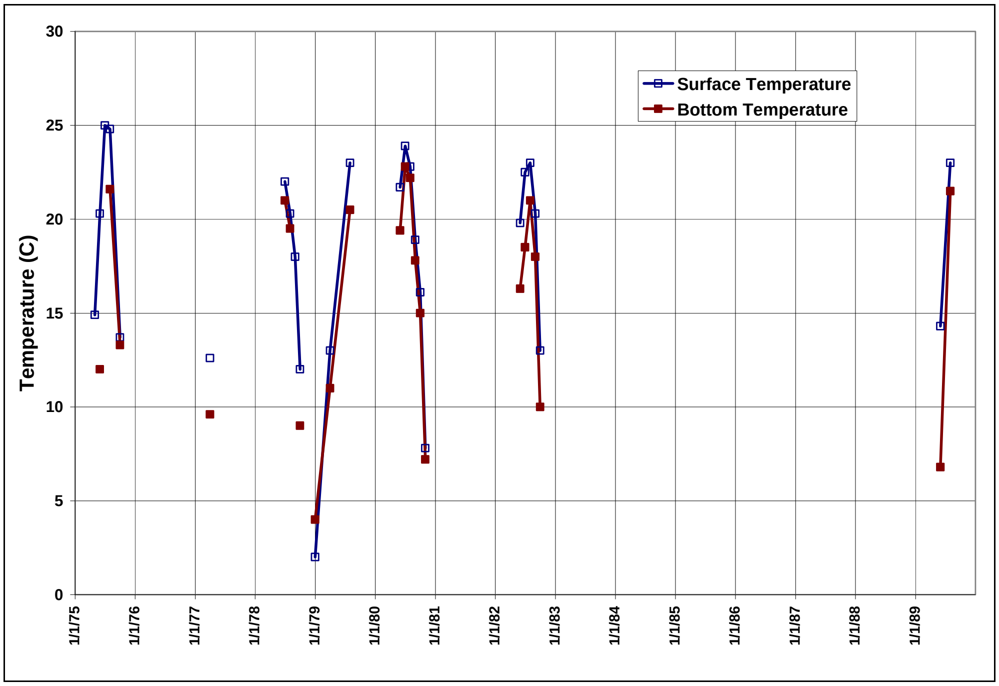

Figure 9. Surface and Bottom Temperatures in Barr Lake - Historical Data (1975-1989)

A subset of temperature profile data for 2005 is displayed in Figure 10. Some level of stratification occurs in May, June, and into July. During July and August, the reservoir releases increase (Figure 5) resulting in a decrease in reservoir depth (Figure 3). A more shallow depth coupled by large bottom-level reservoir releases help to breakup the level of stratification achieved earlier.

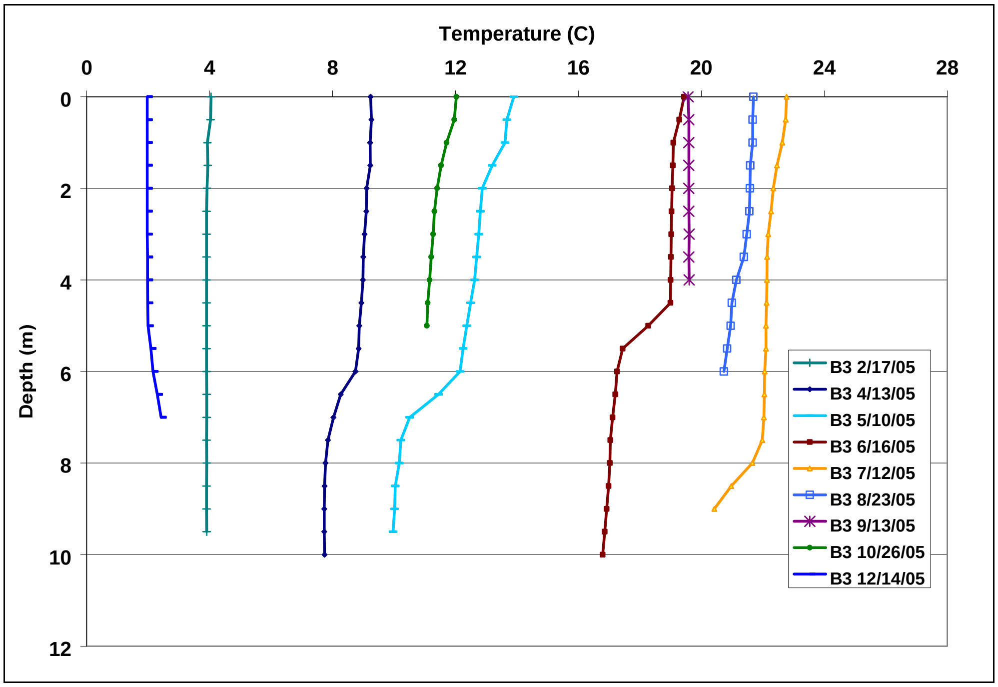

Figure 10. 2005 Temperature Profiles in Barr Lake (Station B3)

Dissolved Oxygen

Recent and historical surface and bottom layer dissolved oxygen concentrations are displayed in Figures 11 and 12. There is some level of oxygen depletion near the bottom of the reservoir in the summer when the lake is temporarily stratified. This is most pronounced in 2003 as the reservoir surface water elevation didn’t drop as low as the other years (Figure 4). Bottom dissolved oxygen concentrations are higher in the winter when the reservoir is well mixed and cooler. Dissolved oxygen near the surface is erratic, most likely due to the mixing patterns in the reservoir and the changing algal populations. Algae release dissolved oxygen when they are photosynthesizing. The few historical data points are similar to recent data with the exception of the very high bottom concentration of 18.5 mg/l. This data point is suspect due to it magnitude and value relative to the surface. The trend analysis using recent data (2002-2005) shows no trend over time for dissolved oxygen for both the surface and bottom of the reservoir.

Dissolved oxygen profiles in the reservoir for 2005 are shown in Figure 13. The profiles show a sharp decrease in oxygen at the bottom in the summer when the reservoir has higher contents. When dissolved oxygen concentrations drop to below 2 mg/l, the release of constituents such as phosphorus can occur (Chapra, 1993).

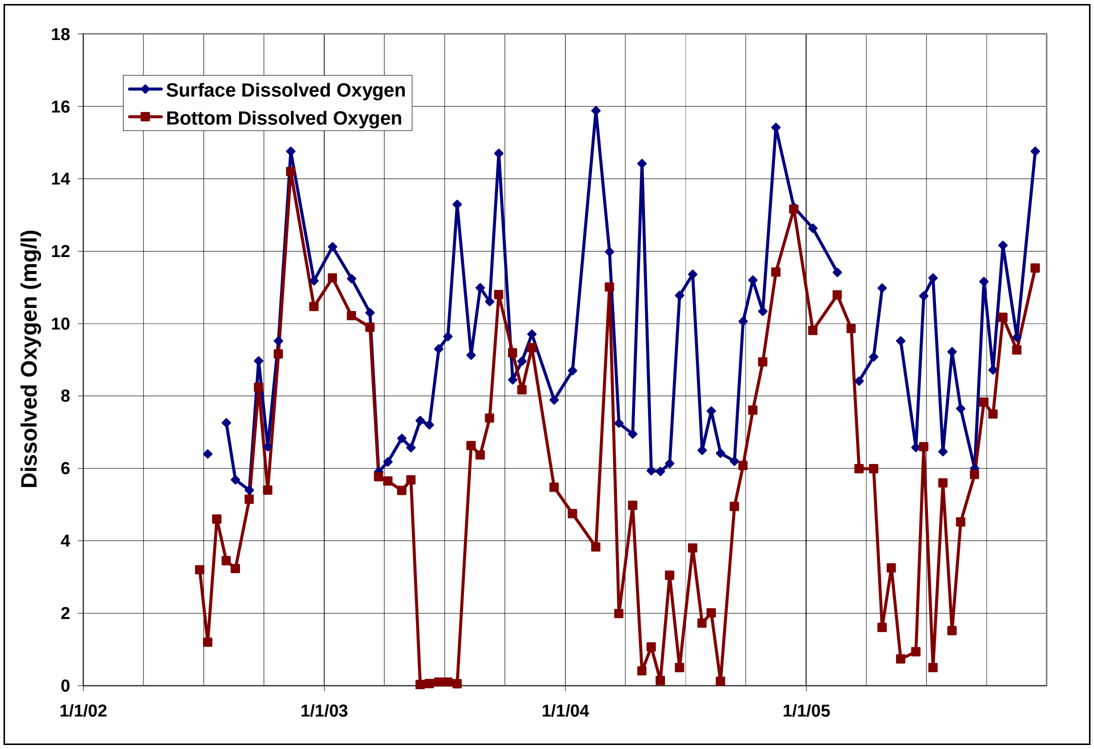

Figure 11. Surface and Bottom Dissolved Oxygen Concentrations in Barr Lake (Station B3)

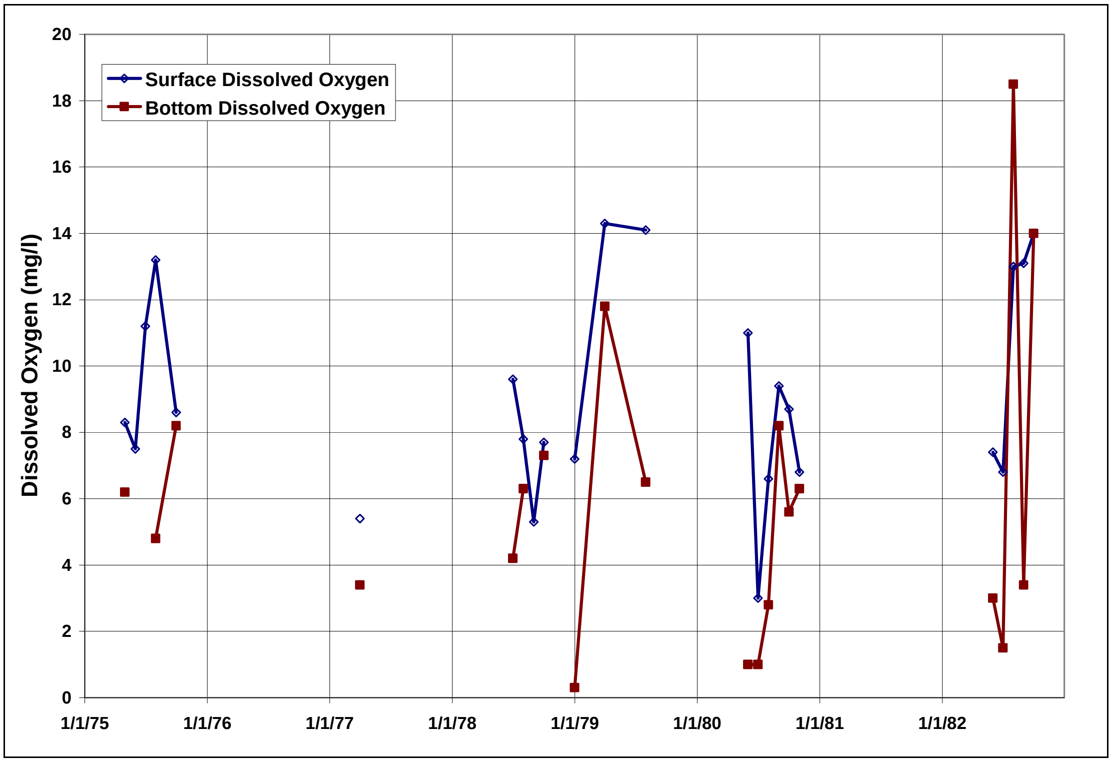

Figure 12. Surface and Bottom Dissolved Oxygen Concentrations in Barr Lake - Historical Data (1975-1982)

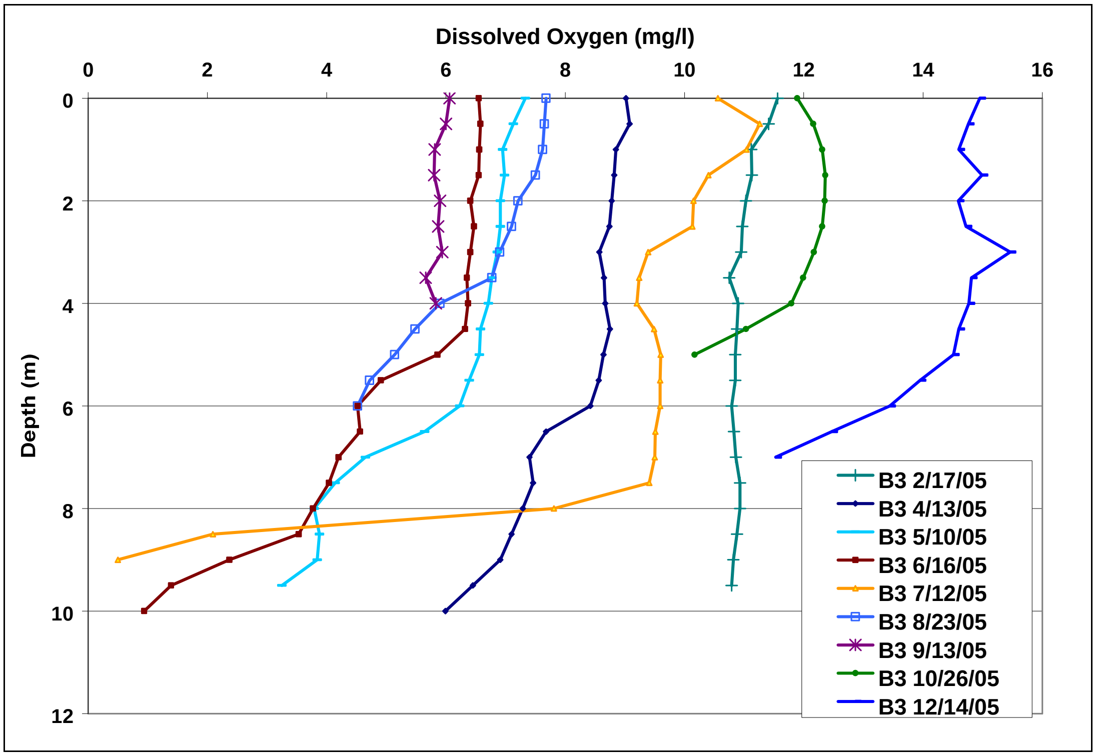

Figure 13. 2005 Dissolved Oxygen Profiles in Barr Lake (Station B3)

pH

Surface and bottom layer pH are displayed in Figures 14 and 15. pH values peak in summer around July of each year. The upper standard for pH (9.0) is exceeded every year during the recent period but was not exceeded in 1978. The pH standard is not exceeded between the months of February though June. The duration of high pH was longer in 2003 and 2005 versus 2002 and 2004.

pH profiles in the reservoir for 2005 are shown in Figure 16. There is not much variation with depth. The trend analysis using recent data (2002-2005) shows an increase in pH over time at the surface of the reservoir and no trend at the bottom.

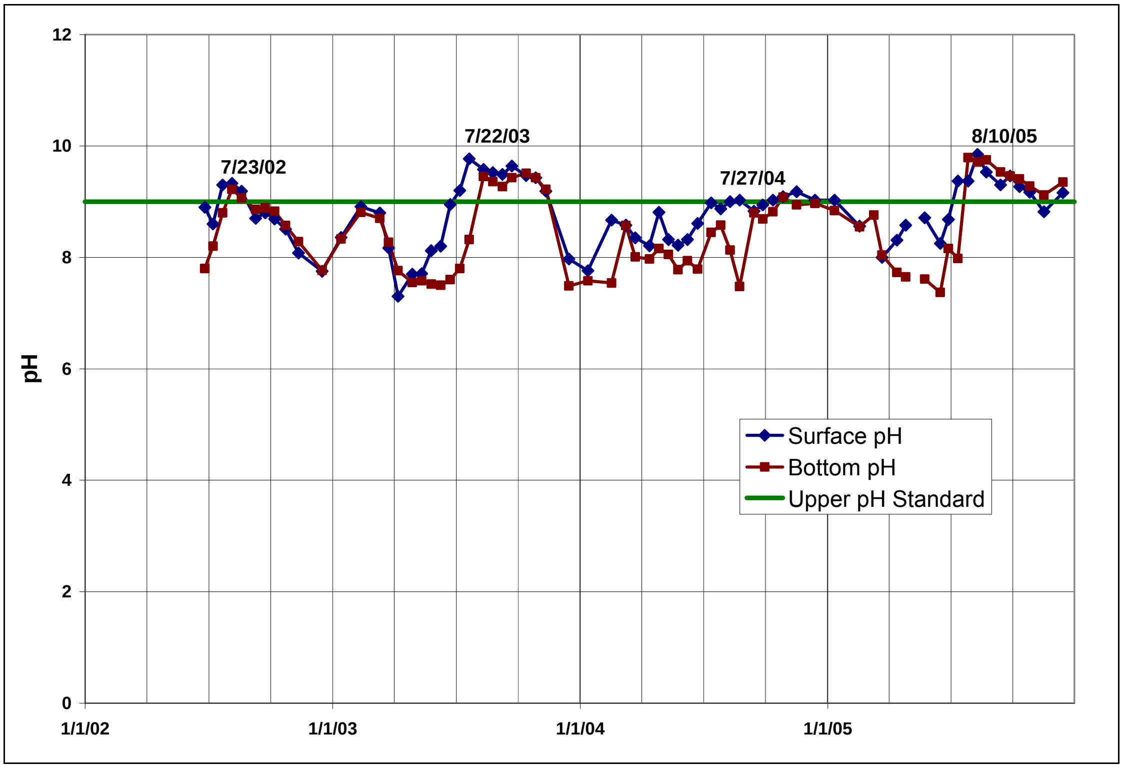

Figure 14. Surface and Bottom pH in Barr Lake (Station B3)

Figure 15. Surface pH in Barr Lake - Historical Data (1975-1979)

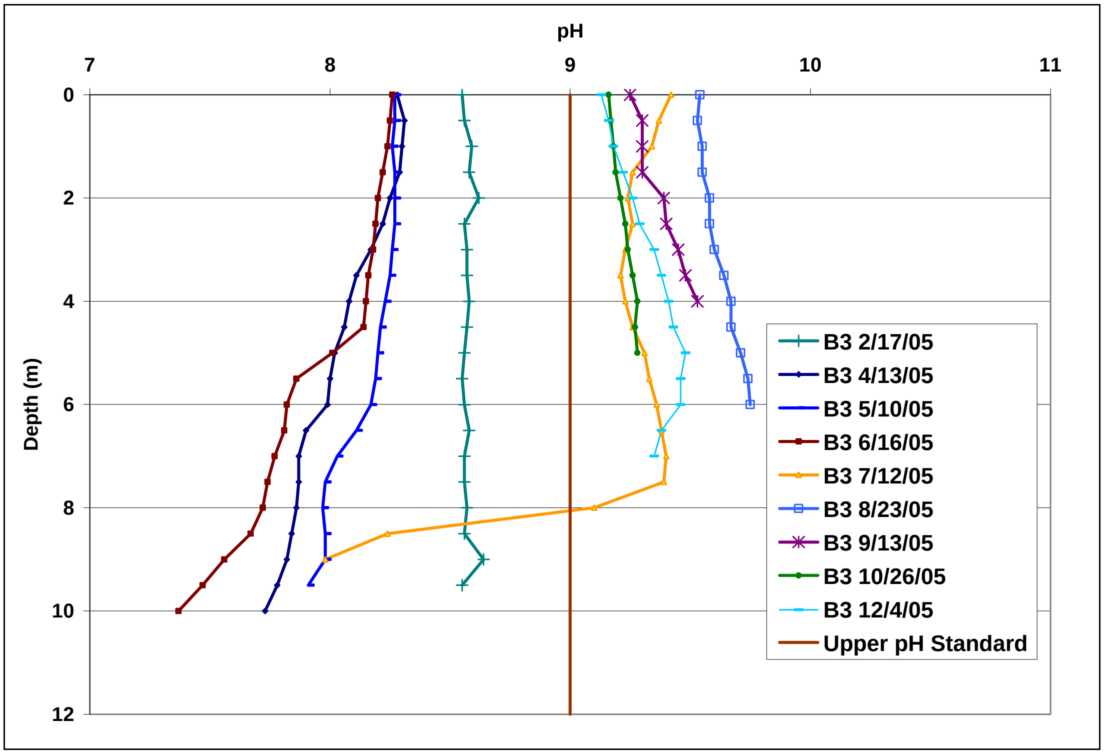

Figure 16. 2005 pH Profiles in Barr Lake (Station B3)

Secchi-Disk Depth

Secchi-disk depth is a measure of water clarity. The higher the value, the greater the clarity. Secchi-disk depths are presented in Figures 17 and 18. The average for 2002-2005 is 1.7 meters while the average summer average (June to September) is 1.4 meters. The historical data show a range of 0.2 to 4.3 meters. The recent data show a range of 0.4 to 6.0 meters possibly indicating an improvement over this longer term period. The pattern varies year to year. The lake was unusually clear during the winter of 2003-2004. For the recent data, Secchi-disk depth is always less than 2 meters during the month of February, and July - November.

The trend analysis using recent data (2002-2005) shows an increase in Secchi-disk depth over time.

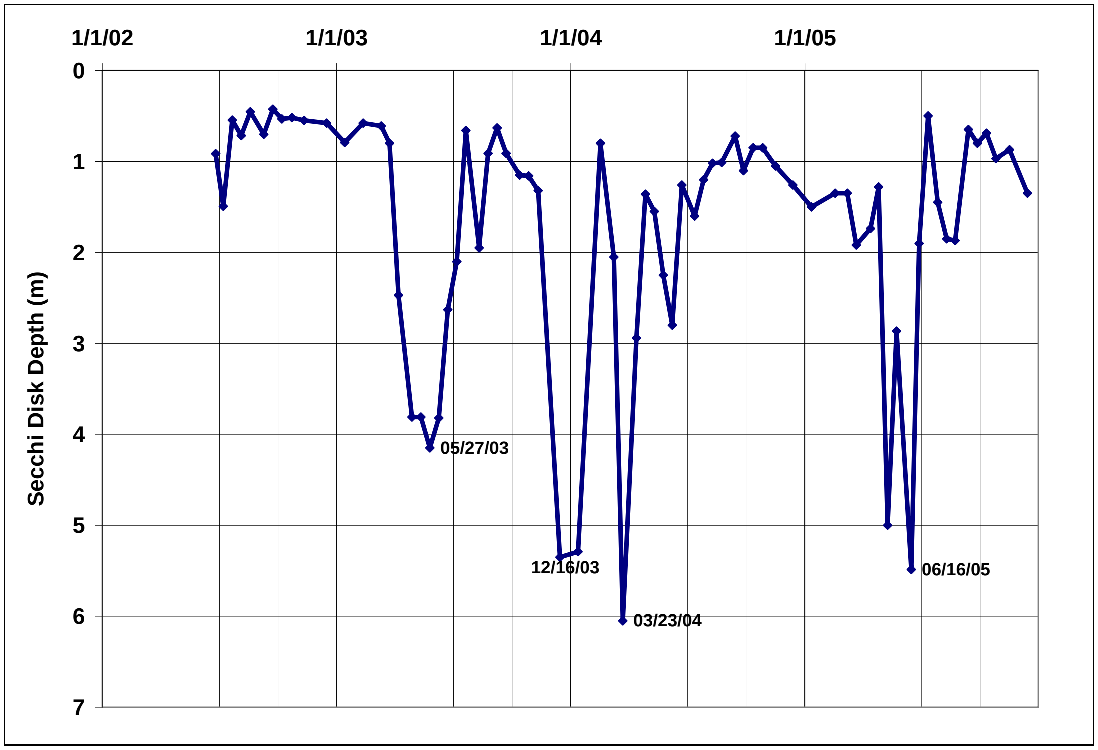

Figure 17. Secchi-Disk Depth in Barr Lake (Station B3)

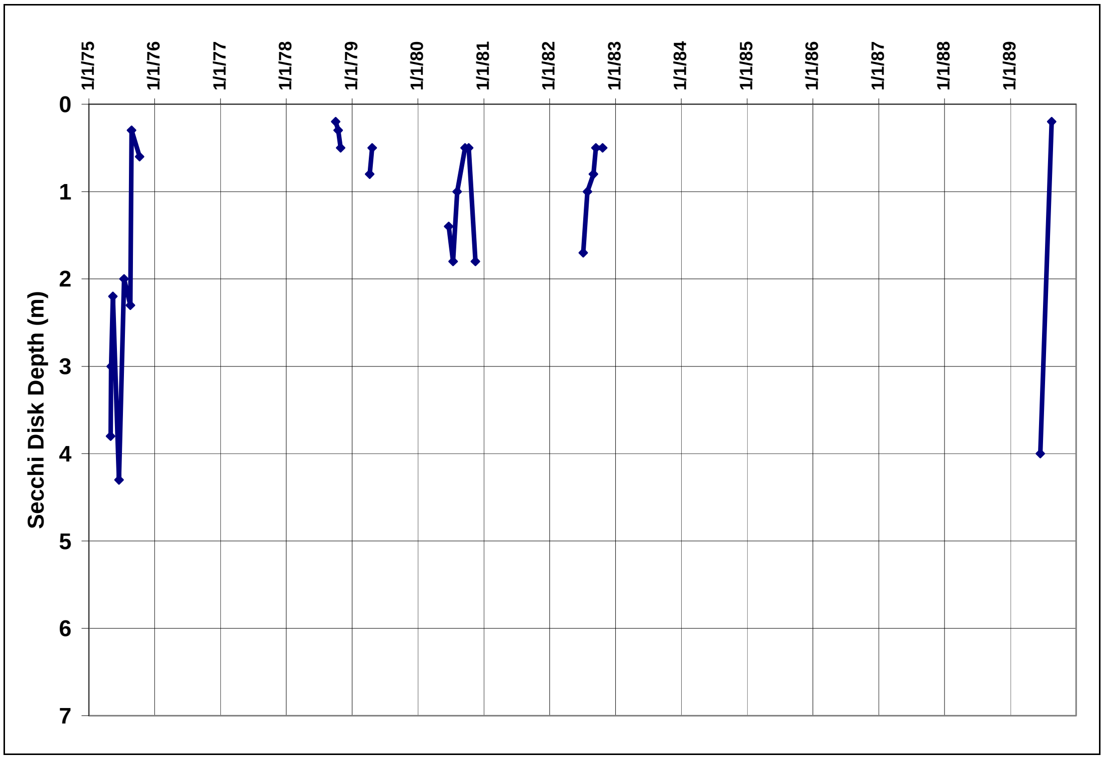

Figure 18. Secchi-Disk Depth in Barr Lake - Historical Data (1975-1989)

Nutrients

Phosphorus

In-reservoir phosphorus data were analyzed over the period 2002 - 2005. These data are shown in Figures 19 and 20. The average total phosphorus concentration over the period is 652 µg/l for the surface layer and 680 µg/l for the bottom layer. The maximum concentration is 1,752 µg/l (bottom layer in the winter of 2002). Note that the highest historical total phosphorus is 1,700 µg/l (Figure 21). The bulk of the total phosphorus is in the form of orthophosphate (the bioavailable form) as opposed to organic phosphorus. This is also the case for the primary inflow into the lake, the Burlington—O'Brian Canal (see Figure 27). Concentrations of the surface layer and bottom layer are similar much of the time. In general, concentrations of total phosphorus and orthophosphate are highest in the winter. For both layers, the trend analysis shows total phosphorus decreasing over time and orthophosphate.

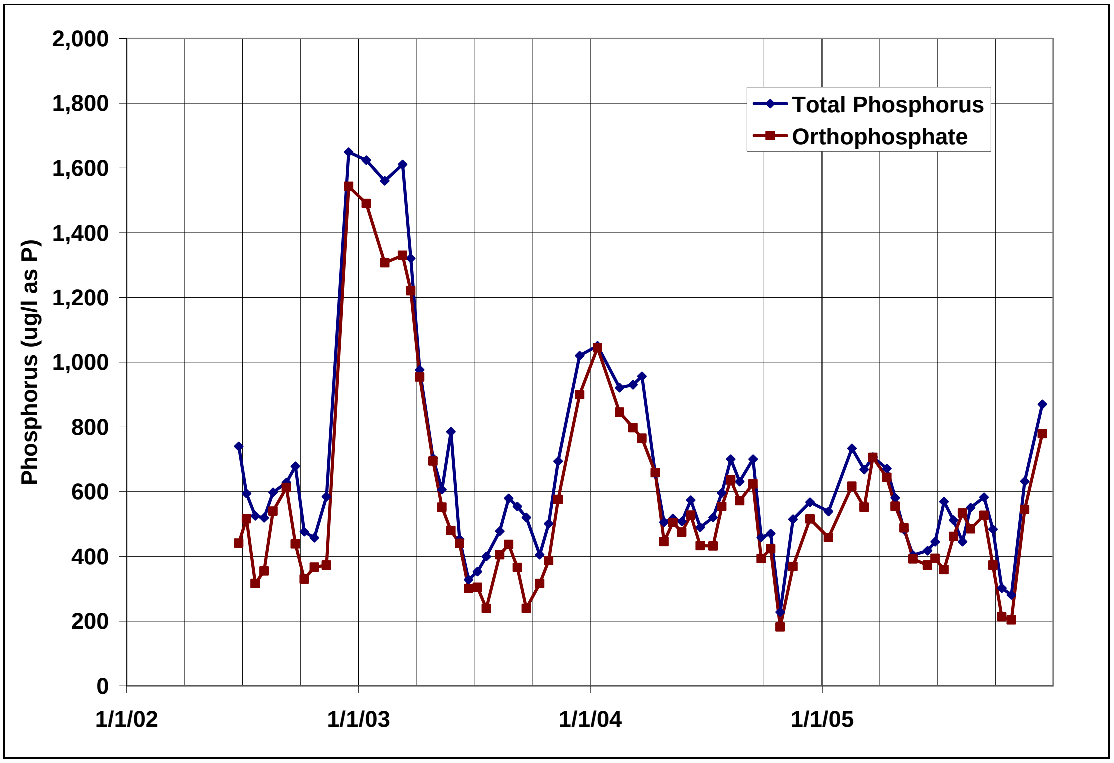

Figure 19. Phosphorus Concentrations Near the Surface of Barr Lake

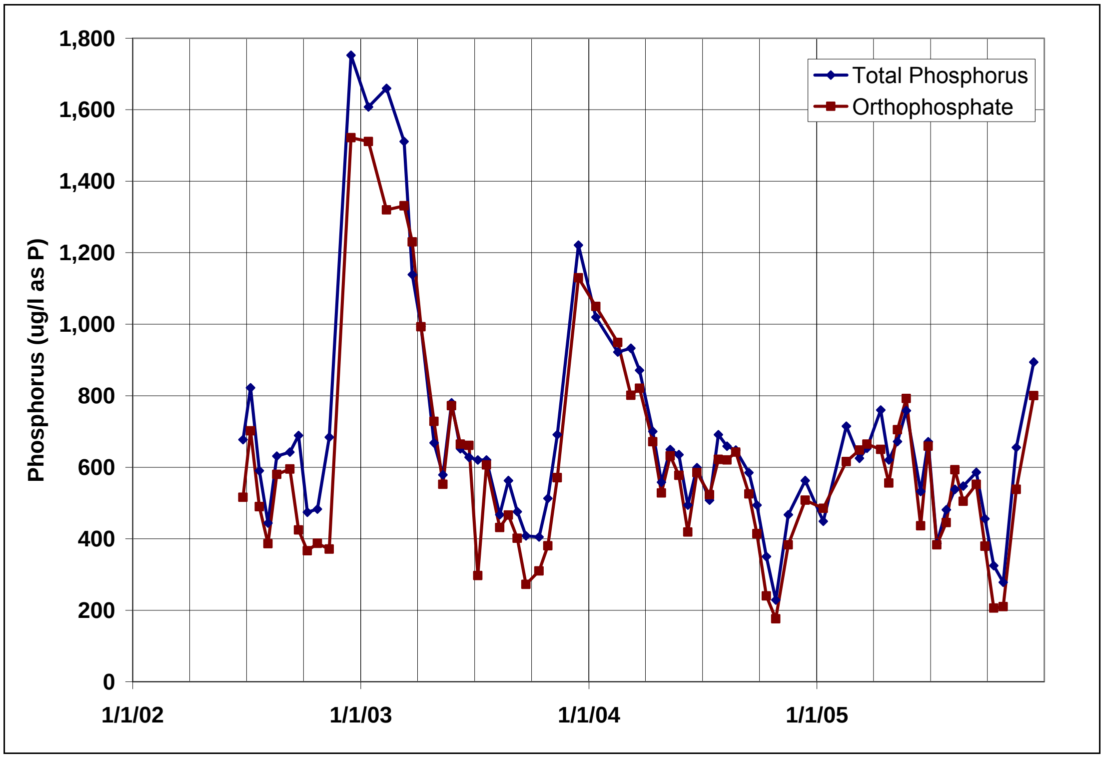

Figure 20. Phosphorus Concentrations Near the Bottom of Barr Lake

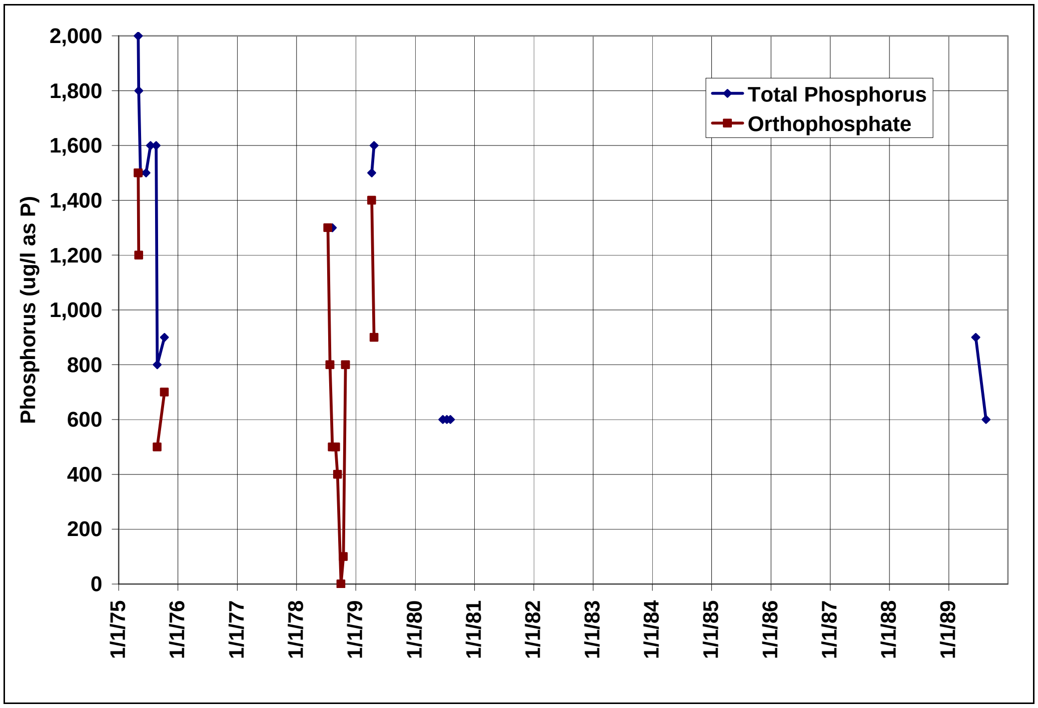

Figure 21. Historical Phosphorus Concentrations Near the Surface of Barr Lake (1975-1989)

Nitrogen

In-reservoir nitrogen data were analyzed over the period 2002 - 2005[2]. These data are shown in Figures 22 and 23. The average total nitrogen concentration over the period is 4,800 µg/l for the surface layer and 4,600 µg/l for the bottom layer. The maximum concentration is 15,000 µg/l (surface layer). Note that the highest historical total nitrogen is 17,500 µg/l (Figure 24). Concentrations of the sub-species increase in the winter while the lowest concentrations are in the mid-summer. For both the recent data and the historical data, inorganic nitrogen (ammonia, nitrate, and nitrite) concentrations are low during the August / September timeframe. The trend analysis for both layers shows that total nitrogen and nitrate + nitrite have no trend over time while ammonia concentrations are decreasing in both layers.

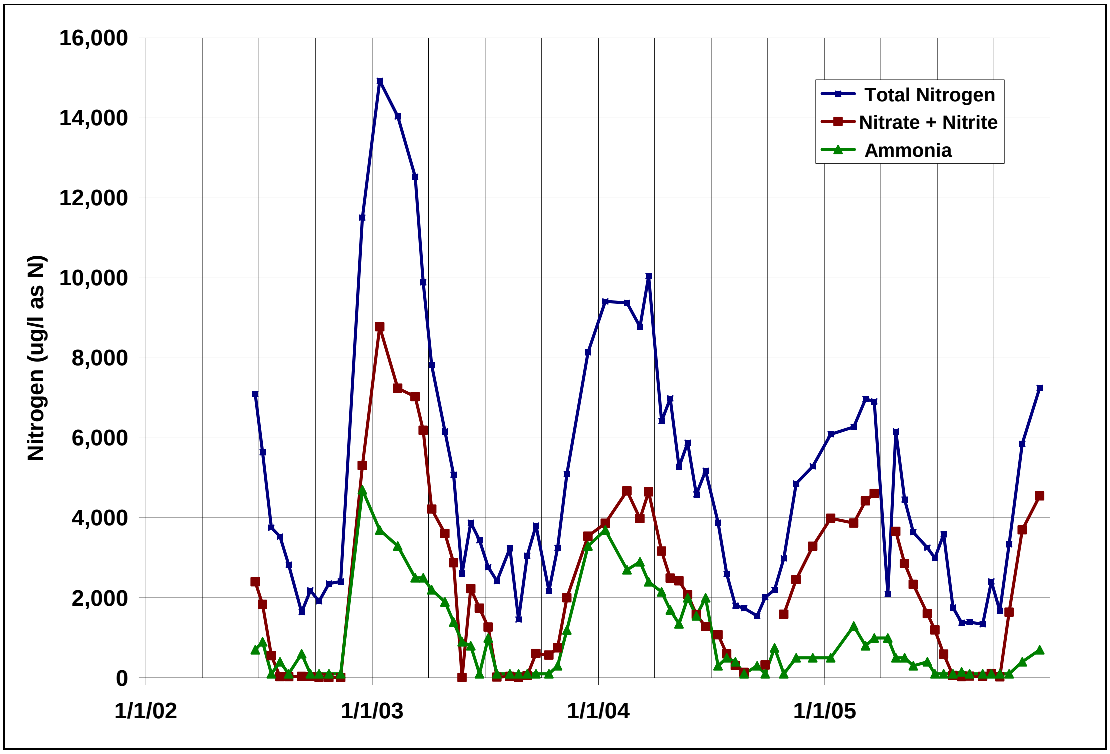

Figure 22. Nitrogen Concentrations Near the Surface of Barr Lake

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[2] Note that one of the dischargers to the South Platte River (above the diversion that feeds Barr Lake) recently upgraded its facility. The Littleton/Englewood Wastewater Treatment Plant installed a nitrate removal system in 2007 (Rink, 2008).

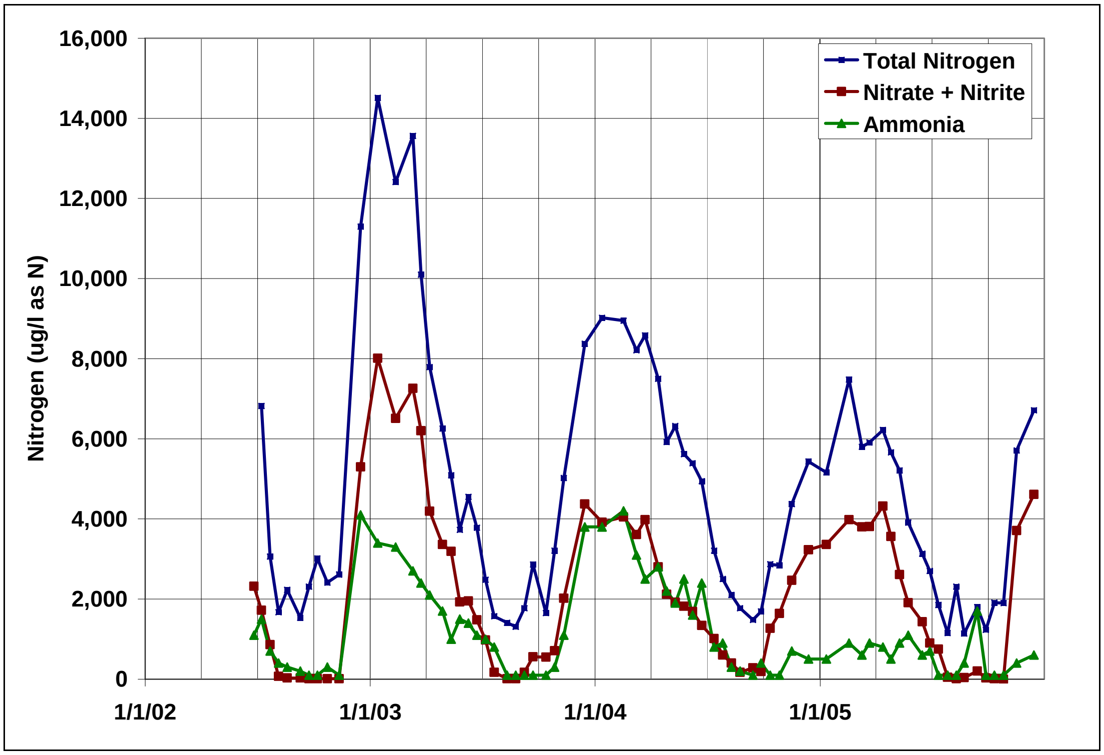

Figure 23. Nitrogen Concentrations Near the Bottom of Barr Lake

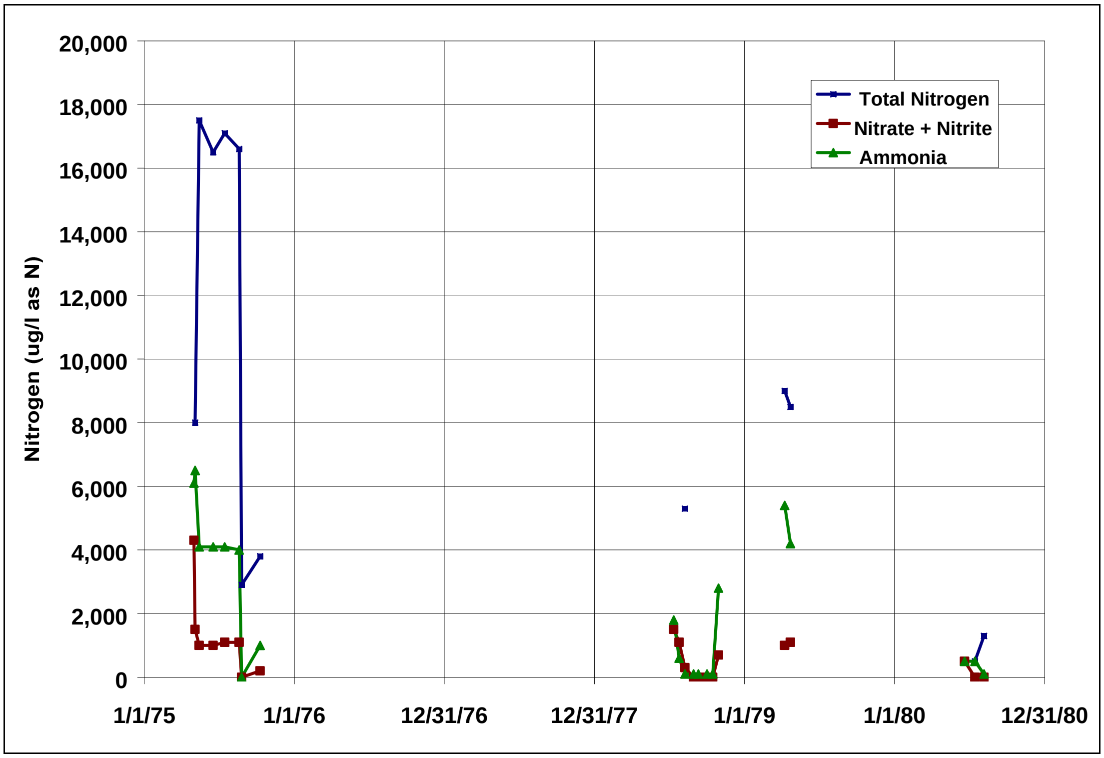

Figure 24. Historical Nitrogen Concentrations Near the Surface of Barr Lake (1975-1980)

Algae and Zooplankton

Chlorophyll *a* measurements serve as a measure of the concentration of suspended algae or phytoplankton. These data are displayed in Figure 25.

The mean concentration over the period 2002-2005 is 54 µg/l while the mean summer (June-September) concentration is 78 µg/l. The peak concentration of over 300 µg/l occurred in August of 2002. In general, chlorophyll *a* concentrations peak in July and again in September. Historical data are few but indicate values of 9.0, 52, and 26 µg/l in May, August, and October of 1975. In August of 1989, the chlorophyll *a* concentration was 25 µg/l. These values are less than the recent mean value.

Using Carlson's Trophic State Index (Carlson and Simpson, 1996), the observed growing season chlorophyll *a* concentrations place the reservoir in a hyper-eutrophic state. The trend analysis indicates no trend over the period 2002-2005.

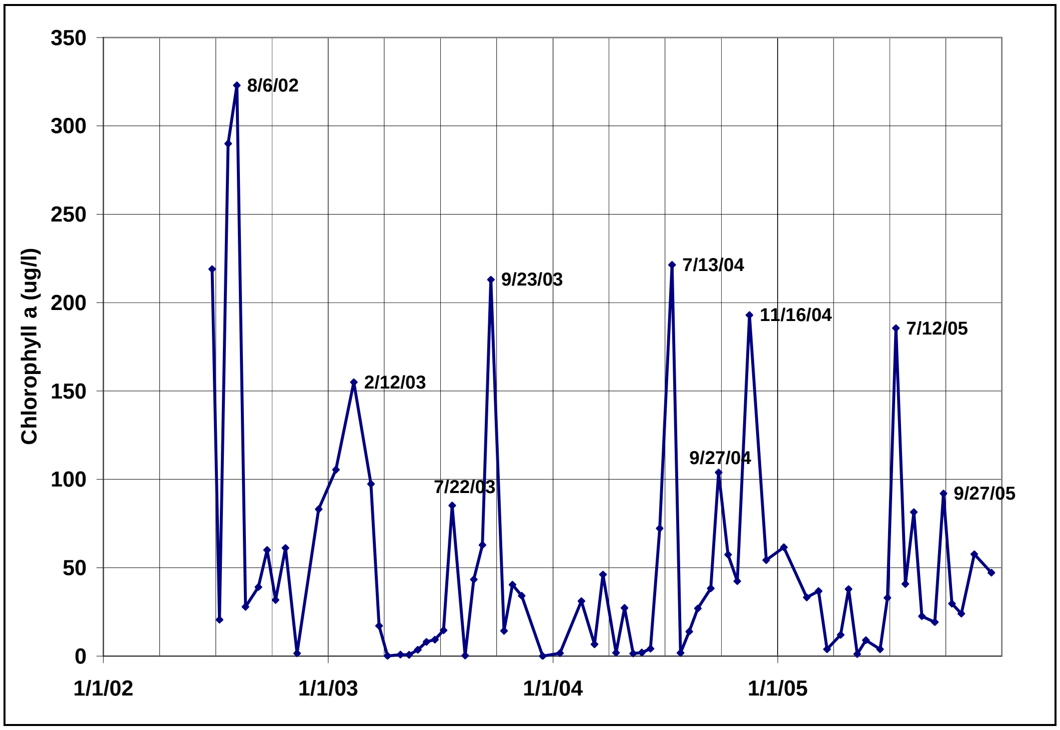

Figure 25. Chlorophyll a Concentrations in Barr Lake

Phytoplankton species data were received for the period July 2002 - August 2004. Diatom species were often grouped together and labeled as diatoms. The most dominant blue-green species were *Microcystis* and *Aphanizomenon*. *Microcystis* does not fix nitrogen but *Aphanizomenon* does. Both are often found in highly enriched reservoirs and lakes. Note that the reservoir is dominated by diatoms during some portions of the year and dominated by blue-green algae at other times (Figure 26).

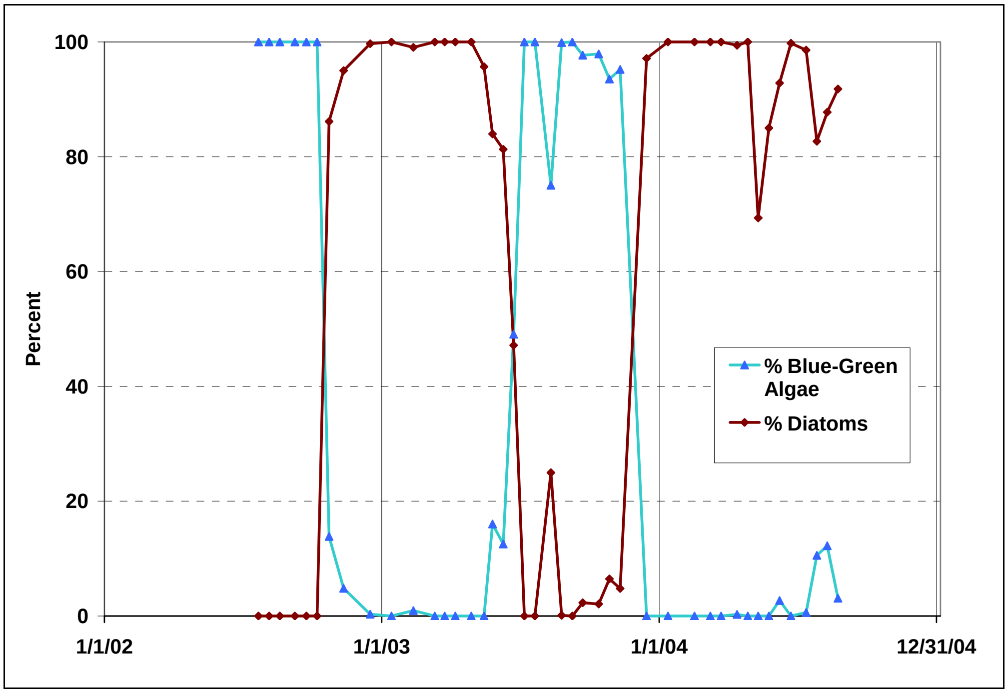

Figure 26. Dominant Algal Species Over Time

Some zooplankton data were available for this analysis but were not analyzed due to the number of data records and the suspected quality of the data (Lundt, 2006b).

Reservoir Data Analysis Summary

Barr Lake is a hyper-eutrophic plains reservoir. It is shallow and exhibits signs of temporary stratification in the summer before the reservoir becomes drawn down near the end of the summer. It has many of the signs of a highly enriched system:

- High nutrient concentrations;
- Low clarity;
- High levels of chlorophyll *a;*
- Blue-green algae dominating during portions of the year; and
- Dissolved oxygen depletion at the bottom of the reservoir.

Trends over the period 2002-2005 and mean concentrations of several constituents are displayed in Table 6. The lake has shown improvement over the period 2002-2005 although the nutrient concentrations in the reservoir at the beginning of the trend period (2002) were much higher than the subsequent years. Irrigation year 2002 was a drought year with low reservoir contents (less dilution) and warmer temperatures. It is difficult to draw conclusions on long term trends due to the lack of sufficient historical data.

Table 6. Barr Lake Trend Summary and Mean Concentrations (2002-2005)

Constituent	Mean (Surface / Bottom)	Trend
Total Phosphorus (µg/l)	652 / 680	Decreasing
Orthophosphate (µg/l)	558 / 612	No Trend
Total Nitrogen (µg/l)	4,795 / 4,596	No Trend
Total Kjeldahl Nitrogen (µg/l)	2,789 / 2,639	Decreasing
Nitrate + Nitrite (µg/l)	2,094 / 1,994	No Trend
Ammonia (µg/l)	957 / 1,117	Decreasing
Chlorophyll *a* (µg/l)	54	No Trend
Secchi-Disk Depth (m)	1.7	Increasing
pH (SU)	8.8* / 8.5*	Increasing (Surface) No Trend (Bottom)
Dissolved Oxygen (mg/l)	9.4 / 5.6	No Trend
Temperature (°C)	14.5 / 13.1	No Trend
Total Organic Carbon (mg/l)	9.0	Decreasing
Specific Conductance (µS/cm)	828 / 842	Decreasing
Total Suspended Solids (mg/l)	15	Decreasing (Surface) Not Enough Data (Bottom)

* Although we recognize that calculating the mean of observed pHs introduces a bias as compared to –log (mean [H+]), the mean of the observed pHs is presented as a useful value to the reader.

INFLOW / OUTFLOW DATA ANALYSIS

There is a longer data set for inflow and outflow water-quality data than for in-reservoir data. The inflow / outflow water-quality monitoring program began in 1994 (Mountain River Associates, 1995).

Phosphorus

Inflow concentrations of phosphorus are displayed in Figure 27. Most of the total phosphorus is in the form of orthophosphate. One can see a decrease in inflow concentrations from 1994-2000, followed by an increase and then a decrease over the period 2002-2005. Note that the in-reservoir phosphorus concentrations also decrease over the period 2002-2005. Mean total phosphorus concentration over the twelve-year period is 745 µg/l. The peak concentration is 2,760 µg/l. The mean total phosphorus in 1975 (EPA, 1977) was 1,960 µg/l. By contrast, the average total phosphorus concentration in the South Platte River below Chatfield Reservoir is 38 µg/l (Chatfield Reservoir is upstream of the Burlington-O’Brian Canal Diversion on the South Platte River). The trend analysis for Barr Lake inflows shows an increase in both total phosphorus and orthophosphate over the period 1994-2005.

Outflow concentrations via releases through the east and west outfalls show considerable variation (Figures 28 and 29). Concentrations for the east outfall are similar to those in the west outfall. Note that east and west outfall concentrations are not measured in the winter (when in-reservoir concentrations are high) due to lack of flow. There appears to be the same general pattern over time as the inflow concentrations.

Inflow and outflow concentrations are shown in Figure 30 for total phosphorus for comparison purposes. Since the east outfall and west outfall concentrations are very similar, only the east outfall concentration is shown to represent the outflow.

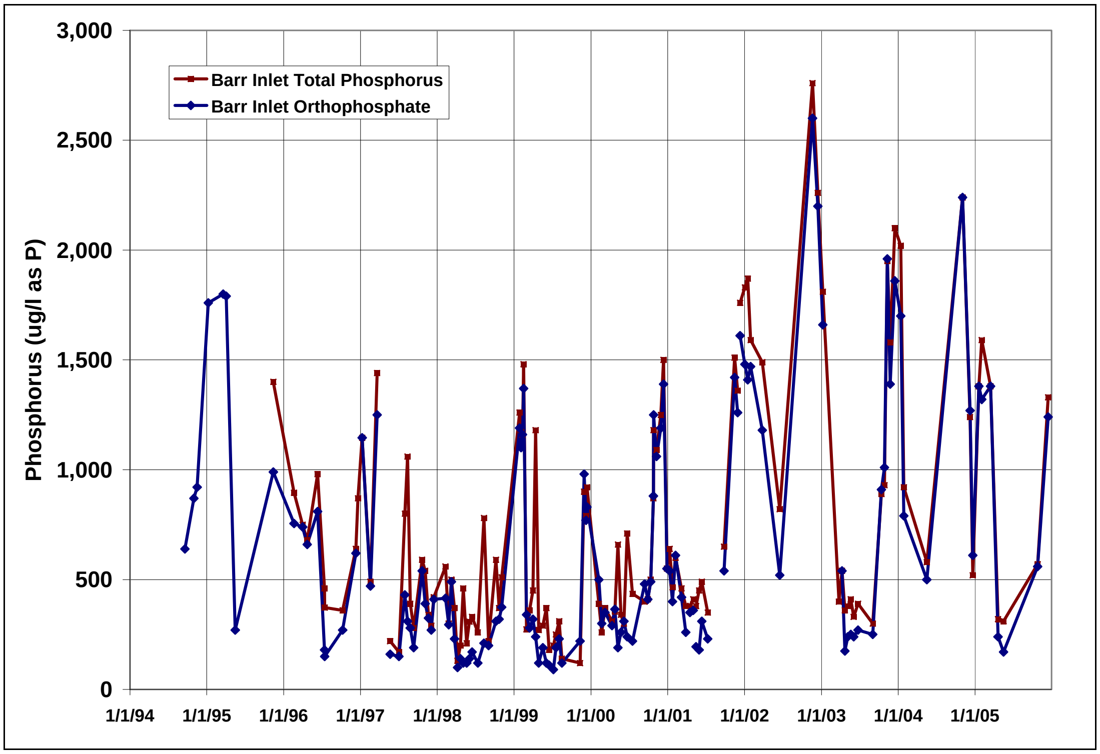

Figure 27. Phosphorus Concentrations in the Inflow to Barr Lake (Burlington-O'Brian Canal)

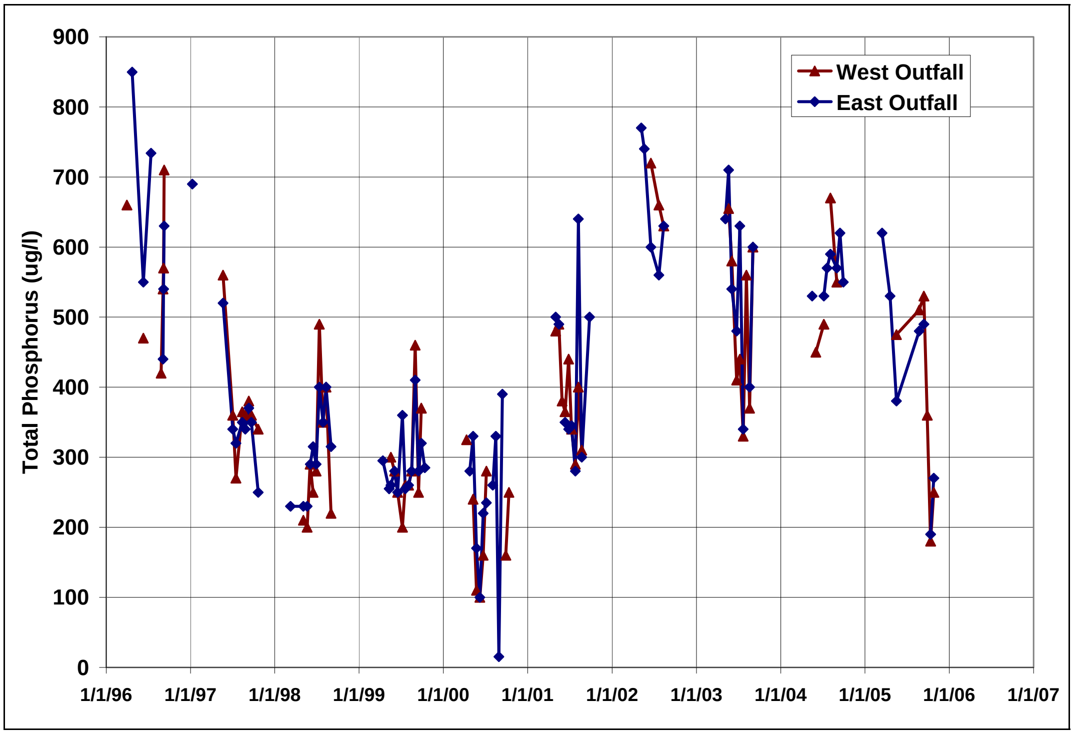

Figure 28. Total Phosphorus Concentrations in the Releases from Barr Lake

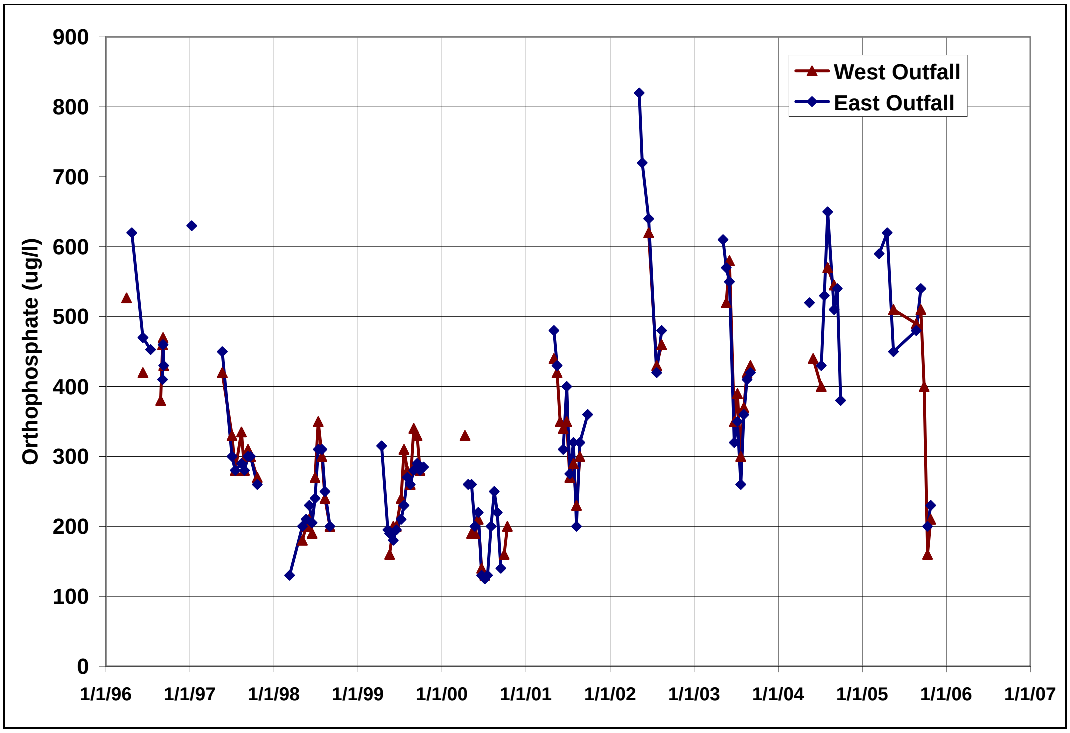

Figure 29. Orthophosphate Concentrations in the Releases from Barr Lake

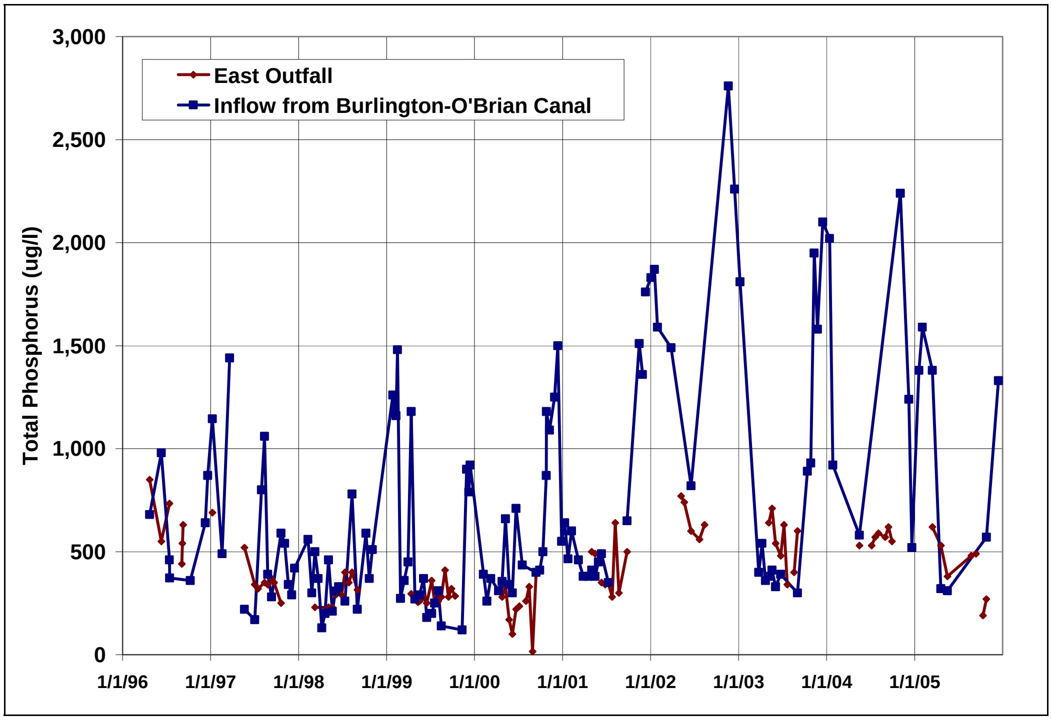

Figure 30. Total Phosphorus Concentrations in the Inflow to Barr Lake (via the Burlington-O’Brian Canal) and the East Outfall

Nitrogen

Inflow concentrations of nitrogen are displayed in Figure 31[3]. The mean total nitrogen concentration over the twelve-year period is 7,053 µg/l. The mean nitrate plus nitrite concentration is 4,434 µg/l and the mean ammonia concentration is 1,414 µg/l. The mean total nitrogen concentration in 1975 (EPA, 1977) was 7,701 µg/l. By contrast, the average total nitrogen concentration in the South Platte River below Chatfield Reservoir is 428 µg/l (Chatfield Reservoir is upstream of the Burlington-O'Brian Canal Diversion on the South Platte River). Total nitrogen concentrations in Barr Lake typically peak during the winter (November - January) and are lowest during May to June. The trend analysis for the inflow shows an increase in each of the nitrogen species over the period 1994-2005.

Outflow concentrations are shown in Figures 32 - 34. Concentrations for the east outfall are similar to those in the west outfall.

Inflow and outflow concentrations are shown in Figure 35 for total nitrogen for comparison purposes. Since the east outfall and west outfall concentrations are very similar, only the east outfall concentration is shown to represent the outflow.

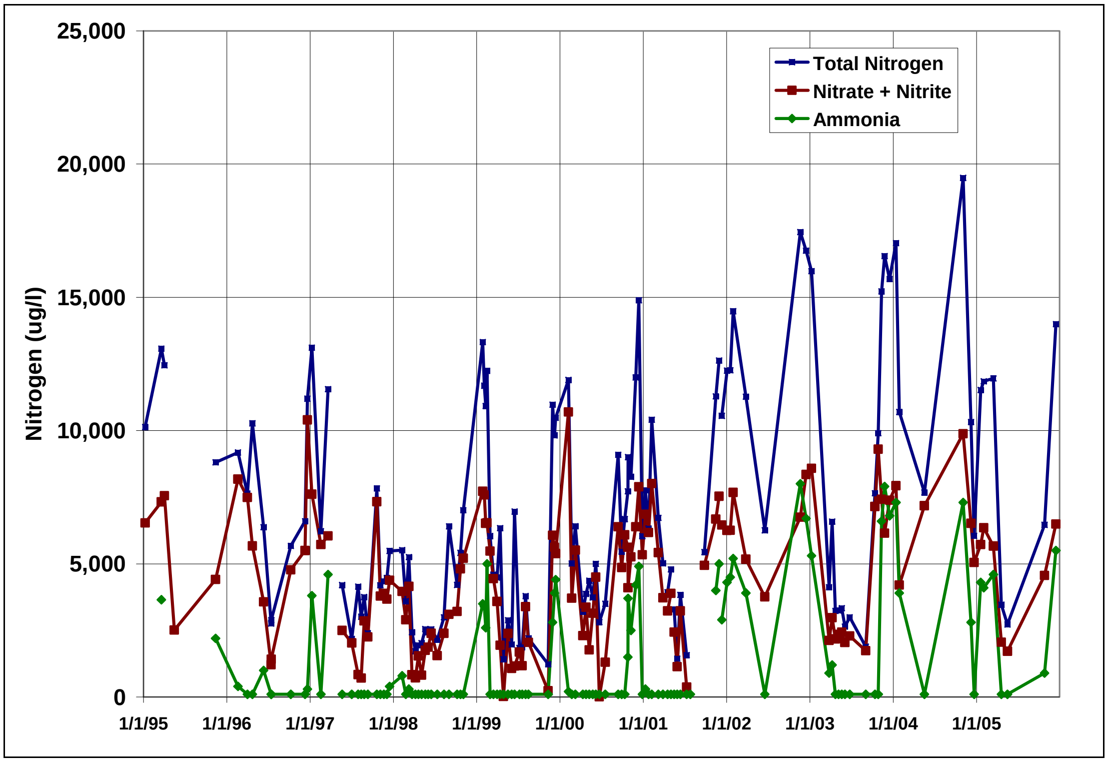

Figure 31. Nitrogen Concentrations in the Inflow to Barr Lake (Burlington-O'Brian Canal)

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[3] See footnote on page 20.

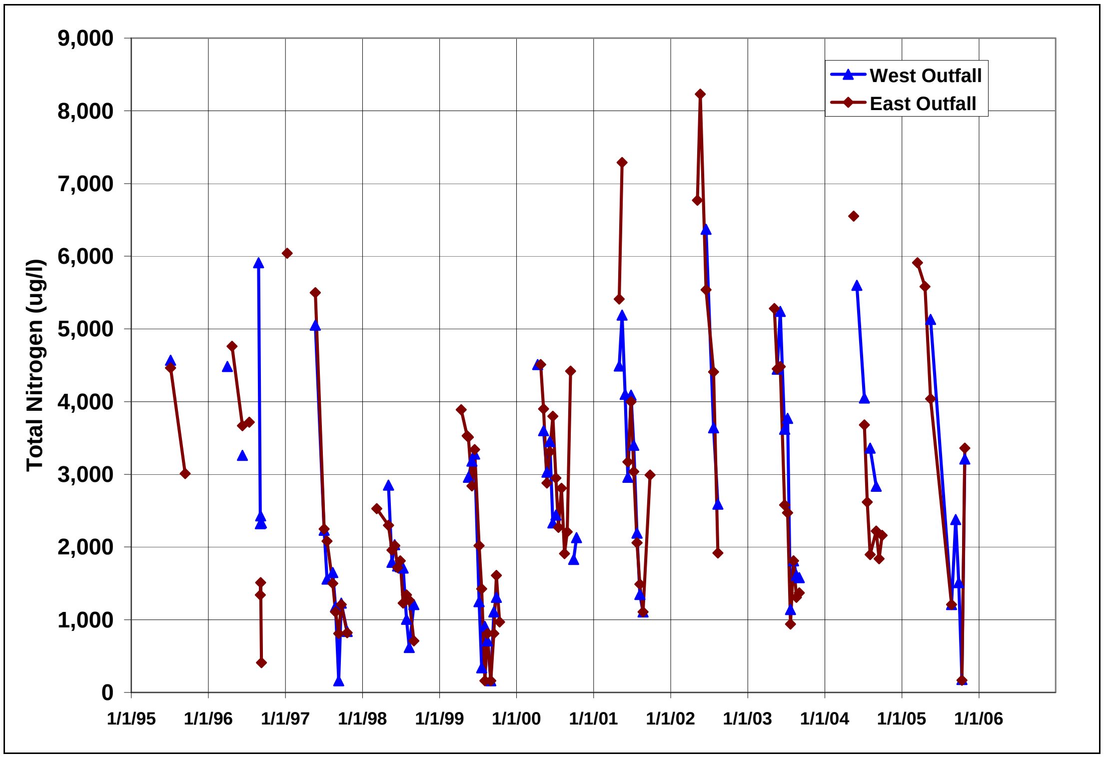

Figure 32. Total Nitrogen Concentrations in the Releases from Barr Lake

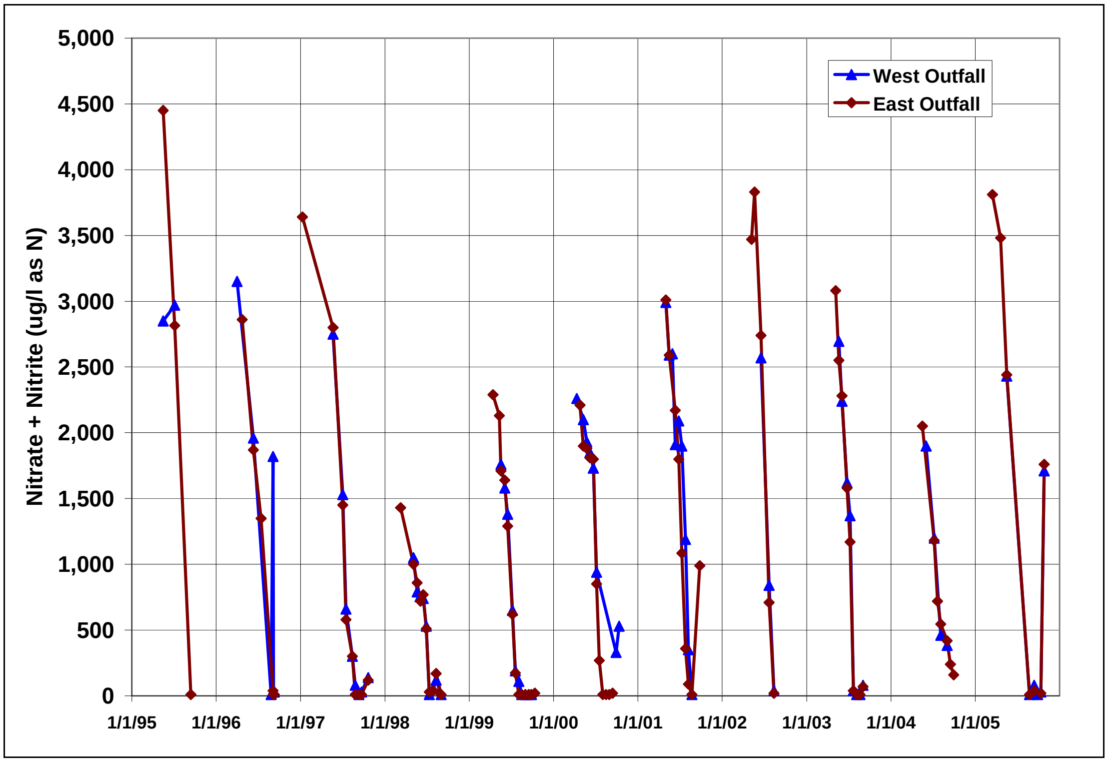

Figure 33. Nitrate Plus Nitrite Concentrations in the Releases from Barr Lake

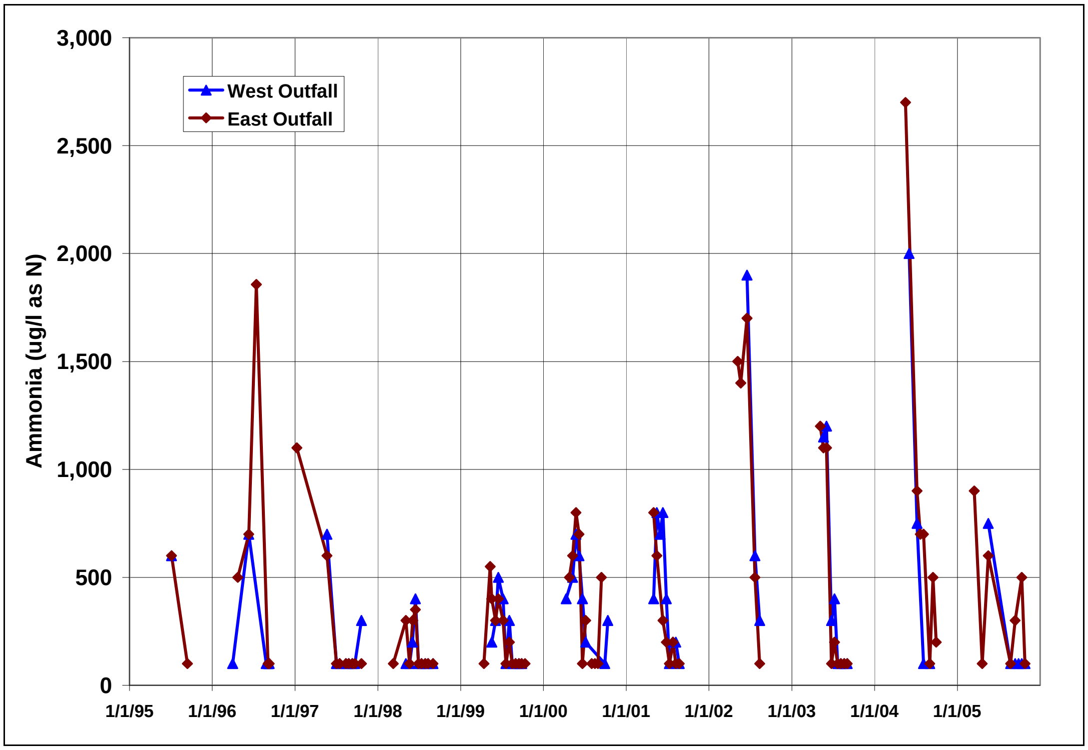

Figure 34. Ammonia Concentrations in the Releases from Barr Lake

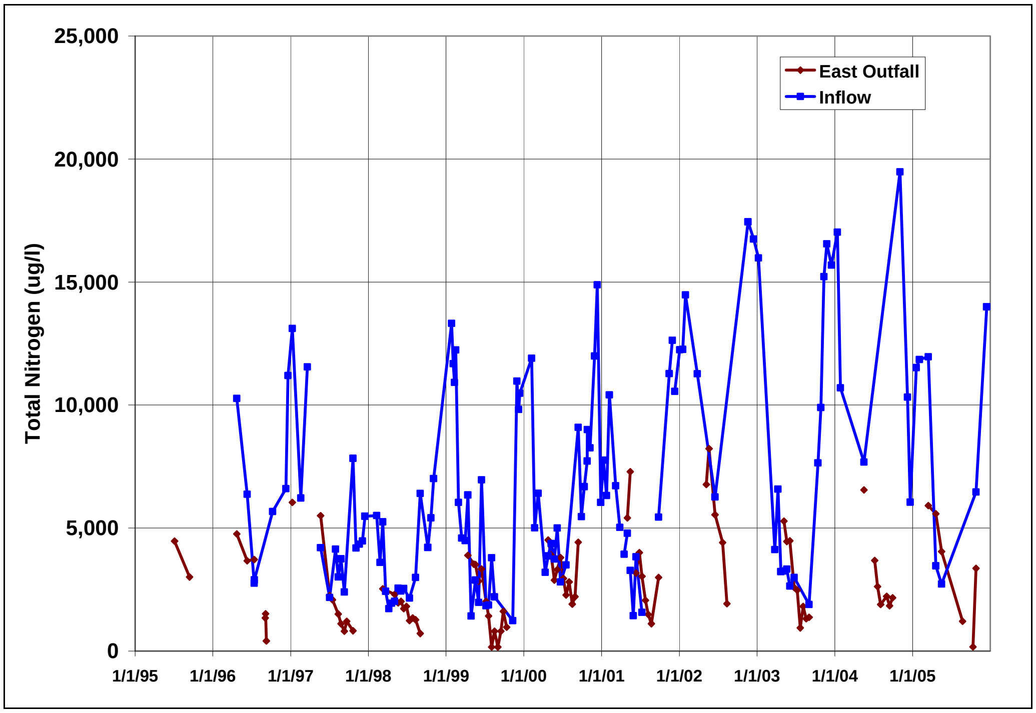

Figure 35. Total Nitrogen Concentrations in the Inflow to Barr Lake (via the Burlington-O'Brian Canal) and the East Outfall

Inflow / Outflow Data Analysis Summary

The concentrations of nutrients in the inflows and outflows of Barr Lake are high and have increased over the period 1994 to 2005. Inflow nutrient concentrations are generally higher during the winter months and are higher than reservoir release concentrations. Mean concentrations and the results of the trend analyses for the inflow from the Burlington-O'Brian Canal are shown in Table 7.

Table 7. Barr Lake Inflow Summary (1994-2005) – Burlington-O'Brian Canal

Constituent	Mean	Trend
Total Phosphorus (µg /l)	745	Increasing
Orthophosphate (µg /l)	659	Increasing
Total Nitrogen (µg /l)	7,053	Increasing
Total Kjeldahl Nitrogen (µg /l)	2,604	Increasing
Nitrate + Nitrite (µg /l)	4,434	Increasing
Ammonia (µg /l)	1,414	Increasing
pH (SU)	7.9*	No Trend
Dissolved Oxygen (mg/l)	8.1	No Trend
Temperature (°C)	12.4	No Trend
Specific Conductance (µS/cm)	801	Increasing

* Although we recognize that calculating the mean of observed pHs introduces a bias as compared to –log (mean [H+]), the mean of the observed pHs is presented as a useful value to the reader.

RESERVOIR WATER BALANCE

A reservoir water balance was computed for Barr Lake using the relationship:

$$\text{Change in Storage} = \text{Total Inflow} - \text{Total Outflow} \qquad (1)$$

The change in storage was computed as:

$$\text{Change in Storage} = \text{Contents at the End of the Period} - \text{Contents at the Beginning of the Period} \qquad (2)$$

Reservoir contents were developed on a daily basis by D. Helton Consulting (Rink, 2007a). The computed changes in storage by irrigation year are summarized in Table 8.

Table 8. Change in Storage by Irrigation Year

	IY00	IY01	IY02	IY03	IY04	IY05	Average (IY00-IY05)
Change in Storage (AF)	-1,713	-4,230	-5,617	7,008	-696	133	-853

Water enters Barr Lake via 1) the Burlington-O'Brian Canal, 2) precipitation, 3) subsurface inflow, and 4) runoff from the direct watershed. It is assumed that the fourth inflow is relatively insignificant given the small watershed area directly surrounding the reservoir and is not included as a term in the balance. Water leaves the reservoir via 1) the east outfall, 2) the west outfall, 3) releases to stockholders on the Beebe Bowles Seep and East Neres Canals, 4) toe drain seepage (dam seepage), 5) subsurface losses that flow under the clay layer under the dam, and 6) evaporation. Quantification of each of these inflows and outflows, along with beginning and ending reservoir contents allows for the computation of a water balance for the reservoir. This was done over the period IY2000 through IY2005 (November 1999 - October 2005).

Daily inflows from the Burlington-O'Brian Canal and reservoir contents were developed by D. Helton Consulting (Rink, 2007a). Precipitation estimates were made by AMEC Earth & Environmental using reservoir surface area and precipitation records from Denver International Airport. Subsurface inflows into Barr Lake were estimated by D. Helton Consulting as being 8% of the flow diverted from the Burlington-O'Brian Canal to the Denver-Hudson Canal (Rink, 2007b; Helton, 2007). Inflows by source and by year are summarized in Table 9. A pie chart representing the average of the six years is shown in Figure 36.

Table 9. Inflows by Source into Barr Lake by Irrigation Year (AF/Year)

	IY00	IY01	IY02	IY03	IY04	IY05	Average (IY00-IY05)
Burlington-O'Brian Canal	35,723	31,388	26,861	52,919	38,539	55,655	40,181
Precipitation	2,145	2,472	1,208	2,106	2,151	1,544	1,938
Inflow Seepage	1,104	1,135	604	930	617	1,278	945
TOTAL INFLOW	38,972	34,996	28,672	55,955	41,306	58,477	43,063

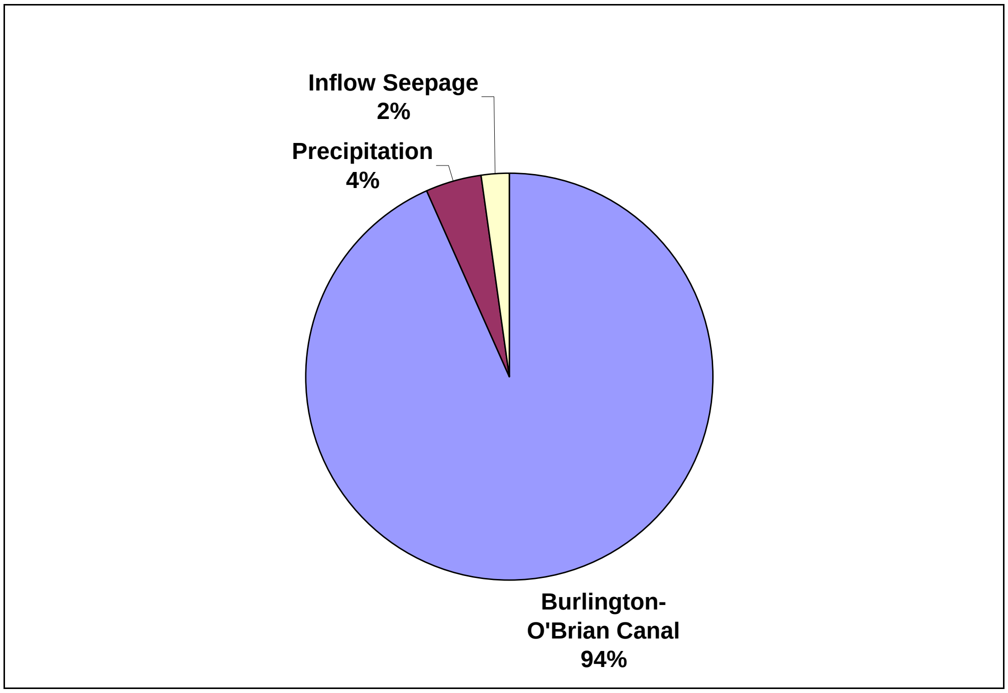

Figure 36. Distribution of Total Inflows into Barr Lake (Based on Average of IY00-IY05)

Daily reservoir releases via the east and west outfalls were also developed by D. Helton Consulting (Rink, 2007a) along with daily estimates of the water that accrued in the Beebe Canal below Barr Lake. This latter discharge is a result of FRICO's releases for delivery to stockholders on the Beebe Bowles Seep and East Neres Canals (Beebe Canal Release). Daily estimates of toe drain seepage were also made by D. Helton Consulting (Rink, 2007a). Evaporation was estimated by AMEC Earth & Environmental using daily reservoir surface areas and pan evaporation estimates. Estimates of subsurface losses were not provided to AMEC Earth & Environmental. Thus, approximations of these losses were made by computing the unaccounted for water to make the reservoir water budget balance. The computation for these approximations is illustrated below:

$$\text{Total Outflow} = \text{East Outfall} + \text{West Outfall} + \text{Beebe Canal Release} + \text{Toe Drain Seepage} + \text{Evaporation} + \text{Subsurface Loss} \qquad (3)$$

Substituting Equation 3 into Equation 1 and solving for Subsurface Loss results in:

$$\text{Subsurface Loss} = \text{Total Inflow} - \text{Change in Storage} - (\text{East Outfall} + \text{West Outfall} + \text{Beebe Canal Release} + \text{Toe Drain Seepage} + \text{Evaporation}) \qquad (4)$$

The outflows by source and by year are summarized in Table 10 and described graphically for an average year in Figure 37. Note that the estimated subsurface loss is about 10 – 20 % of the total reservoir outflow.

Table 10. Outflows from Barr Lake by Irrigation Year (AF/Year)

	IY00	IY01	IY02	IY03	IY04	IY05	Average (IY00-IY05)
East Outfall	10,269	9,074	6,267	9,399	8,060	12,740	9,302
West Outfall	12,185	10,683	9,130	17,994	13,079	18,922	13,665
Beebe Canal Releases	4,686	4,378	4,162	6,319	5,942	8,229	5,619
Toe Drain Seepage	3,161	3,403	2,914	2,697	2,777	3,075	3,004
Subsurface Losses*	4,739	6,038	7,195	7,453	7,836	9,855	7,186
Evaporation	5,645	5,650	4,622	5,085	4,308	5,523	5,139
TOTAL OUTFLOW	40,685	39,225	34,290	48,947	42,002	58,344	43,916

* Subsurface Losses estimated based on Equation 4.

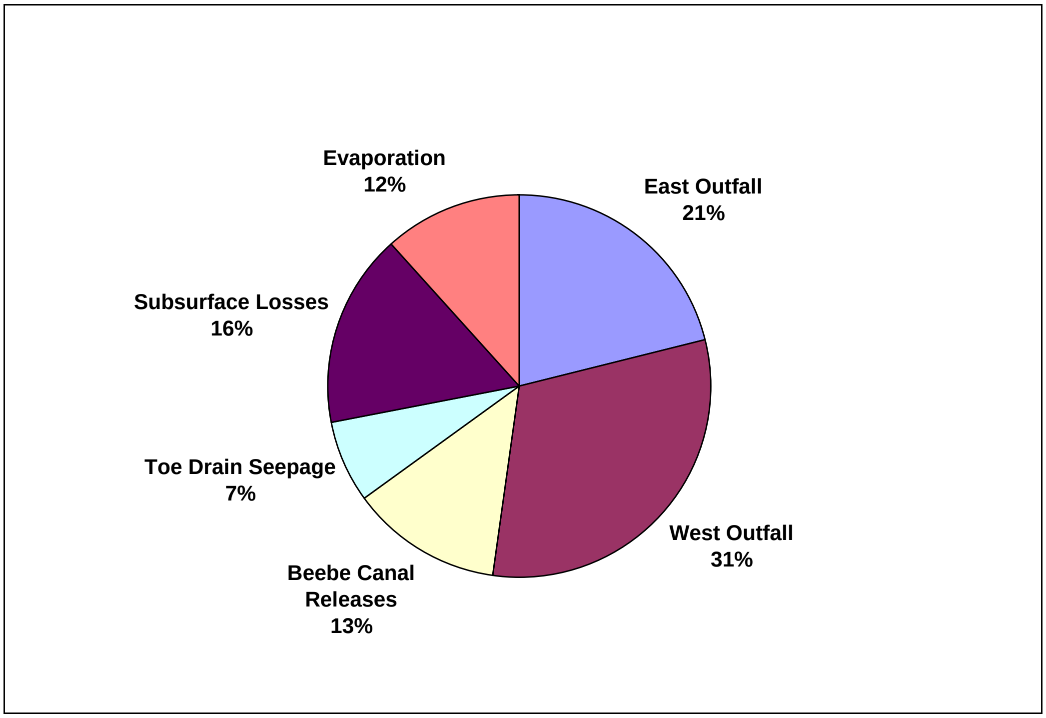

Figure 37. Distribution of Total Outflows from Barr Lake (Based on Average of IY00-IY05)

The overall water balance by year is shown in Table 11. There is variability between the individual years. Highest inflows and outflows occurred in IY05. Lowest inflows and outflows occurred in IY02. The largest drop in contents occurred in IY02 while the largest gain occurred in IY03.

Table 11. Barr Lake Water Balance (AF)

	IY00	IY01	IY02	IY03	IY04	IY05	Average (IY00-IY05)
Change in Storage	-1,713	-4,230	-5,617	7,008	-696	133	-853
Total Inflow	38,972	34,996	28,672	55,955	41,306	58,477	43,063
Total Outflow	40,685	39,225	34,290	48,947	42,002	58,344	43,916
Unaccounted For	0	0	0	0	0	0	0

RESERVOIR NUTRIENT BALANCE

A nutrient balance was conducted for Barr Lake over a three-year period (IY03-IY05). Adequate in-reservoir nutrient data were not available prior to June 2002. Phosphorus and nitrogen enter the reservoir via the Burlington-O'Brian canal, atmospheric deposition, internal loading from the bottom sediments, subsurface inflow, and runoff from the direct watershed. Nitrogen can also be introduced to the reservoir via fixation by cyanobacteria (blue-green algae) and lost via denitrification. Nutrients leave the reservoir via the east outfall, the west outfall, releases to stockholders via the Beebe Canal, and reservoir seepage. Estimates were made for each of these sources and sinks for both total phosphorus and total nitrogen, with the exception of nitrogen fixation. Loading as a result of nitrogen fixation is assumed to be small compared to the other sources of nitrogen. In addition, losses due to denitrification were assumed to be relatively insignificant.

Total phosphorus and total nitrogen loads were estimated using flow and nutrient concentrations. For the inflows, water-quality samples were provided for the Burlington-O'Brian Canal as it enters Barr Lake (Dorsch, 2004; Lundt, 2006a). The inflow seepage flow was assumed to have the same water-quality characteristics as the Burlington-O'Brian inflow since it was assumed to be a function of the flow diverted to the Denver-Hudson Canal. Loads from the Burlington-O'Brian Canal and inflow seepage were computed using the time-interval method (Scheider, et al., 1979). Atmospheric deposition contributions were estimated based on precipitation data measured at Denver International Airport and precipitation chemistry data taken near Cherry Creek Reservoir (2001-2005). Internal loading from the bottom sediments is described in the following section.

For the outflows, the mass of nutrients leaving the reservoir was also estimated using flow and nutrient concentrations, along with the time-interval method. Water-quality samples were provided for the west outfall and the east outfall (Dorsch, 2004; Lundt, 2006a). For releases to the Beebe Canal and outflow seepage (both seepage through the dam [toe drain seepage] and seepage that flows under the clay layer under the dam), it was assumed that phosphorus and nitrogen concentrations could be approximated by the west outfall concentrations. Nutrient water balances are described after the next section on internal loading.

Internal Loading

Orthophosphate and ammonia (dissolved forms of nutrients which are bioavailable) can be released from the bottom sediments during periods of anoxia (low dissolved oxygen) at the sediment-water interface. Low dissolved oxygen concentrations near the bottom are accompanied by a reduction in redox potential, which govern the release of phosphorus from the sediments (Bostrom, et al., 1988). Ammonia has not been studied to the degree that phosphorus has and less is understood about the driving forces behind its release. However, Beutel (2003) has shown that the amount of ammonia released by the sediments is controlled by the presence or lack of oxygen in the overlying waters. Although releases of phosphorus and ammonia under oxic conditions have been reported, it is widely accepted that oxic releases are much lower than anoxic releases. Note also that feeding activities of benthic fish can disturb the sediments and increase diffusion of nutrients into the water column. (Keen and Gagliardi, 1981). When external loadings to a lake or reservoir are small, these activities can be important (Wetzel, 2001). For Barr Lake, there are insufficient data to quantify the impacts of fish on nutrient loading. Due to the amount of external loading (see below), the impacts of fish on overall loading to Barr Lake are assumed to be relatively small. An additional internal source of phosphorus could be due to resuspension of bottom sediments during reservoir filling or drawdown. Again, this source is assumed to be relatively small compared to other nutrient sources.

For some lakes and reservoirs, internal loading can be a significant source of nutrients relative to the external loads. If this is the case, decreasing the external loading to the lake will not result in the same in-reservoir improvements one might see for a lake that is dominated by external loads.

For this effort, phosphorus and ammonia release rates were estimated based on three methods. The first method involves using published release rates from similar lakes and reservoirs. Phosphorus release rates measured in lakes and reservoirs have been compiled by Nurnberg (1988). For hyper-eutrophic lakes listed in her compilation (n = 20), phosphorus release rates range from 6 mg P/m^2/day to 42.5 mg P/m^2/day. The median value is 20 mg P/m^2/day.

If one considers the hyper-eutrophic lakes listed with sediment phosphorus concentrations similar to Barr Lake (approximately 1.2 mg/gm dry weight), the release rates range from 6 to 31 mg P/m^2/day with a median of 12 mg P/m^2/day. A value of 12 mg P/m^2/day is assumed using this method for Barr Lake.

There is much less literature published on the release of ammonia than the release of phosphorus. Published rates are displayed in Table 12.

Table 12. Published Ammonia Release Rates (Beutel, 2001)

Ammonia Release Rate	Notes	Source
12-50 mg N/m^2/day	- 4 Wisconsin Lakes - Anoxic conditions - Incubation Results	Graetz et al., 1973
80 mg N/m^2/day	- A Danish Lake - Anoxic Conditions - Incubation Results	Rysgaard, et al., 1994
6-13 mg N/m^2/day	- A Swiss Lake - Hypolimnetic Accumulation before Oxygenation	Hohener and Gachter, 1994
18.1 - 20.6 mg N/m^2/day	- Walker Lake, CA - Anoxic Conditions - Incubation Results	Beutel, 2001
16.5 mg N/m^2/day	- Walker Lake, CA - Anoxic Conditions - Hypolimnetic Accumulation	Beutel, 2001

Based on the values in Table 6, a release rate of 19 mg N/m^2/day is assumed for Barr Lake. This is the median of the mid-point results and is in line with the recent work conducted by Beutel (2001) on a western reservoir.

The second method involves the use of an empirical relationship between sediment total phosphorus concentrations and phosphorus release rates, which was formulated by Nurnberg (1988). The regression is based on lakes world wide (n = 63) and has an R^2 of 0.21. Using a sediment total phosphorus concentration of 1.2 mg/g dry weight, the predicted total phosphorus release rate is 7.2 mg P/m^2/day. Note that empirical relationships for ammonia were not located in the literature.

The third method involves making an estimate based on changes in hypolimnetic concentrations. This approach is often considered to provide the best estimate of internal phosphorus loadings and has been found to be in agreement with results from laboratory experiments (Nurnberg, 1987). It is complicated, however, by failing to isolate sediment releases from other sinks and sources from and to the hypolimnion (e.g., diffusion to epilimnion, settling decaying phosphorus from epilimnion, etc.) (Effler, et al., 1996).

The application of this method to Barr Lake is less straight forward than it is for a typical dimictic lake (a lake that completely mixes twice per year) due to periodic mixing during the summer months. In 2003, however, there is a period between May 27, 2003 and July 22, 2003 where the reservoir is somewhat stratified and dissolved oxygen concentrations at the bottom are < 1 mg/l (Figure 9). During this period, there is an increase in orthophosphate at the bottom of the reservoir between July 8 and July 22, 2003. In addition, there were no stormwater events and no inflow from the Burlington-O'Brian Canal. Orthophosphate concentrations at the bottom rose from 297 µg/l as P to 606 µg/l as P. Using profile data and elevation - volume relationships to determine the size of the hypolimnion, the phosphorus release is computed to be approximately 41 mg P/m^2/day. Ammonia at the bottom of the reservoir continually decreased over the period May 27 - July 22, 2003 period so a similar computation could not be made for nitrogen.

Since this method is considered to be better than the other two methods and the result is within the range found using the first method, a release rate of 41 mg P/m^2/day was assumed for the nutrient mass balance. The best estimate of nitrogen release is 19 mg N/m^2/day based on published rates and is used in the nutrient mass balance described below.

In order to translate the release rates to pounds of nutrients released into the reservoir, one needs to estimate the active sediment area, and the average period of anoxia. In addition, since Barr Lake is warmer than other reservoirs whose rates were published, a temperature correction factor is used for the nitrogen loading calculation.

The active sediment area was estimated at 398 acres based on the average thermocline depth. The average period of anoxia was estimated to be 61 days / year based on the average period of anoxia for 2003-2005. The temperature correction factor using the Arrhenius equation (Chapra, 1997) was estimated to be 1.1 based on a summertime bottom reservoir temperature of 23 °C (Figure 7) and a θ of 1.02 (Chapra, 2005). These values were used in an initial estimate to compute the mass of nutrients released per year. In addition, release rates, active sediment area, and the period of anoxia were varied up and down by 50%, 20%, and 15% respectively to estimate a range of possible releases. Note that in the case of nitrogen, the release rate was varied between 6 and 80 mg N/m^2/day, the range of published rates. The results are listed in Table 13.

Table 13. Computed Internal Nutrient Loading (lbs / year)

	Phosphorus	Nitrogen
Initial Estimate	8,881	4,527
Minimum	4,440	1,430
Maximum	13,321	19,061

Based on these results, the values of 9,000 pounds/year of phosphorus and 4,500 pounds / year of nitrogen were used in the nutrient balance described below.

Phosphorus Balance

A phosphorus balance was computed using the same methodology used in the water balance computation.

$$\textit{Change in Mass in Storage} = \textit{Total Mass In} - \textit{Total Mass Out} \qquad (5)$$

The change in storage is based on the reservoir contents and phosphorus concentrations at the beginning and end of the irrigation year. The results are shown in Table 14.

Results for loads from inflows are shown in Table 15 and displayed graphically in Figure 38. The total annual loading of phosphorus is about 157,000 pounds / year, which translates to about 9.8 g P/m^2-yr. Note that for lakes with a mean depth similar to that of Barr Lake, a permissible loading rate of 0.07 g P/m^2-yr is suggested while a rate of 0.13 g P/m^2-yr and above is referred to as excessive (Vollenweider, 1968).

Table 14. Estimated Change in Mass in Storage of Total Phosphorus (lbs)

	IY03	IY04	IY05	Average (IY03-IY05)
Change in Mass in Storage (based on initial contents/ concentration and final contents / concentration)	15,902	-10,239	5,560	3,741

Table 15. Estimated Mass of Total Phosphorus Entering Barr Lake (lbs)

	IY03	IY04	IY05	Average (IY03-IY05)
Burlington-O'Brian Canal	123,037	164,986	140,270	142,764
Precipitation	567	173	277	339
Inflow Seepage	4,817	4,356	5,512	4,895
Internal Loading	9,000	9,000	9,000	9,000
TOTAL INFLOW	137,420	178,515	155,059	156,998

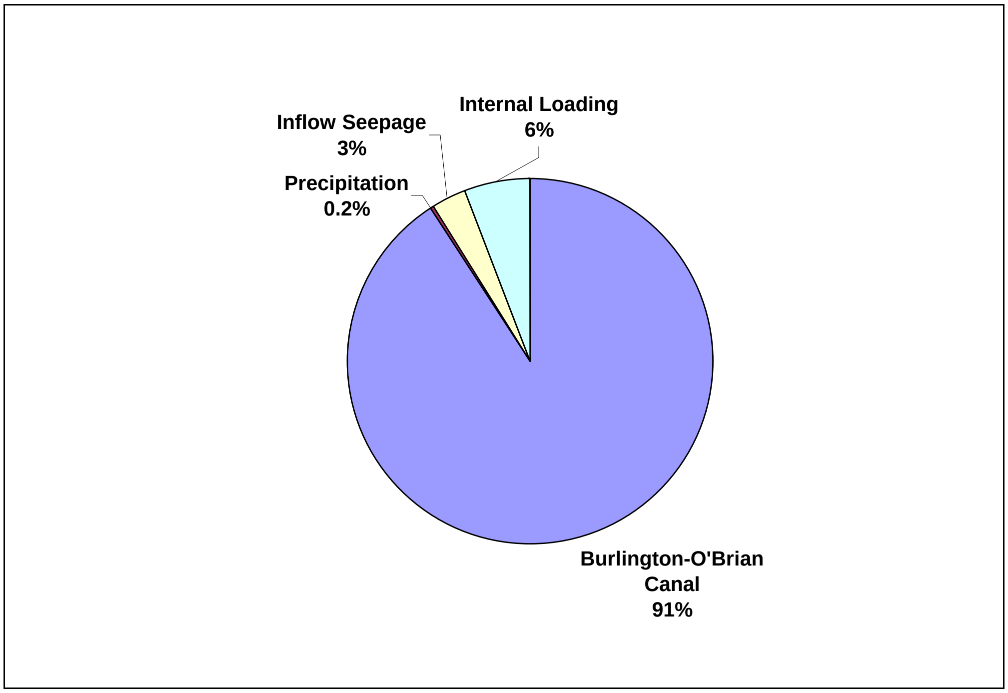

Figure 38. Distribution of Total Phosphorus Entering Barr Lake (Based on the Average of IY03-IY05)

For the incoming phosphorus, 91% was from the Burlington-O'Brian Canal, <1 % was from precipitation, 3% from seepage, and the remaining 6% was from internal loading. Note that using the maximum internal loading numbers computed in the previous section would not significantly change the overall distribution.

The mass of phosphorus leaving the reservoir are summarized in Table 16 and shown graphically in Figure 39. Each of the sinks of phosphorus is over 15% of the total outflow.

Table 16. Estimated Mass of Total Phosphorus Leaving Barr Lake (lbs)

	IY03	IY04	IY05	Average (IY03-IY05)
East Outfall	12,015	12,205	15,044	13,088
West Outfall	24,972	19,517	25,336	23,275
Beebe Canal Releases	9,059	8,697	10,782	9,513
Total Outflow Seepage	16,202	15,216	16,666	16,028
TOTAL OUTFLOW	62,248	55,635	67,828	61,904

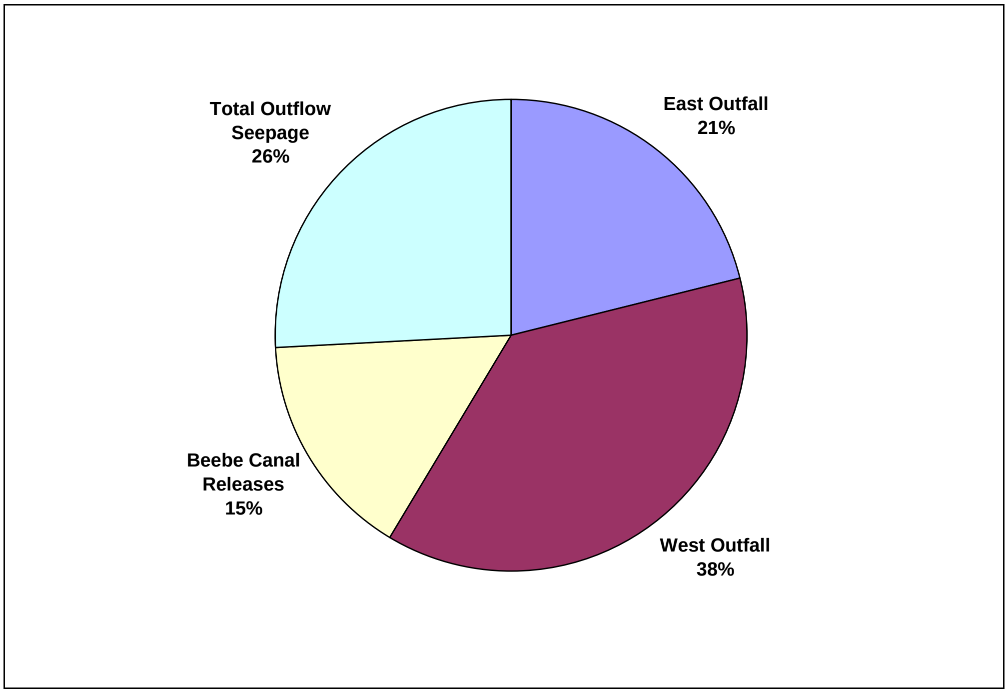

Figure 39. Distribution of Total Phosphorus Leaving Barr Lake (Based on the Average of IY03-IY05)

The overall phosphorus balance in shown in Table 17 by irrigation year. Reservoir retention is the unaccounted for mass divided by the sum of the initial mass stored in the reservoir and the total inflow. The reservoir retained an average of 52% of the inflowing phosphorus, which is in the range of values (5% to 86%) found on other plains reservoirs (Sprague, 2002a). It is also close to the values found using data from 149 lakes and reservoirs around the world (Kronvang, et al., 2004). Kronvang, et al. (2004) found nutrient retention to vary by hydraulic residence times and reported that lakes and reservoirs with hydraulic residence times of 0.1 to 1 year (Table 5) had a median phosphorus retention of 45%. Reservoirs tended to have higher retention rates than lakes. For Barr Lake, the year with the highest retention rate had a slightly higher hydraulic retention time. This is consistent with the findings of Kronvang, et al. (2004).

Phosphorus retention occurs in reservoirs due to several factors including 1) sedimentation of phosphorus imported from the inflow, 2) adsorption of phosphorus with inorganic compounds, and 3) sedimentation of phosphorus with algae and other organic matter (Wetzel, 2001). The latter two mechanisms are most likely important for Barr Lake.

Table 17. Barr Lake Phosphorus Balance (lbs)

	IY03	IY04	IY05	Average (IY03-IY05)
Change in Storage	15,902	-10,239	5,560	3,741
Total Inflow	137,420	178,515	155,059	156,998
Total Outflow	62,248	55,635	67,828	61,904
Unaccounted For	-59,270	-133,119	-81,671	-91,353
% Retained*	41%	66%	49%	52%

* Mass unaccounted for as a percent of total inflow and initial mass in storage

Nitrogen Balance

The nitrogen balance was computed similarly to the phosphorus balance. The changes in mass stored in the reservoir are shown in Table 18.

Results for loads from inflows are shown in Table 19 and displayed graphically in Figure 40. The total annual loading of nitrogen is about 1,180,000 pounds / year, which translates to about 80 g N/m^2-yr. Note that for lakes with a mean depth similar to that of Barr Lake, a permissible loading rate of 1.0 g N/m^2-yr is suggested while a rate of 2.0 g N/m^2-yr and above is referred to as excessive (Vollenweider, 1968).

Table 18. Estimated Change in Mass in Storage of Total Nitrogen (lbs)

	IY03	IY04	IY05	Average (IY03-IY05)
Change in Mass in Storage	125,289	-50,155	33,609	108,744

Table 19. Estimated Mass of Total Nitrogen Entering Barr Lake (lbs)

	IY03	IY04	IY05	Average (IY03-IY05)
Burlington-O'Brian Canal	1,025,632	1,518,038	1,239,405	1,261,025
Precipitation	10,475	9,590	3,782	7,949
Inflow Seepage	38,446	42,375	50,610	43,811
Internal Loading	4,500	4,500	4,500	4,500
TOTAL INFLOW	1,079,052	1,574,503	1,298,297	1,317,284

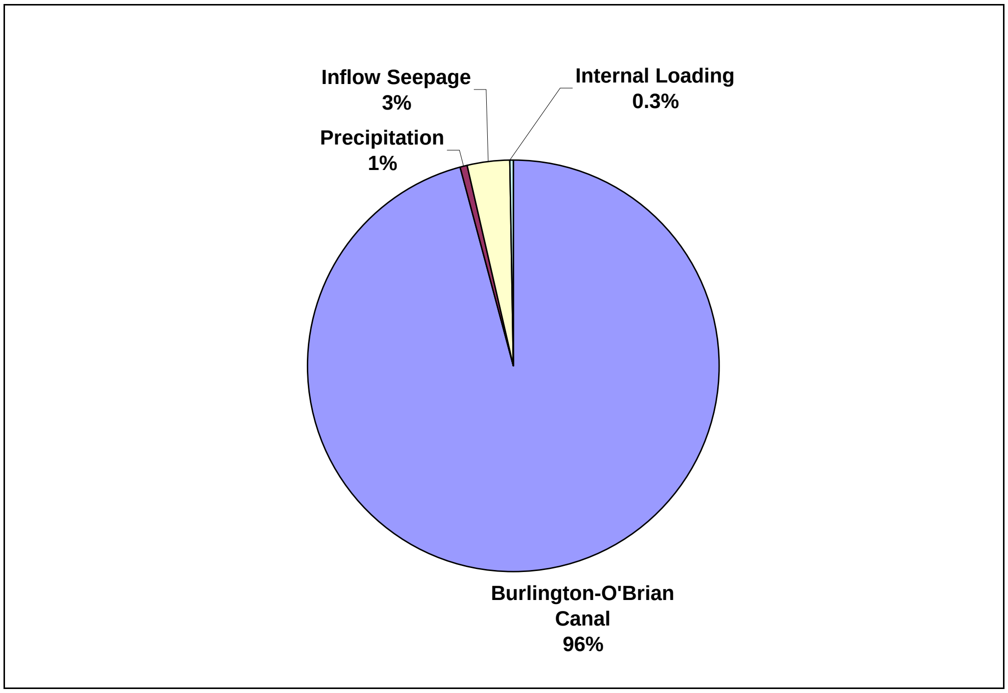

Figure 40. Distribution of Total Nitrogen Entering Barr Lake (Based on the Average of IY03-IY05)

For the incoming nitrogen, 96% was from the Burlington-O'Brian Canal, 1% was from precipitation, 3% from inflow seepage, and <1% was from internal loading. Note that using the maximum internal loading numbers computed in the previous section would not significantly change the overall distribution.

The mass of nitrogen leaving the reservoir is summarized in Table 20 and shown graphically in Figure 41.

Table 20. Estimated Mass of Total Nitrogen Leaving Barr Lake (lbs)

	IY03	IY04	IY05	Average (IY03-IY05)
East Outfall	64,238	70,734	152,771	95,914
West Outfall	149,011	128,826	179,054	152,297
Beebe Canal Releases	54,357	61,520	79,996	65,291
Total Outflow Seepage	90,380	114,338	125,965	110,228
TOTAL OUTFLOW	357,986	375,419	537,786	423,730

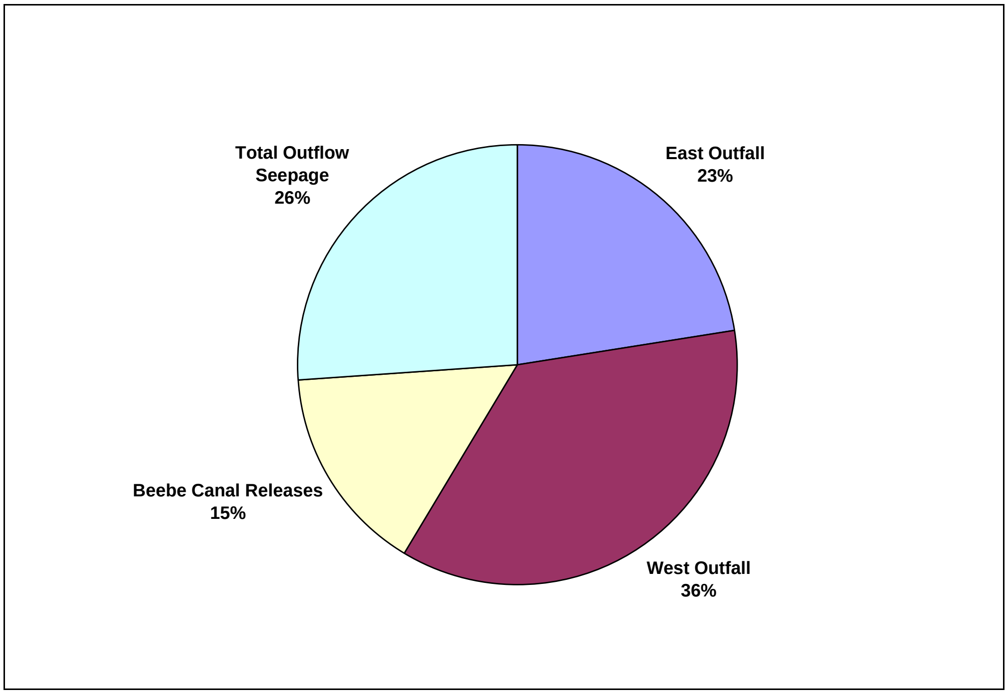

Figure 41. Distribution of Total Nitrogen Leaving Barr Lake (Based on the Average of IY03-IY05)

The overall nitrogen balance is shown in Table 21. Reservoir retention is the unaccounted for mass divided by the sum of the initial mass stored in the reservoir and the total inflow. The reservoir retained an average of 59% of the inflowing nitrogen plus that initially stored, which is in the range of values (49% to 88%) found on other plains reservoirs (Sprague, 2002a). It is also close to the values found using data from 149 lakes and reservoirs around the world (Kronvang, et al., 2004). Kronvang, et al. (2004) found nutrient retention to vary by hydraulic residence times and reported that lakes and reservoirs with hydraulic residence times of 0.1 to 1 year (Table 5) had a median nitrogen retention of 50%. Reservoirs tended to have higher retention rates than lakes. For Barr Lake, the year with the highest retention rate had a slightly higher hydraulic retention time. Also, nitrogen retention is somewhat higher than phosphorus retention. These results are consistent with the findings of Kronvang, et al. (2004). Nitrogen retention occurs in reservoirs due to biological uptake and deposition of particulate organic nitrogen (Sprague, 2002a).

Table 21. Barr Lake Nitrogen Balance (lbs)

	IY03	IY04	IY05	Average (IY03-IY05)
Change in Storage	125,289	-50,155	33,609	108,744
Total Inflow	1,079,052	1,574,503	1,298,297	1,317,284
Total Outflow	357,986	375,419	537,786	423,730
Unaccounted For	-595,777	-1,249,239	-726,902	-857,306
% Retained*	53%	72%	52%	59%

* Mass unaccounted for as a percent of total inflow and initial mass in storage

COMPARISON WITH SIMILAR RESERVOIRS

A comparison with similar reservoirs located in the Colorado plains was made. Several off-channel irrigation reservoirs are located along the Lower South Platte River and some data were available. The US Geologic Survey conducted a study on five reservoirs in 1995 -- Riverside Reservoir, Jackson Reservoir, Prewitt Reservoir, North Sterling Reservoir, and Julesburg Reservoir (Figure 42). Samples were collected throughout the irrigation season (March - September) at several sites for each reservoir. Final results are reported in Sprague, 2002a. Although there are no in-reservoir data for Barr Lake in 1995, some insights can be drawn by comparing the available data (Table 22).

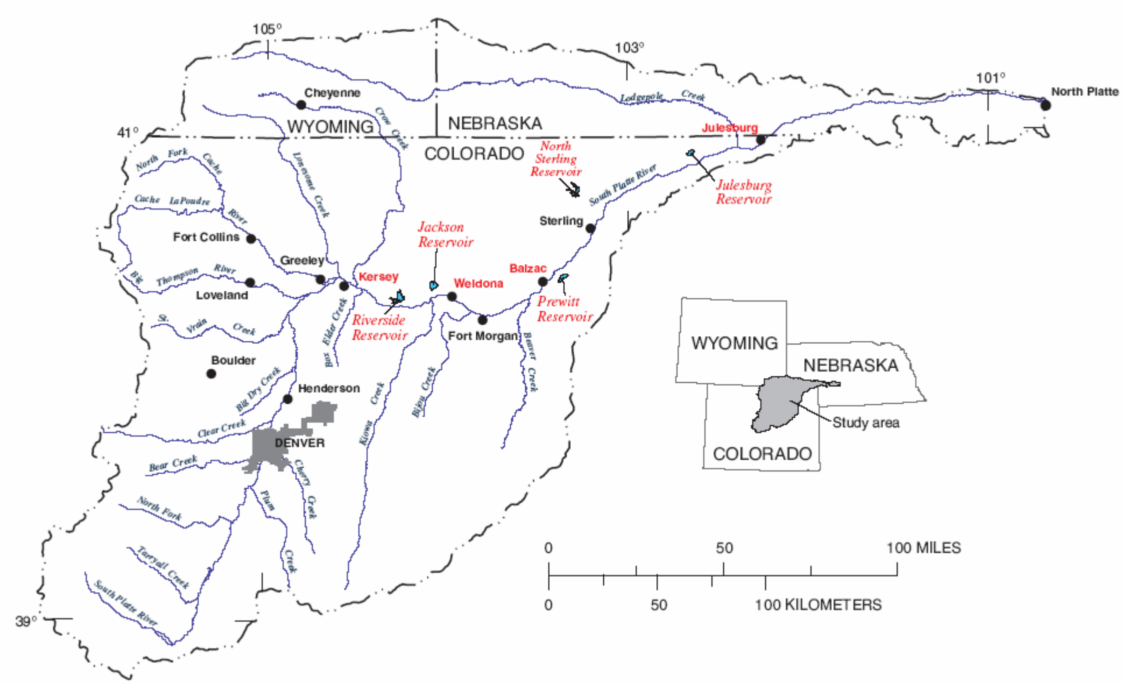

Figure 42. Off-Channel Reservoirs Investigated in 1995 (Figure from Sprague, 2002b)

Barr Lake is similar to these reservoirs in that all are hyper-eutrophic with the exception of Riverside Reservoir, which is eutrophic. Nutrients in Barr Lake exceed those in the other reservoirs, although the chlorophyll *a* levels in Barr Lake are lower than in Jackson and Julesburg Reservoirs. Differences in residence time, lake morphometry, nitrogen to phosphorus ratios, and reservoir operations can cause variations among these systems.

Table 22. Comparison Between Barr Lake and Five Off-Channel Reservoirs Near the Lower South Platte River (Epilimnion)*

Reservoir	Total Phosphorus (µg/l)	Total Nitrogen (µg/l)	Chlorophyll *a* (µg/l)	Secchi-Disk Depth (m)
Barr Lake	618	4,870	40	2.1
Riverside Reservoir	540	3,500	13	1.5
Jackson Reservoir	180	2,900	63	0.3
Prewitt Reservoir	77	2,000	20	1.2
N. Sterling Reservoir	110	3,100	34	0.8
Julesburg Reservoir	52	1,700	52	1.1

* Data for Barr Lake represent means for March - September, 2003-2005. Values for the other reservoirs are means for 1995 (March - September).

A more useful comparison can be made between Barr Lake and the other three nearby reservoirs that are sampled by MWRD. Milton Reservoir, Horse Creek Reservoir, and Prospect Reservoir are often sampled on the same day, providing a means for a direct comparison between the reservoirs. Mean water-quality concentrations were computed for each reservoir, only using data on 25 days when all four reservoirs were sampled. Data were generally available on a monthly basis. The results are displayed in Table 23.

Table 23. Comparison Between the Surface Layers of Barr Lake, Milton Reservoir, Horse Creek Reservoir, and Prospect Reservoir (2003-2005)

Reservoir	Total Phosphorus (µg/l)	Total Nitrogen (µg/l)	Chlorophyll *a* (µg/l)	Secchi-Disk Depth (m)
Barr Lake	590	4,954	37	1.8
Milton Reservoir	625	3,945	27	2.4
Prospect Reservoir	371	5,888	68	1.2
Horse Creek Reservoir	568	5,168	90	0.7

Nitrogen concentrations and chlorophyll *a* concentrations are higher in Prospect Reservoir and Horse Creek Reservoir than in Barr Lake. Water clarity is also diminished and phosphorus concentrations are lower in these two reservoirs. This points to nitrogen-limitation in this set of reservoirs due to high phosphorus concentrations. Milton Reservoir has the lowest nitrogen concentrations, the lowest chlorophyll *a* concentrations, and the highest Secchi-disk depth, even though its phosphorus concentrations are the highest.

BURLINGTON-O'BRIAN CANAL WATER AND NUTRIENT BALANCES

Water Balance

A water balance over the period IY00 through IY05 was conducted around the Burlington-O'Brian Canal. Sources of inflow into the canal include diversions from the South Platte River, pumping from the MWRD facility, stormwater runoff from the canal watershed, and possible subsurface inflows. The quantification of flows diverted from the South Platte River to the Burlington-O'Brian Canal is complicated by operations and gauge locations near MWRD (Figure 43). After water is diverted into the Burlington-O'Brian Canal, water is added at the MWRD facility (if MWRD is pumping to the Canal) and then, just downstream, a portion of the canal flow is sometimes diverted to Sand Creek via a waste gate. The Burlington-O'Brian Canal then moves through a siphon under Sand Creek. The Sand Creek flume, located on the Burlington-O'Brian Canal and used by the State Engineer, is located downstream of the waste gate. Flows are measured at the MWRD pumps and at the Sand Creek flume.

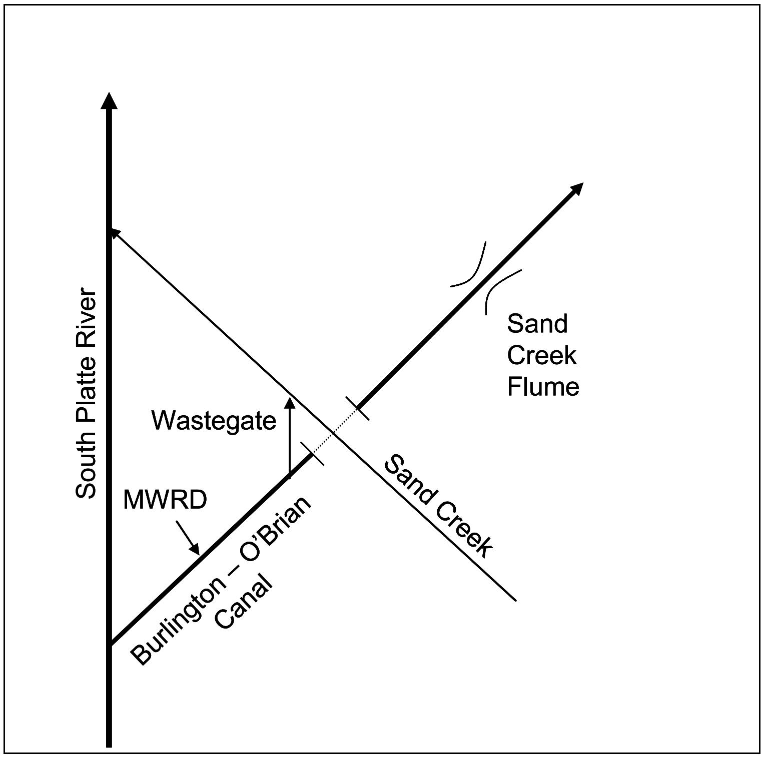

Figure 43. Schematic Showing Flows Between the Burlington-O'Brian Canal Headgate and the Sand Creek Flume

Flow diverted to Sand Creek via the waste gate has been monitored by the USGS since March 2000. The USGS gage Sand Creek at mouth near Commerce City is measured by two flow recorders, one upstream of the Burlington-O'Brian Canal siphon and a flow recorder on the waste gate, the combined flow is the measurement of the Sand Creek at mouth. There is some concern, however, about the level of accuracy of the measurements of the waste gate flow (Van Royen, 2004; Smith, 2004, 2008a). The concerns include:

1) Errors in discharge can occur when the waste gate opening is not submerged and there is low flow in the Burlington-O'Brian Canal (a few cfs) and the waste gate is open more than the upstream head;

2) The waste gate leaks and the leaks are unmeasured; and

3) At times, there are unmeasured overflows over the waste gate.

Errors associated with the first concern are not quantified, but estimates of flow are made when these conditions occur, which do not happen often. The second and third concerns lead one to believe that the discharges are under-reported. Although the flows may be under-estimated by an unknown amount, they currently are the best data available and are used in the water and nutrient balances. Ignoring the waste gate discharge could have significant implications, especially for the nutrient balances.

Daily data representing flows on the Burlington-O'Brian Canal at the Sand Creek flume (downstream of MWRD) were developed by D. Helton Consulting (Rink, 2007a). Daily pumping values from the MWRD facility into the Burlington-O'Brian Canal were provided by MWRD (2006e). These data were also provided by D. Helton Consulting but a comparison of the two datasets by MWRD revealed some periods of missing pumping in the Helton data set (Lundt, 2006c). Flows through the waste gate were provided by the Smith (2004, 2008b). Diversions from the South Platte to the Burlington-O'Brian Canal were estimated by using the following relationship:

Sand Creek flume flow = South Platte diversion + Pumping from MWRD facility – waste gate flow *(6)*

Rearranging and solving for the South Platte diversion:

South Platte diversion = Sand Creek flume flow – Pumping from MWRD facility + waste gate flow *(7)*

Stormwater runoff into the Burlington-O'Brian Canal from the direct watershed has been investigated previously (Brown and Caldwell, 1998). The analysis used information from Urban Drainage and Flood Control District and recommended runoff calculation procedures to quantify contributions from First Creek, Second Creek, Third Creek, Irondale Gulch, and the direct watershed. The Brown and Caldwell analysis resulted in an estimated 72,000 AF/year of stormwater runoff. This number was higher than what FRICO staff observed historically so the number was decreased to a 1,000 AF/year contribution from Third Creek only. Flows from the other tributaries were assumed to either bypass the Burlington-O'Brian Ditch or infiltrate prior to reaching the Burlington-O'Brian Ditch system. For the current study, we ignored this contribution initially and if the water balance resulted in more outflow than inflow, it would be attributed to stormwater runoff. Subsurface inflow into the canal was assumed to be insignificant.

The inflows considered for the initial water balance are displayed in Table 24. Irrigation year 2000 is not included due to lack of a complete dataset for the waste gate (the recorder was operable starting in March, 2000). The average over the five-year period for the initial estimate shows that 88% of the inflow is provided from the South Platte River diversion.

Table 24. Inflows into the Burlington-O'Brian Canal from the South Platte River and the MWRD Facility (AF)

	IY01	IY02	IY03	IY04	IY05	Average (IY01-IY05)
South Platte Diversions	108,950	69,766	132,599	99,760	138,424	109,900
MWRD Facility	7,572	18,771	11,790	15,442	18,090	14,333
TOTAL INFLOW	116,522	88,537	144,388	115,202	156,515	124,233

Outflows from the canal include deliveries to Thornton, deliveries to the South Adams County Water and Sanitation District, deliveries to the Little Burlington Canal, deliveries to the Denver-Hudson Canal, deliveries to Barr Lake, and conveyance losses. Daily flow numbers were developed for each of the deliveries by D. Helton Consulting (Rink, 2007a). Conveyance losses are assumed to be 28% of the flow and are thought to be 95% seepage and 5% evaporation and transpiration (Leonard Rice Engineers, 2005). The outflows considered for the water balance are displayed in Table 25. A graphical representation is shown in Figure 44.

Table 25. Outflow from the Burlington-O'Brian Canal (AF)

	IY01	IY02	IY03	IY04	IY05	Average (IY01-IY05)
Waste Gate Outflows	13,834	9,656	18,566	21,822	15,832	15,942
Deliveries to Thornton	9,874	9,629	8,420	7,906	6,783	8,522
Deliveries to SACWSD	0	1,074	547	961	1,650	846
Deliveries to the Little Burlington Canal	11,380	9,230	11,103	10,374	12,282	10,874
Deliveries to the Denver-Hudson Canal	33,891	18,039	27,753	18,410	38,155	27,250
Deliveries to Barr Lake	31,388	26,861	52,919	38,539	55,655	41,072
Conveyance Loss	28,753	22,087	35,230	26,146	39,391	30,322
TOTAL OUTFLOW	129,120	96,575	154,538	124,157	169,748	134,828

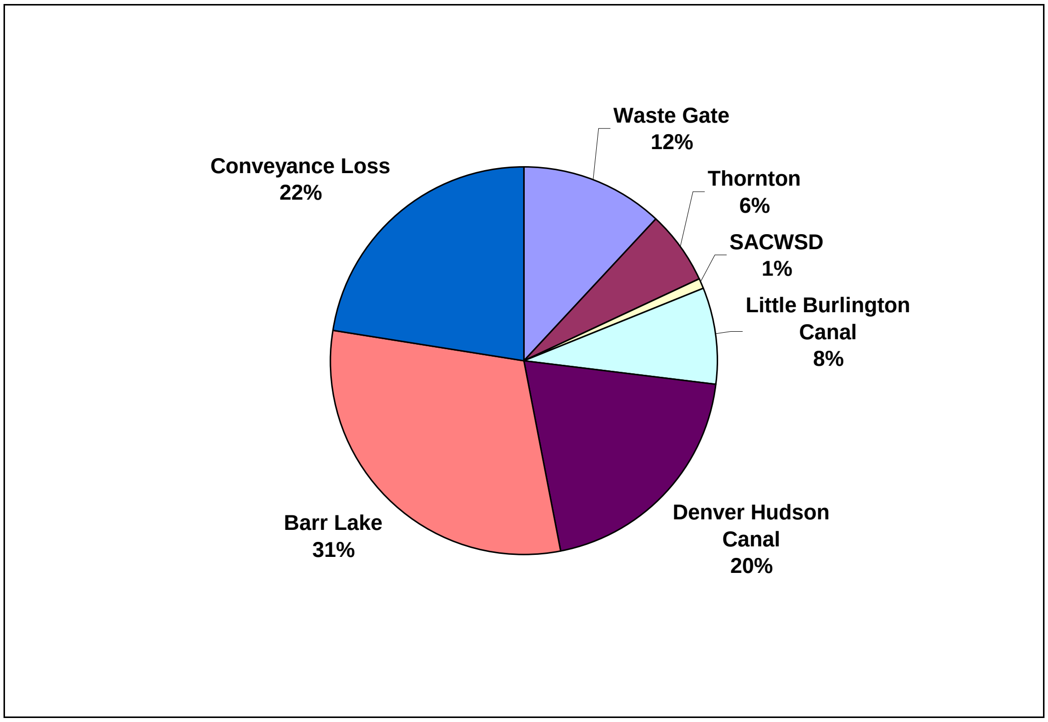

Figure 44. Distribution of Outflows from the Burlington-O'Brian Canal (Based on the Average of IY01-IY05)

Using the numbers described above, a water balance was computed for the Burlington-O'Brian Canal by irrigation year (Table 26). The unaccounted for water is 7-11% of the total inflow and is assumed to approximate stormwater runoff into the canal. Each of the inflows considered for the water balance are displayed in Table 27 and shown graphically in Figure 45. The diversion from the South Platte River accounts for 81% of the inflow into the canal.

Table 26. Burlington-O'Brian Canal Water Balance (AF)

	IY01	IY02	IY03	IY04	IY05	Average (IY01-IY05)
Total Inflow	116,522	88,537	144,388	115,202	156,515	124,233
Total Outflow	129,120	96,575	154,538	124,157	169,748	134,828
Unaccounted For Water (Outflow – Inflow)*	12,598	8,038	10,150	8,955	13,233	10,595
Unaccounted For Water as a Percent of Total Inflow	11%	9%	7%	8%	8%	9%

* Assume equals stormwater runoff

Table 27. Inflows into the Burlington-O'Brian Canal (AF)

	IY01	IY02	IY03	IY04	IY05	Average (IY01-IY05)
South Platte Diversion	108,950	69,766	132,599	99,760	138,424	109,900
MWRD Facility	7,572	18,771	11,790	15,442	18,090	14,333
Stormwater Runoff	12,598	8,038	10,150	8,955	13,233	10,595
TOTAL INFLOW	129,120	96,575	154,538	124,157	169,748	134,828

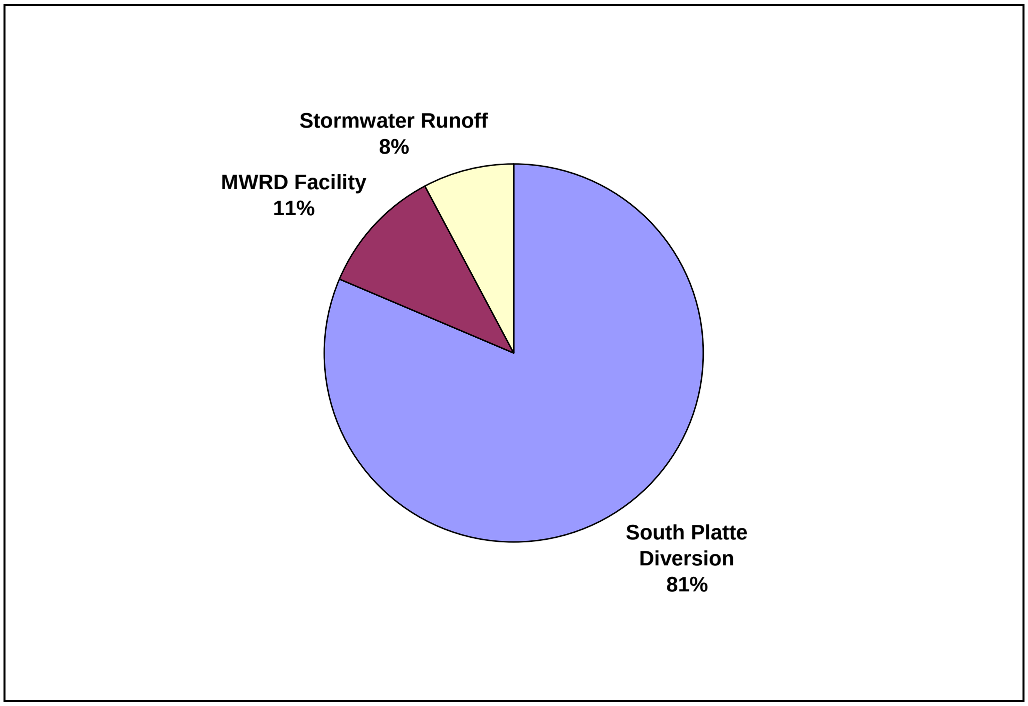

Figure 45. Distribution of Inflows into the Burlington-O'Brian Canal (Based on the Average of IY01-IY05)

Phosphorus Balance

Sources of phosphorus into the Burlington-O'Brian Canal include diversions from the South Platte River, pumping from the MWRD facility, and runoff from the direct watershed. Phosphorus at the Burlington-O'Brian headgate was sampled by Mountain River Associates (Dorsch, 2004; Lundt, 2006a). Note that there were large gaps in the water-quality data at the Burlington-O'Brian headgate in IY2002 and IY2004. In IY2002, there were no phosphorus data at the headgate for February, April, May, July, August, September, and October (seven months). In IY2004, there were no phosphorus data for February, March, April, June, July, August, September and October (eight months). Due to these large gaps in the record, a phosphorus balance was not conducted for these two years.

Concentrations for pumping from the MWRD facility were estimated based on data obtained from Lundt (2007b). Concentrations for the North Plant and the South Plant were provided and it was assumed that the final discharge was comprised as a 40% South Plant / 60% North Plant mixture (Lundt, 2007a). Concentrations for stormwater runoff have a high level of uncertainty and were assumed to be 1,000 µg P/l. The time-interval method was used to estimate phosphorus loading for the Burlington-O'Brian Canal headgate and the MWRD facility.

Inflow loads of phosphorus are shown by irrigation year in Table 28 and displayed graphically in Figure 46. Diversions from the South Platte River contribute 52% of the total phosphorus entering the Burlington-O'Brian Canal while the MWRD facility contributes 35%.

Table 28. Total Phosphorus Entering the Burlington-O'Brian Canal (lbs)

	IY01	IY03	IY05	Average (IY01, IY03, IY05)
South Platte Diversion	141,424	137,421	122,170	133,672
MWRD Facility	56,026	84,354	127,156	89,179
Stormwater Runoff	34,258	27,601	35,987	32,615
TOTAL INFLOW	231,708	249,376	285,313	255,466

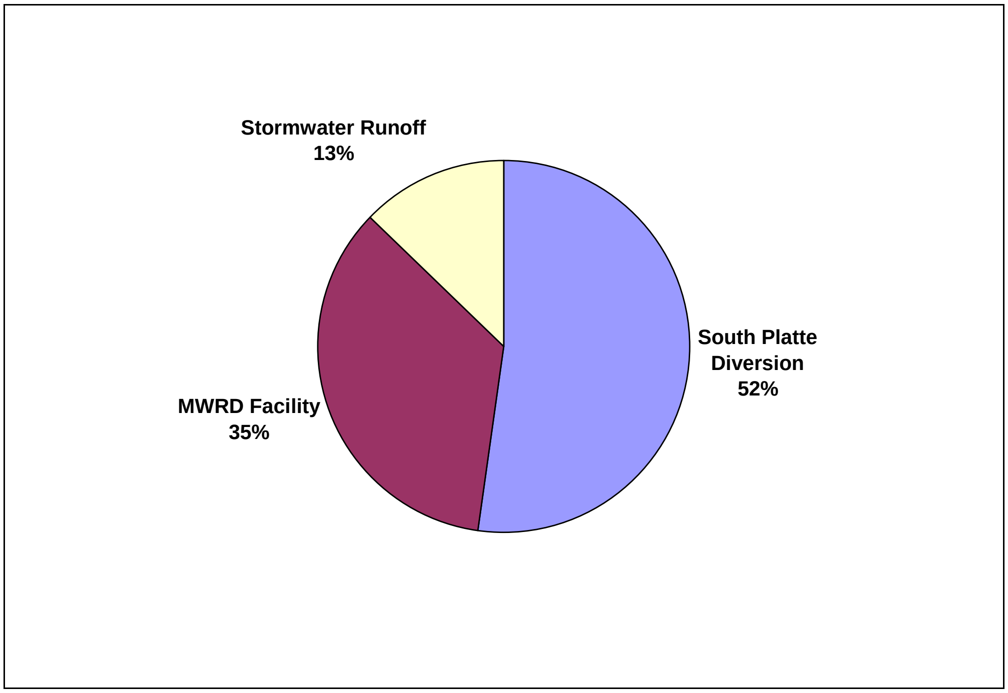

Figure 46. Distribution of Total Phosphorus Entering the Burlington-O'Brian Canal (Based on the Average of IY01, IY03, and IY05)

Phosphorus leaves the Burlington-O'Brian system via deliveries to Thornton, SACWSD, the Little Burlington Canal, the Denver-Hudson Canal and Barr Lake. Phosphorus also leaves via seepage and the waste gate. Losses of phosphorus due to settling were considered negligible due to the high percentage of orthophosphate. Concentrations at the waste gate were computed by mixing the flows from the MWRD facility and the South Platte diversions into the canal. Concentrations were available at the inflow into Barr Lake but not at the other delivery points. Initial estimates of the phosphorus balance were made assuming that the concentrations of the other deliveries (with the exception of the Denver-Hudson Canal) and conveyance losses equaled the average of the concentrations estimated at the waste gate and measured at the inflow into the lake. The concentration of the Denver-Hudson delivery was assumed to be the concentration of the inflow into the lake, due to the proximity of the delivery. The time-interval method was used on a daily basis to estimate the loads. Results by irrigation year for IY01, IY03, and IY05 are shown in Table 29 and Figure 47.

Table 29. Total Phosphorus Leaving the Burlington-O'Brian Canal (lbs)

	IY01	IY03	IY05	Average (IY01, IY03, IY05)
Waste Gate Outflows	15,785	16,270	14,409	15,488
Deliveries to Thornton	10,298	14,698	4,487	9,828
Deliveries to SACWSD	0	1,505	1,483	996
Deliveries to the Little Burlington Canal	13,560	14,581	10,734	12,958
Deliveries to the Denver-Hudson Canal	55,905	32,351	83,338	57,198
Deliveries to Barr Lake	60,000	123,037	140,270	107,769
Conveyance Losses	49,415	62,403	76,195	62,671
TOTAL OUTFLOW	204,963	264,846	330,916	266,908

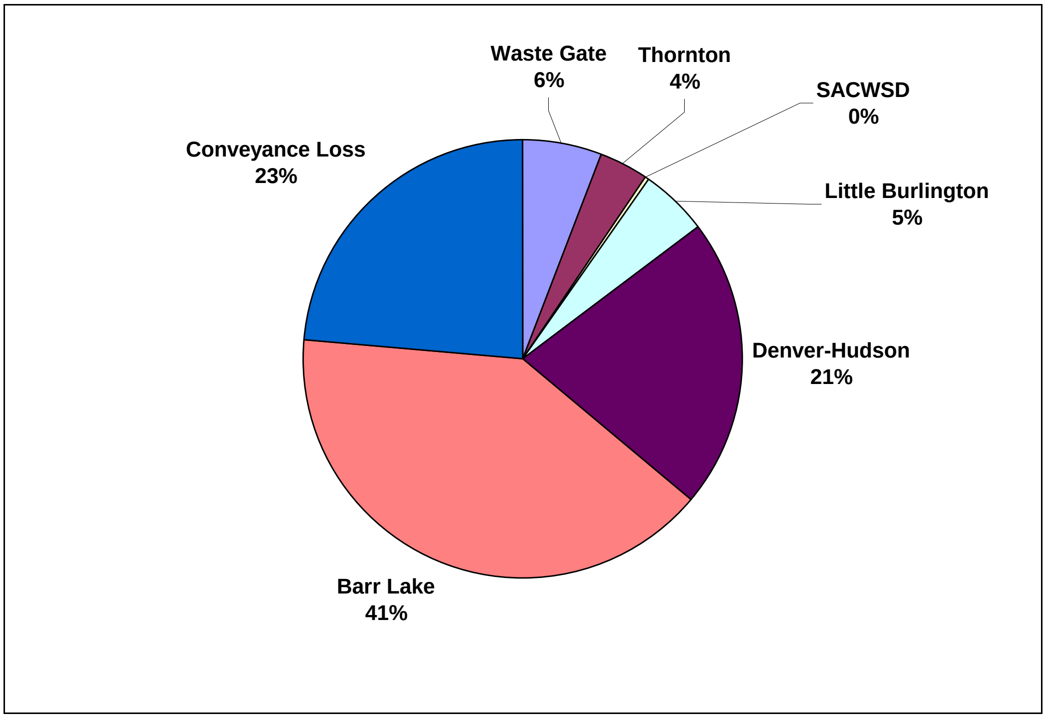

Figure 47. Distribution of Total Phosphorus Leaving the Burlington-O'Brian Canal (Based on the Average of IY01, IY03, and IY05)

Based on the assumptions and methods described above, the phosphorus balance is summarized in Table 30. The results show the unaccounted for phosphorus to be less than 15% in any given year and less than 5% overall. The unaccounted for phosphorus is the combined error in load estimates. Since the errors are small, it appears that the estimates of overall phosphorus sources and sinks are sound.

Table 30. Total Phosphorus Balance for the Burlington-O'Brian Canal (lbs)

	IY01	IY03	IY05	Average (IY01, IY03, IY05)
Incoming Phosphorus	231,708	249,376	285,313	255,466
Outgoing Phosphorus	204,963	264,846	330,916	266,908
Unaccounted For (Out – In)	-26,745	15,470	45,603	11,442
Unaccounted For Mass as a Percent of the Total Outflow Load	-13.0%	5.8%	13.8%	4.3%

Nitrogen Balance

Sources of nitrogen into the Burlington-O'Brian Canal include diversions from the South Platte River, pumping from the MWRD facility, and runoff from the direct watershed. Nitrogen at the Burlington-O'Brian headgate was sampled by Mountain River Associates (Dorsch, 2004; Lundt, 2006a). Concentrations for pumping from the MWRD facility were estimated based on data obtained from Lundt (2007b). Concentrations for the North Plant and the South Plant were provided and it was assumed that the final discharge was comprised as a 40% South Plant / 60% North Plant mixture. (Lundt, 2007a). Concentrations for stormwater runoff have a high level of uncertainty and were assumed to be 5,000 µg N/l. The time-interval method was used to estimate phosphorus loading.

Inflow loads of nitrogen are shown by irrigation year in Table 31 and displayed graphically in Figure 48. Diversions from the South Platte River contribute 71% of the total nitrogen while the MWRD facility contributes 22%.

Table 31. Total Nitrogen Entering the Burlington-O'Brian Canal (lbs)

	IY01	IY03	IY05	Average (IY01, IY03,-IY05)
South Platte Diversion	1,950,399	1,518,567	1,707,344	1,725,437
MWRD Facility	293,097	516,115	821,647	543,620
Stormwater Runoff	171,289	138,005	179,933	163,076
TOTAL INFLOW	2,414,785	2,172,687	2,708,925	2,432,132

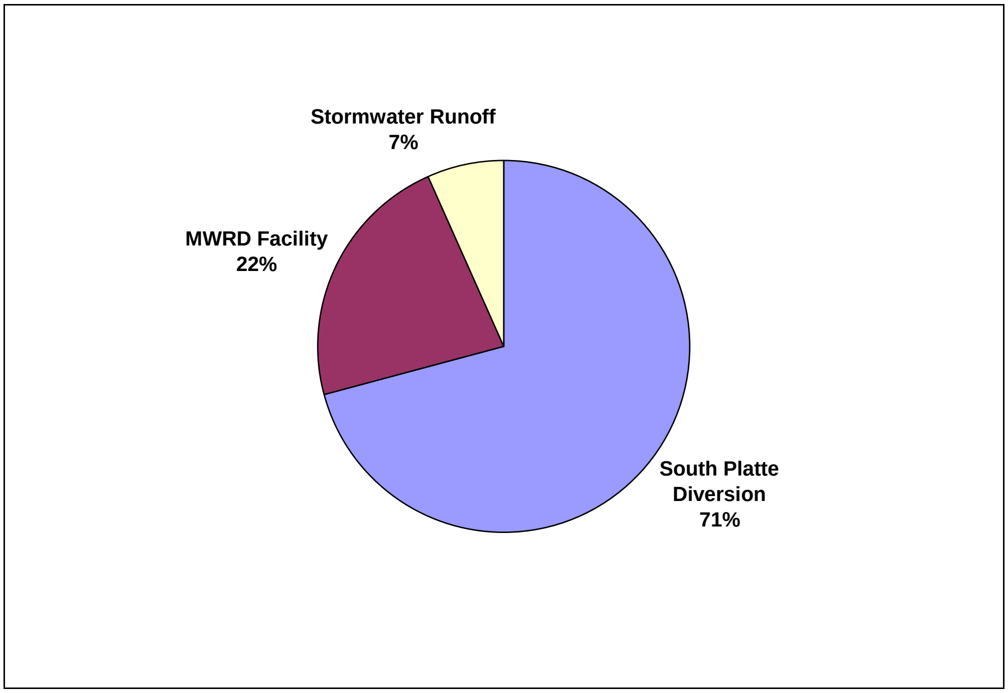

Figure 48. Distribution of Total Nitrogen Entering the Burlington-O'Brian Canal (Based on the Average of IY01, IY03, and IY05)

Nitrogen leaves the Burlington-O'Brian system via deliveries to Thornton, SACWSD, the Little Burlington Canal, the Denver-Hudson Canal and Barr Lake. Nitrogen also leaves via seepage and the waste gate. Losses due to denitrification were assumed to be insignificant. Concentrations are available at the inflow into Barr Lake but not at the other delivery points. Initial estimates of the phosphorus balance were made assuming that the concentrations of the other deliveries (with the exception of the Denver-Hudson Canal) and conveyance losses equaled the average of the concentrations estimated at the waste gate and measured at the inflow into the lake. The concentration of the Denver-Hudson delivery was assumed to be the concentration of the inflow into the lake, due to the proximity of the delivery. The concentration at the waste gate was assumed to be the mixed concentration of the Burlington headgate and pumping from the MWRD facility. The time-interval method was used on a daily basis to estimate the loads. Results by irrigation year are shown in Table 32 and Figure 49.

Table 32. Total Nitrogen Leaving the Burlington-O'Brian Canal (lbs)

	IY01	IY03	IY05	Average (IY01, IY03, IY05)
Waste Gate Outflows	233,603	172,346	175,327	193,758
Deliveries to Thornton	125,680	128,929	53,980	102,863
Deliveries to SACWSD	0	13,393	16,488	9,960
Deliveries to the Little Burlington Canal	162,273	161,629	173,546	165,816
Deliveries to the Denver-Hudson Canal	614,621	284,544	730,087	543,084
Deliveries to Barr Lake	535,844	1,025,632	1,239,405	933,627
Conveyance Losses	509,278	539,675	716,405	588,452
TOTAL OUTFLOW	2,181,299	2,326,147	3,105,238	2,537,562

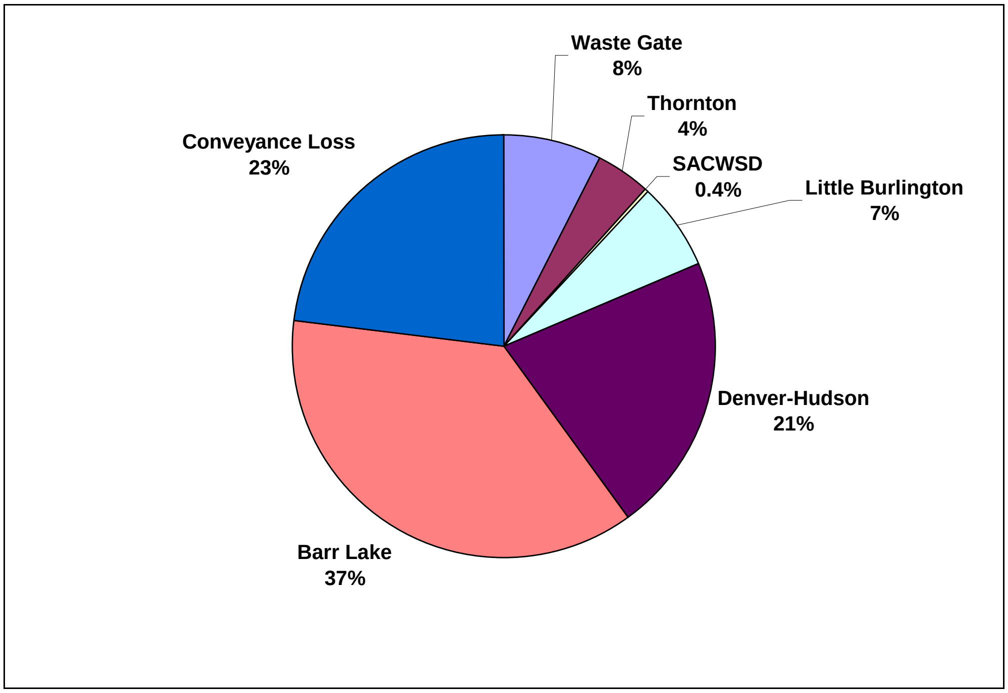

Figure 49. Distribution of Total Phosphorus Leaving the Burlington-O'Brian Canal (Based on the Average of IY01, IY03, and IY05)

Based on the assumptions and methods described above, the nitrogen balance is summarized in Table 33. The results show the unaccounted for nitrogen to be less than

15% in any given year and less than 5% overall. The unaccounted for nitrogen is the combined error in load estimates. Since the errors are small, it appears that the estimates of overall phosphorus sources and sinks are sound.

Table 33. Total Nitrogen Balance for the Burlington-O'Brian Canal (lbs)

	IY01	IY03	IY05	Average (IY01, IY03, IY05)
Incoming Nitrogen	2,414,785	2,172,687	2,708,925	2,432,132
Outgoing Nitrogen	2,181,299	2,326,147	3,105,238	2,537,562
Unaccounted for (Out – In)	-233,486	153,460	396,314	105,429
Unaccounted For Mass as a Percent of the Total Outflow Load	-10.7%	6.6%	12.8%	4.2%

OBSERVATIONS AND DISCUSSION

Barr Lake is on the State of Colorado's 303(d) list for exceeding the upper pH standard. Although it is unusual for the pH of a lake to exceed 9.0 (Hem, 1992), it is not unknown. Lakes and reservoirs can have high pH levels for a number of reasons, including geology, certain types of industry, and excessive algal populations.

Lakes can have naturally elevated pH levels due to the surrounding geology, especially in volcanic areas. Runoff from certain types of industries in the watershed such as soda ash processing plants or cement kilns has been known to cause elevated pH levels in lakes. When algae photosynthesize, they remove carbon dioxide from the water column which tends to result in increases in pH. In very productive lakes, large changes in pH can occur. In an extreme case, maximum pH values have exceeded 12.0 in a poorly buffered, highly productive lake (Livingstone, 1963).

For Barr Lake, the data points to excessive algal populations as the cause for high pH levels. The lake is highly productive, as evidenced by the hyper-eutrophic trophic status. In addition, pH levels begin to exceed the upper standard at the same time that algae start to bloom in July. There is also a relationship between chlorophyll *a* concentrations and pH in the lake, especially at higher concentrations of chlorophyll *a* (Figure 50). There is no evidence of the high levels of pH being caused by geologic or industrial impacts.

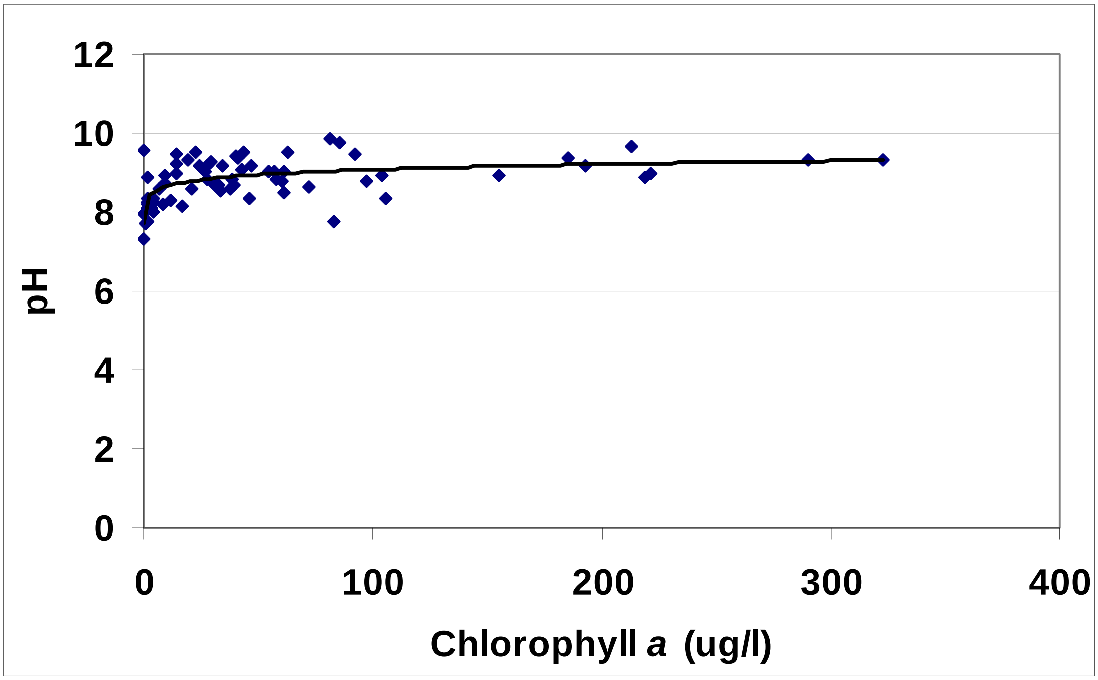

Figure 50. Surface pH versus Chlorophyll a Concentrations

With respect to overall water-quality dynamics within Barr Lake, there are certain patterns that can be identified by reviewing the data. First of all, it is noted that the type of algae growing in Barr Lake changes with nitrogen to phosphorus ratios (N:P) as shown in

Figure 51. In general, when N:P ratios (computed using the inorganic subspecies) increase, diatoms dominate. When N:P ratios decline, blue-green algae (cyanobacteria) dominate. Some forms of blue-green algae can fix nitrogen when supplies in the water column are low.

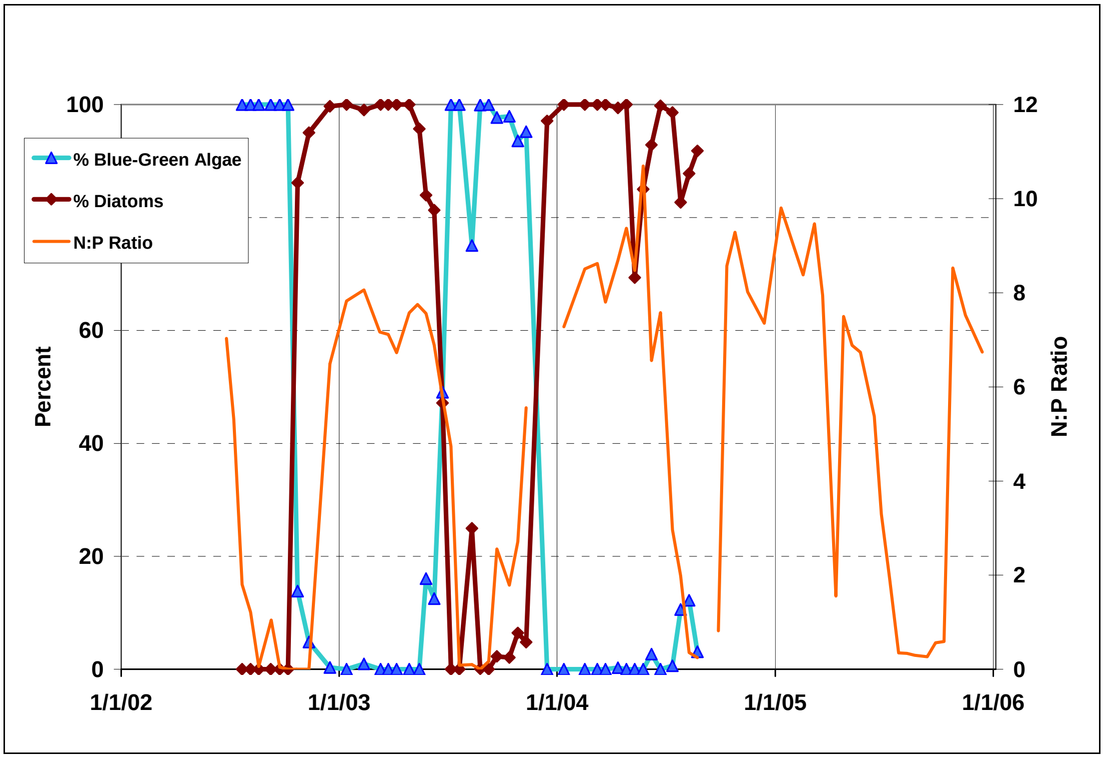

Figure 51. Relationship Between N:P Ratios and Algae

Throughout the year, changes in algal growth can be tied to other changes in the reservoir. Starting in August and September, the N:P ratios are typically low. Inorganic nitrogen concentrations are at their lowest (Figure 52).

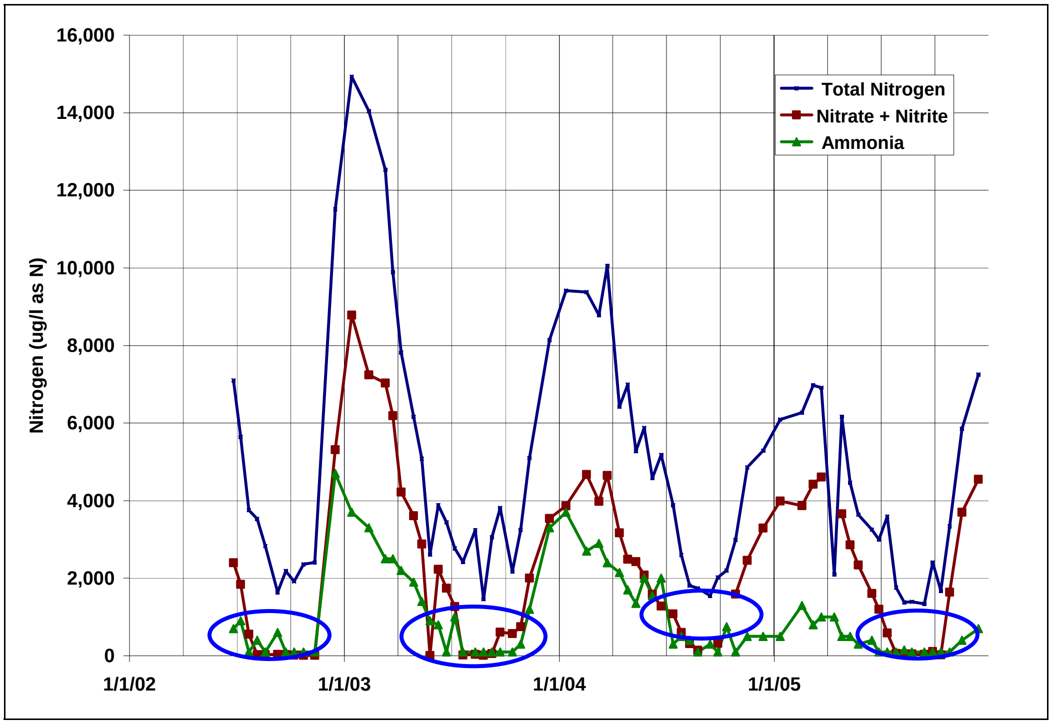

Figure 52. Inorganic Nitrogen Concentrations in Barr Lake

Then, in the late fall, there is an increase in nutrient loading to Barr Lake via the Burlington-O'Brian canal (Figure 53). This is the beginning of the fill season for the reservoir. Also, starting in November, the outflow from the reservoir is minimal.

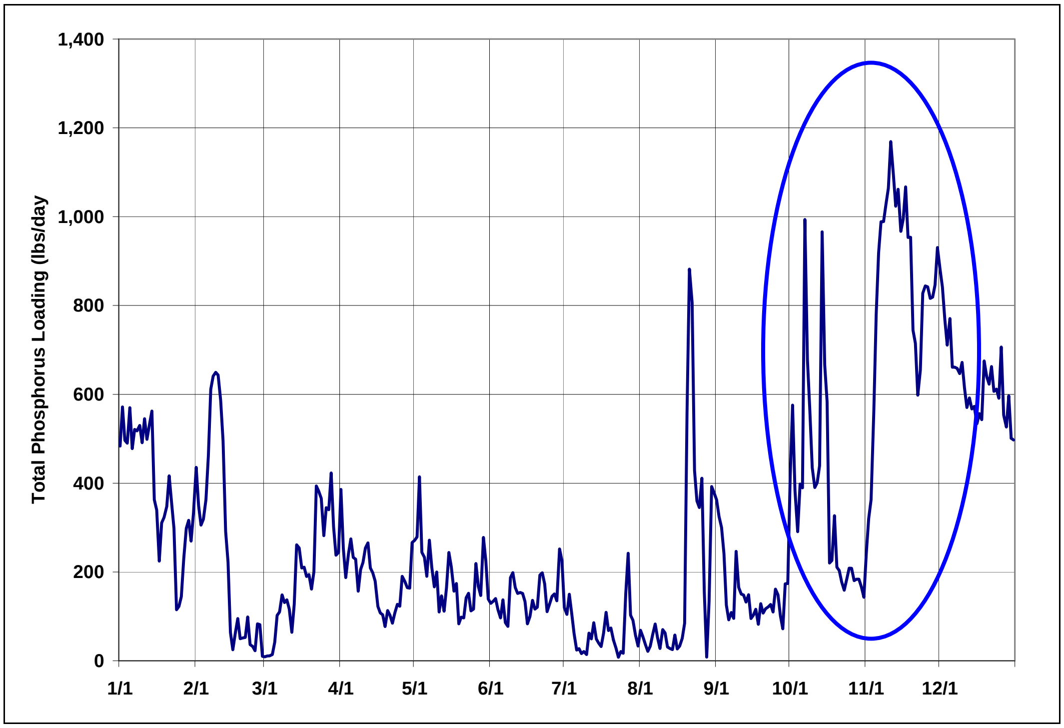

Figure 53. Composite Graph of Total Phosphorus Loading via the Burlington-O'Brian Canal (IY01-IY05)

The reservoir responds with an increase in nutrients (Figure 54) and a shifting N:P ratio.

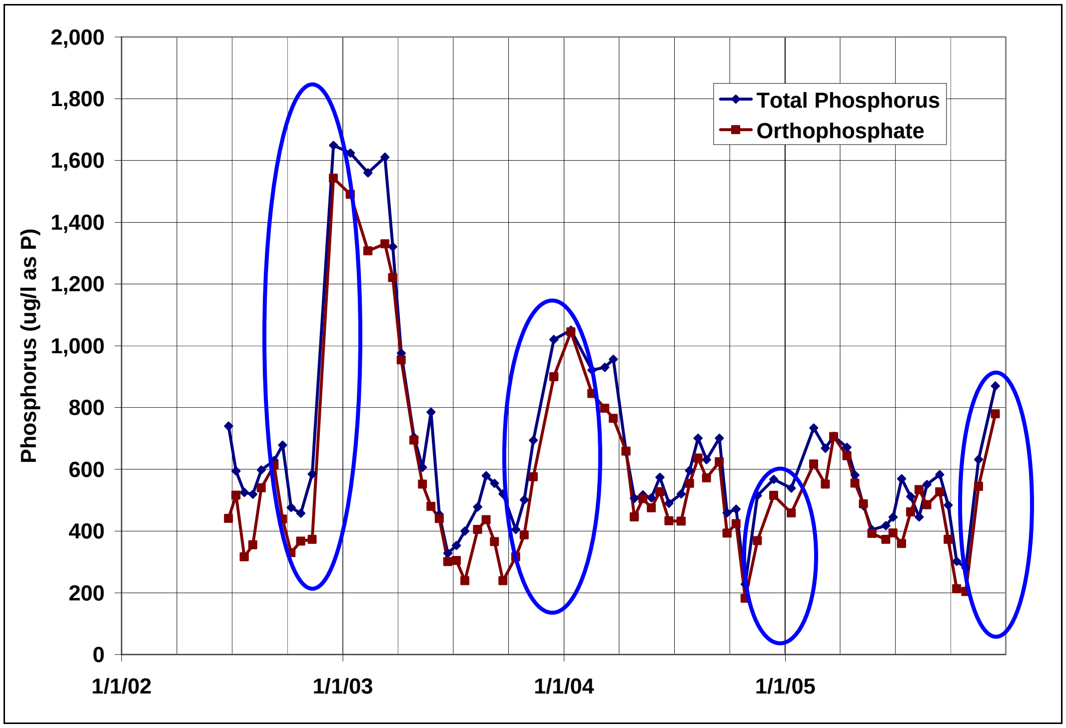

Figure 54. Increases in Late Fall Epilimnetic Phosphorus Concentrations in Barr Lake

As the water warms and the periods of sunlight increase in the spring, diatom growth occurs (Figure 55). Note that the chlorophyll *a* concentrations are about 25 µg/l, which is already indicative of a eutrophic-hypereutrophic system.

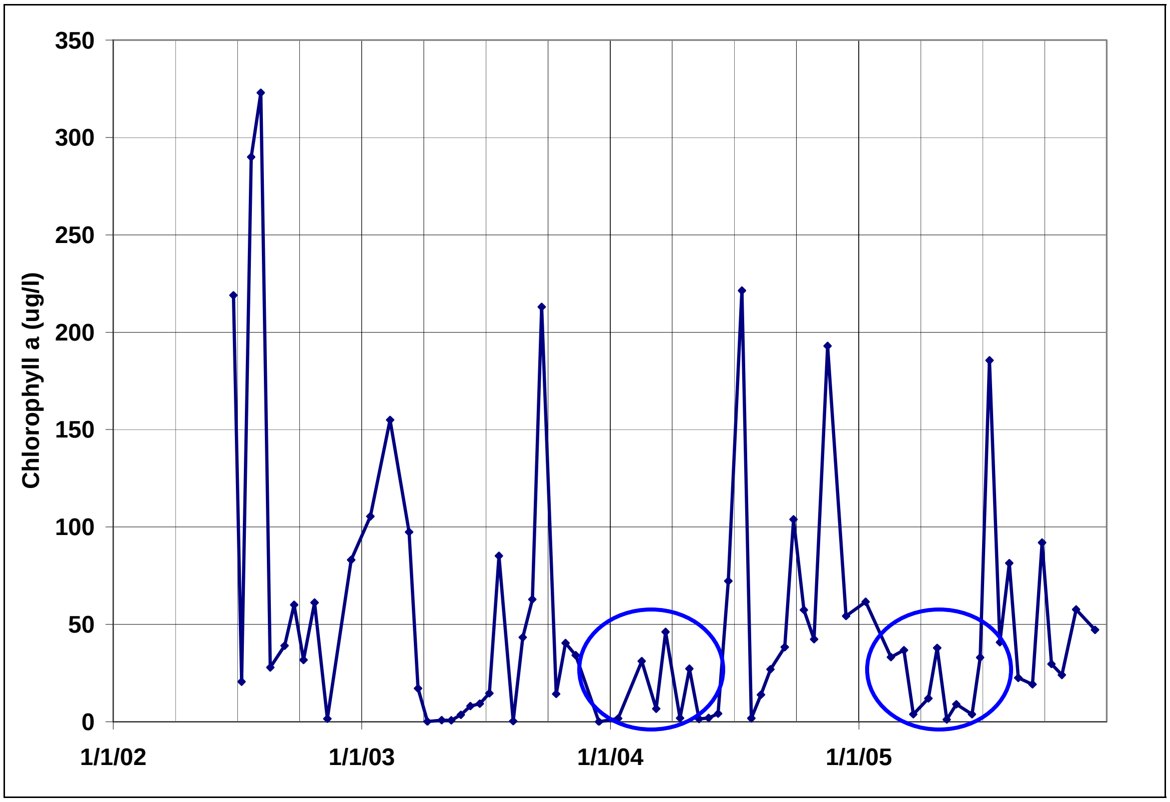

Figure 55. Springtime Diatom Growth in Barr Lake

During the early summer, the N:P ratio decreases due to internal loading and biological uptake. Starting in July, *Microcystis* (a blue-green algae) starts to bloom (Figure 56). This also corresponds to the period when pH values exceed 9.0. *Microcystis* populations quickly decline as the N:P ratio drops to below 1. Although *Microcystis* is a blue-green algae, it does not have the capability to fix nitrogen.

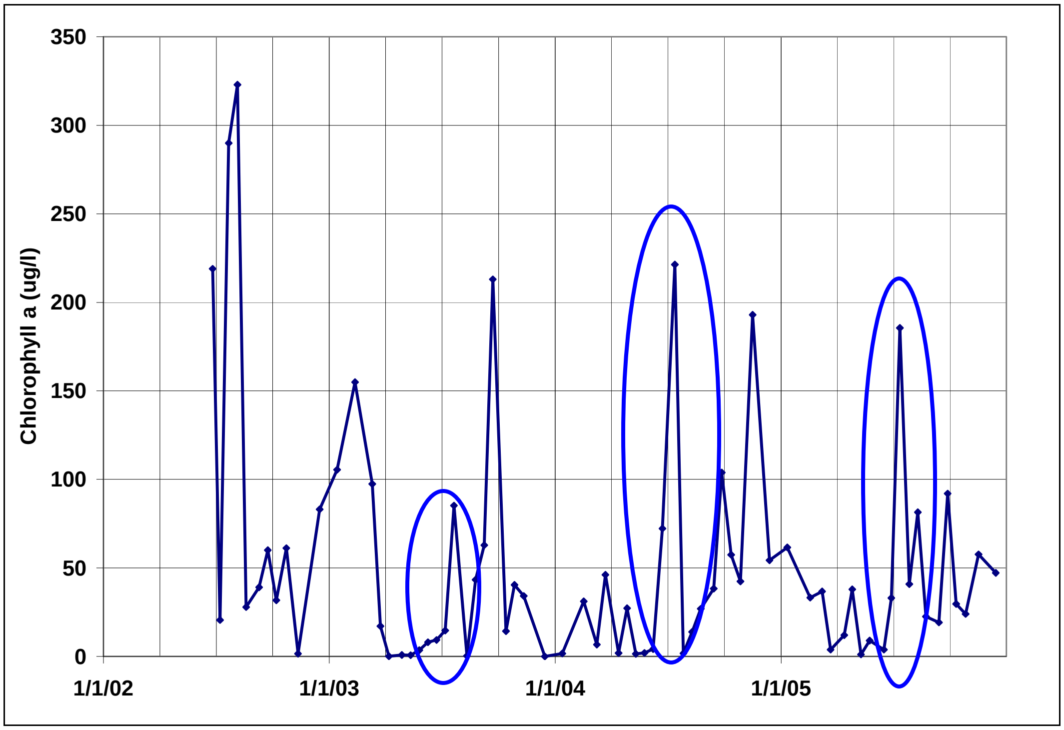

Figure 56. Microcystis Blooms in July

When the light intensity has subsided in September, *Aphanizomenon*, a nitrogen-fixing blue-green algae blooms (Figure 57). *Aphanizomenon* prefers less intense sunlight. At this point, inorganic nitrogen concentrations are very low and the cycle starts over again.

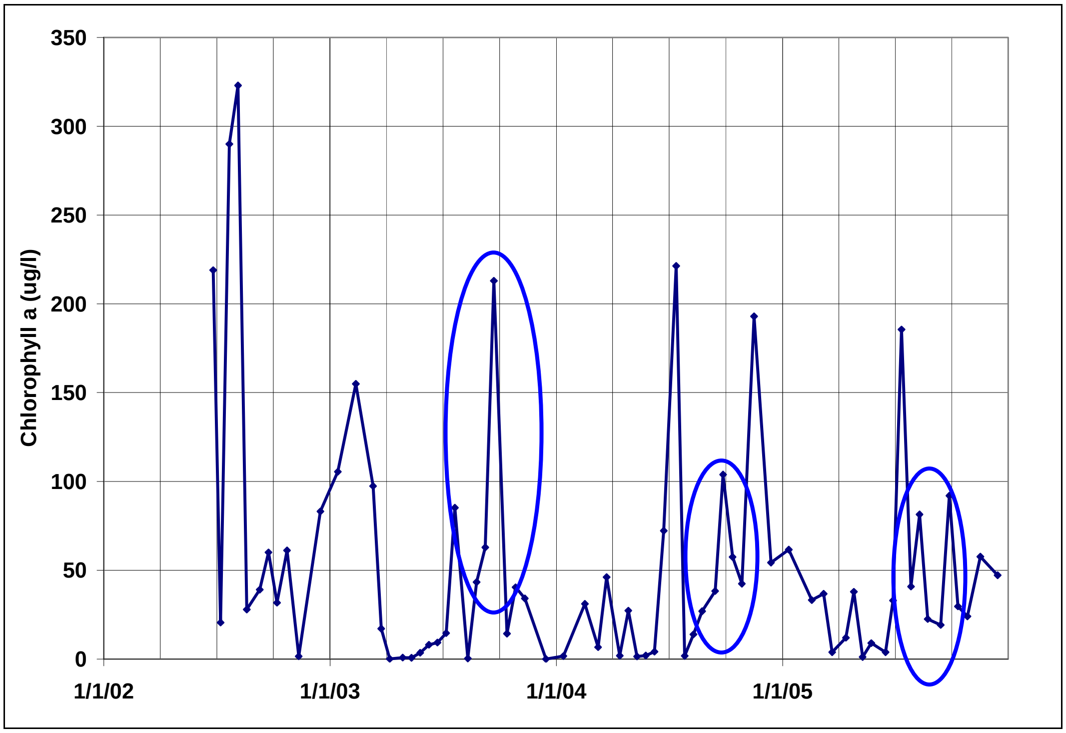

Figure 57. Aphanizomenon Blooms in September

FUTURE MONITORING AND MODELING RECOMMENDATIONS

Based on this study, the following recommendations are made with respect to future monitoring and reservoir modeling:

1. Practical improvements to the accuracy of flow measurements around the reservoir and along the Burlington-O'Brian Canal should be identified by working with D. Helton Consulting.

2. Due to concerns about the accuracy of waste gate flow monitoring, improvements should be made to more accurately conduct a flow balance in the area between the Burlington-O'Brian headgate and the Sand Creek flume. One suggestion is to improve the monitoring at the waste gate itself. Another is to measure the flow at the Burlington-O'Brian Canal headgate.

3. A two-dimensional dynamic model is recommended for Barr Lake due to its fluctuating water surface, its mixing patterns, and the dynamic nature of the reservoir (Hydrosphere, 2005). The recommended reservoir model is CE-QUAL-W2. It has a proven track record and has been applied successfully for several Colorado reservoirs. It also has the capability to simulate pH, multiple algal groups. In addition, it allows one to model internal loading mechanistically.

4. Total organic carbon and dissolved organic carbon should be added to the monitoring program for the reservoir inflow. This will aid in reservoir modeling to differentiate between the autochthonous (originating within the reservoir) and the allochthonous (originating from the inflows) organic carbon.

5. The number of water-quality data records for the west outfall is less than the east outfall, even though it has a higher total flow and it had flow more often than the east outfall (IY00-IY05). The reason for this should be determined.

6. The number of data points per year and the frequency of water-quality data collection for the flows into and out of the reservoir and at the Burlington-O'Brian headgate varies considerable. The reason for this should also be determined.

7. Improvements in the quality of phytoplankton and zooplankton data analysis are suggested.

8. Stormwater water-quality samples should be collected for the Burlington-O'Brian Canal to verify the estimates used in this analysis.

9. A study should be conducted to investigate possible short-circuiting on the Burlington-O'Brian Canal between the MWRD facility and the waste gate. This study assumed a fully mixed condition after the MWRD facility and the waste gate.

CONCLUSIONS

Barr Lake is a shallow hyper-eutrophic reservoir located in the high plains of Colorado. This highly-enriched reservoir has low clarity, low summertime hypolimnetic dissolved oxygen, high chlorophyll *a* concentrations, and high pH. Elevated pH values are a result of photosynthesizing algae. In general, the water quality in the reservoir has improved between IY2003 through IY2005, although nutrient concentrations in the reservoir were unusually high during the drought year of 2002. Analysis of the data indicates specific patterns between reservoir operations, mixing, nutrient loading, in-reservoir nutrient concentrations, N:P ratios, and chlorophyll *a*.

The main source of water supply to the reservoir is the Burlington-O'Brian canal, supplying 94% of its water. This inflow has elevated concentrations of nutrients and these concentrations have increased over the period 1994 to 2005. The nutrient loading analysis indicates that for the period IY2003-IY2005 phosphorus loads to the reservoir on average are approximately 157,000 pounds per year. The corresponding number for nitrogen is 1,317,000 pounds per year. Less than 10% of the nutrient loading is from inflow seepage, internal loading, and precipitation. The areal loading rates to the reservoir are elevated -- 9.8 g/m^2-yr for phosphorus and 80 g/m^2-yr for nitrogen. These values are more than 40 times the values suggested as excessive nutrient loading with respect to lake and reservoir eutrophication (Vollenweider, 1968).

A water balance around the Burlington-O'Brian Canal indicates that 81% of the flow, 52% of the total phosphorus, and 71% of the total nitrogen comes from the South Platte River diversion. The MWRD facility accounts for 11% of the flow, 35% of the total phosphorus, and 22% of the total nitrogen.

The water quality of Barr Lake is similar in some respects to several other local plains reservoirs. Chlorophyll *a* concentrations in Prospect Reservoir and Horse Creek Reservoir are significantly higher than in Barr Lake.

REFERENCES

Beutel, M.W. 2001. Oxygen consumption and ammonia accumulation in the hypolimnion of Walker Lake, Nevada. Hydrobiologia 466:107-117.

Beutel, M.W. 2003. Managing Sediment-Water Interface Processes in Lakes & Reservoir to Improve Water Quality. Presentation 10/27/03 at University of California, Merced.

Bostrom, B., J.M. Andersen, S. Fleischer, and M. Jansson. 1988. “Exchange of phosphorus across the sediment-water interface. Hydrobiologia 170:229-244.

Brown and Caldwell. 1998. Barr Lake Joint Water Quality Study. Technical Memorandum. Prepared for the City of Aurora, Farmers Reservoir and Irrigation Company, Metro Water Reclamation District, and Denver Water. August 12, 1998.

Carlson, R.E. and J. Simpson. 1996. Trophic state. IN: A Coordinator’s Guide to Volunteer Lake Monitoring Methods. North American Lake Management Society.

Chapra, S.C. 1993. Professor and Louis Berger Chair, Tufts University. Personal communication with J.M. Boyer, AMEC Earth & Environmental (formerly Hydrosphere).

Chapra, S.C. 1997. Surface Water-Quality Modeling. McGraw-Hill.

Chapra, S.C. 2005. Professor and Louis Berger Chair, Tufts University. Personal communication with J.M. Boyer, AMEC Earth & Environmental (formerly Hydrosphere). October 7, 2005.

Dorsch, J. 2004. Metro Wastewater Reclamation District. EXCEL file ‘Final FRICO Templates 2-11-2004.xls. Sent to J.M. Boyer, AMEC Earth & Environmental (formerly Hydrosphere) via email. February 26, 2004.

Effler, S.W. et al. 1996. Chemistry. IN: Limnological and Engineering Analyses of a Polluted Urban Lake. Steven W. Effler, Editor. Springer-Verlag New York, Inc.

Environmental Protection Agency. 1977. Report on Barr Lake, Adams County Colorado. EPA Region VIII. Working Paper No 766. July 1977.

Environmental Protection Agency. 1998. Guidance for Data Quality Assessment: Practical Methods for Data Analysis. EPA QA/G-9. QA97 Version. EPA/600/R-96/084. January 1998.

Environmental Protection Agency, 2000, Guidance for Data Quality Assessment, Practical Methods for Data Analysis, EPA QA/G-9, QA00 Version

Gilbert, R.O. 1987. Statistical Methods for Environmental Pollution Monitoring. John Wiley & Sons, Inc.

Helton, D. 2007. D. Helton Consulting, LLC. Personal communication with R. Blair Hanna, AMEC Earth & Environmental (formerly Hydrosphere). July 19, 2007.

Helton, D. 2008. D. Helton Consulting, LLC. Personal communication with R. Blair Hanna, AMEC Earth & Environmental (formerly Hydrosphere). April 18, 2008.

Hem, J.D. 1992. Study and Interpretation of the Chemical Characteristics of Natural Water. 3rd Edition. U.S. Geological Survey Water-Supply Paper 2254.

Hydrosphere Resource Consultants. 2005. Evaluation of Approaches and Tools - Draft. Barr / Milton Watershed Project. Submitted to the Barr Lake & Milton Reservoir Watershed Association.

Keen, W.H. and J. Gagliardi. 1981. Effect of brown bullheads on release of phosphorus in sediment and water systems. Prog. Fish-Cult. 43:183-185.

Kronvang, B., J. Hezlar, P. Boers, J.P. Jensen, H. Behrendt, T. Anderson, B. Arheimer, M. Venohr, and C.C. Hoffmann. 2004. Nutrient Retention Handbook. Software Manual for EUROHARP-NUTRET and Scientific review on nutrient retention. EUROHARP report 9-2004. NIVA report SNO 4878/2004. Oslo, Norway, 103 pp.

Leonard Rice Engineers. 2005. Task 5 – Key Structure Operating Memorandum – Burlington, FRICO–Barr, and Henrylyn Systems. SPDSS Memorandum Final. Prepared for Ray Alvarado and Ray Bennett. March 21, 2005.

Lewis, W.M. and J.F. Saunders. 1990. Present and Future Water Quality and Aquatic Life in Barr Lake and Beebe Draw. Prepared for Jonathan Jones, Wright Water Engineers.

Livingstone, D.A. 1963. Chemical composition of rivers and lakes. Data of geochemistry (6th edition): U.S. Geological Survey Professional Paper 440-G. p. G1-G64.

Lundt, S. 2003. Metro Wastewater Reclamation District. EXCEL file ‘Metro Wastewater 1979.xls’. Sent to J.M. Boyer, AMEC Earth & Environmental (formerly Hydrosphere) via email. December, 22, 2003.

Lundt, S. 2004. Metro Wastewater Reclamation District. EXCEL file ‘Barr Phyto.xls’. Sent to J.M. Boyer, AMEC Earth & Environmental (formerly Hydrosphere) via email. December 1, 2004.

Lundt, S. 2005. Metro Wastewater Reclamation District. EXCEL file ‘Sediment Survey.xls’. Sent to J.M. Boyer, AMEC Earth & Environmental (formerly Hydrosphere) via email. May 4, 2005.

Lundt, S. 2006a. Metro Wastewater Reclamation District. EXCEL file ‘Barr.FRICO Storet Dataset.2005.xls’. Sent to J.M. Boyer, AMEC Earth & Environmental (formerly Hydrosphere) via email. April 3, 2006.

Lundt, S. 2006b. Metro Wastewater Reclamation District. Personal communication with J.M. Boyer, AMEC Earth & Environmental (formerly Hydrosphere). April 17, 2006.

Lundt, S. 2006c. Metro Wastewater Reclamation District. Personal communication with J.M. Boyer, AMEC Earth & Environmental (formerly Hydrosphere). April 17, 2006.

Lundt, S. 2006d. Metro Wastewater Reclamation District. EXCEL file 'Metro.Barr.Milton.Reservoir data 2002.2005.05-01-06 correctionsxls.xls'. Sent to J.M. Boyer, AMEC Earth & Environmental (formerly Hydrosphere) via email. May 1, 2006.

Lundt, S. 2006e. Metro Wastewater Reclamation District. EXCEL file ''Metro Pumping Flows.xls'. Sent to J.M. Boyer, AMEC Earth & Environmental (formerly Hydrosphere) via email. June 14, 2006.

Lundt, S. 2007a. Metro Wastewater Reclamation District. Personal communication with J.M. Boyer, AMEC Earth & Environmental (formerly Hydrosphere). August 2, 2007.

Lundt, S. 2007b. EXCEL file 'Metro Effluent WQ data.1994-2007.xls'. Sent to J.M. Boyer, AMEC Earth & Environmental (formerly Hydrosphere) via email. August 2, 2007.

Mountain River Associates. 1995. Water Quality in the Barr Lake – Burlington Canal System. Submitted to The Farmers Reservoir and Irrigation Company. November 1995.

Nurnberg, G.K. 1987. A comparison of internal phosphorus loads in lakes with anoxic hypolimnia: Laboratory incubation versus in situ hypolimnetic phosphorus accumulation. Limnol. Oceanogr. 32(5):1160-1164.

Nurnberg, G.K. 1988. Prediction of phosphorus release rates from total and reductant-soluble phosphorus in anoxic lake sediment. Can. J. Fish. Aquat. Sci. 45: 453-462.

Rink, L. 2007a. Mile High Wetlands Group. EXCEL sheet 'Copy of 06-07-07 BL-MR Data 1985-2005.xls'. Sent to J.M. Boyer, AMEC Earth & Environmental (formerly Hydrosphere) via email. June 8, 2007.

Rink L. 2007b. Mile High Wetlands Group. EXCEL sheet 'Laurie'sBarrWaterBalance_060707.xls'. Sent to J.M. Boyer, AMEC Earth & Environmental (formerly Hydrosphere) via email. June 8, 2007.

Rink, L. 2008. Mile High Wetlands Group. Personal communication with J.M. Boyer, AMEC Earth & Environmental (formerly Hydrosphere). May 9, 2008.

Scheider, W.A., Moss, J.J., and Dillon, P.J. 1979, Measurement and uses of hydraulic and nutrient budgets—Proceedings, national conference on lake restoration, Minneapolis, Minnesota, August 22-24, 1978: U.S. Environmental Protection Agency Report EPA 440/5–79–001, p. 77–83.

Smith, G. 2004. U.S. Geological Survey. Text file 'tainterdvs'. Sent to J.M. Boyer, AMEC Earth & Environmental (formerly Hydrosphere) via email. May 7, 2004.

Smith, G. 2008a. U.S. Geological Survey. Personal communication with R. Blair Hanna, AMEC Earth & Environmental (formerly Hydrosphere), via email. April 24, 2008.

Smith, G. 2008b. U.S. Geological Survey. Text file 'tainter_dvs'. Sent to R. B. Hanna, AMEC Earth & Environmental (formerly Hydrosphere) via email. April 24, 2008.

Sprague, L.A. 2002a. Nutrient Dynamics in Five Off-Stream Reservoir in the Lower South Platte Basin, March - September 1995. U.S. Geological Survey, Water-Resources Investigations Report 02-4142.

Sprague, L.A. 2002b. What happens to nutrients in offstream reservoirs in the lower South Platte River Basin? U.S. Geological Survey, Fact Sheet 044-02. September 2002.

Tri-County District Health Department. 1975. Barr Lake Water Quality Study 1975.

Van Royen, J. 2004. Personal communication with J.M. Boyer via email. March 1, 2004.

Vollenweider, R.A. 1968. Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters, With Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication. OECD Report No. DAS/CSI/68.27. Paris. OECD.

Wetzel, R.G. 2001. Limnology: Lake and River Ecosystems. 3rd Edition. Academic Press.