Abstract

The Red Lake Watershed District conducted a study of the Good Lake Impoundment water quality from April 1997 to May 1999, which was soon after its completed construction in 1995. Mass balance budget methods were used to determine the effect of the shallow impoundment on nutrient and solids parameters. In general, water quality was worse downstream of the impoundment, with dissolved oxygen problems being the most significant issue. During late winter months in 1999, both the inflow and the impoundment pool had low, near anoxic, dissolved oxygen levels (0.15 to 0.6 mg/L).

Key Word List

Minnesota
Shallow Impoundment
Water Quality
Hydrologic Budget
Mass Balance
Red Lake Watershed District
Red Lake Indian Reservation

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Acknowledgements

This study was funded through a cooperative effort between the Red Lake Watershed District (RLWD), Thief River Falls, MN, and the Red River Watershed Management Board (RRWMB), Ada, MN, each contributing 50%.

HDR Engineering, Inc., Minneapolis, MN, provided the study design.

Ryan Odenbach (Water Quality Technician) managed the data collection and authored this report. David C. Lanning P.E. (Administrator/Engineer) provided report editing.

Other RLWD staff involved in data collection included Loren Sanderson (Engineering Technician), Gary Lane (Engineering Technician), Matt Lemoine (Engineering Technician), Maggie Leach (Water Quality Technician), Jason Haugen (Summer Worker) and Ryan Aamot (Summer Worker).

Houston Engineering, Inc., Minneapolis, MN, provided development and report of the hydrologic data.

Executive Summary

The Preliminary Study Design for this study identified specific technical goals. The goals include:
1) Determining physical and chemical characteristics of the inflow, pool and outflow;
2) Estimation of the hydrologic budget by measuring or estimating the amount of precipitation, surface inflow, surface outflow and evaporation;
3) Determine mass balances for total phosphorus, total nitrogen, total solids and total suspended solids, and estimate the removal efficiency of the impoundment on an annual basis;
4) Obtain information about the stratification dynamics of the impoundment;
5) Use an adjacent ditch system as a "control", allowing comparison of water quality between unimpounded and impounded ditch systems

These goals were completed as follows:
1) To a certain extent, physical and chemical characteristics of the inflow, permanent pool, and outflow have been determined (Deutschman and Erickson, 1999);
2) A preliminary hydrologic budget for 1998 has been developed;
3) Mass balances for the water quality parameters listed above have been developed for part of 1998;
4) No stratification was found, due to the shallow depth and growth of vegetation in the impoundment;
5) Water quality measurements were taken on an adjacent unimpounded ditch system, designated "Control Ditch", but flow measurements were not obtained. A comparison of water quality on the adjacent ditch system with the Good Lake

Impoundment was not made. The water quality data for the adjacent ditch system can be found in Appendix A.

Conclusions drawn from this report include the following:

- According to the mass balances, the outlet water was degraded in quality compared to the inlet;

- The impoundment pool and inlet ditch were anoxic during ice cover periods with corresponding higher levels of many measured parameters.

Recommendations from this report dealing with impoundment management include the following:

- Outlet structures on shallow impoundments should be developed which ensure thorough mixing with air. This will help maintain an some level of dissolved oxygen and lessen detrimental effects on downstream surface water.

- Improved management of impoundments during certain critical times, such as in late winter, will ease impacts on aquatic life in the downstream rivers;

- Groundwater may play a significant role in water quality in low flow periods and should be taken into account.

Introduction and Project Overview

Little quantitative information is available concerning the potential water quality effects associated with impoundments in the Red Lake Watershed District in northwestern Minnesota (Figure 1). The purpose of this study is to provide a basic understanding of the effects of a new impoundment on downstream water quality and to estimate the annual retention or release of solids and nutrients using a mass budget method.

The Good Lake Impoundment (Figure 2) was constructed between 1989 and 1995. It is a multipurpose project that can be characterized as an on-channel, ungated structure with a permanent pool and a flood pool. It consists of 8.8 miles of dike, ranging in height from 3 to 8.5 feet in two unorganized townships (T152N, R38W and T153N, R38W) in Clearwater and Beltrami counties within the Red Lake Indian Reservation. Additional impoundment morphological information is found in Table 1. This location is approximately 17 miles southeast of the City of Goodridge, Minnesota. The sources of water coming into the impoundment are the interception of overland flow and ditch systems entering from the north and east. The outlet structure for the impoundment is located in the southwest quarter of Section 5, T152N, R38W, and discharges into a ditch system which outlets into the Red Lake River. Impoundment operation is a cooperative effort between the RLWD and the Red Lake Band of Chippewa.

Water quality samples were collected from April 1997 until May 1999. Flow information was collected during ice-free periods in 1997 and 1998. Due to budgetary constraints the study had to be halted in the spring of 1999 even though the Preliminary Study Design specified data collection to continue on a limited basis until the impoundment reached a stable state, estimated two to four years.

RLWD staff participation in this study included the installation of flow monitoring equipment, stream gaging, surveying, collection and analysis of water quality samples, some reduction of hydrologic data, summarization of the water quality information and final report generation. Houston Engineering, Inc. used the information collected by RLWD staff to develop rating curves and the hydrologic budgets for the study. The firm determined the methods used to develop the hydrologic data including the hydrologic budgets, some perspective relative to the accuracy of the hydrologic budgets and recommendations relative to the need for additional hydrologic monitoring.

Figure 1. Vicinity Map

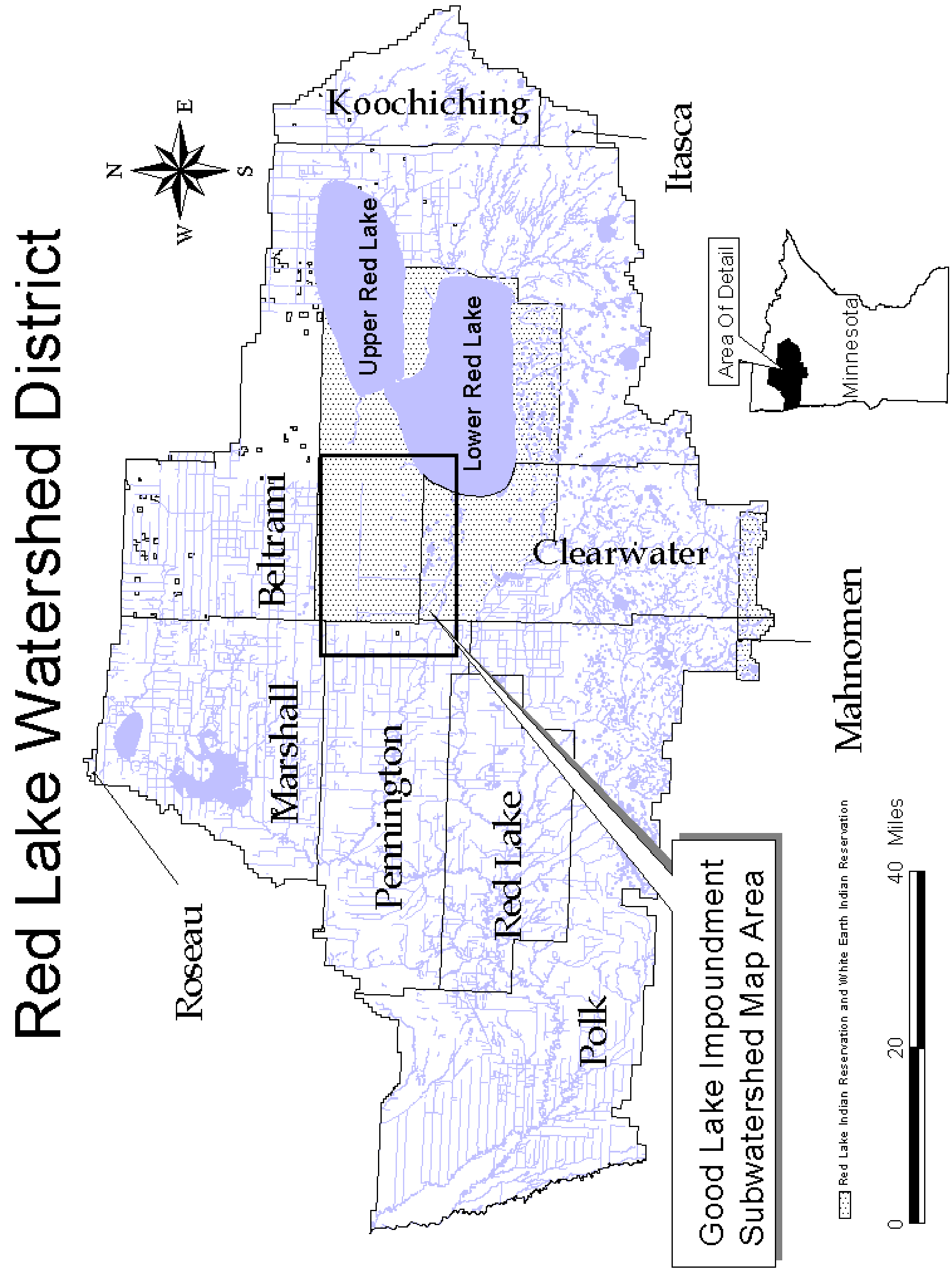


Figure 2. Good Lake Subwatershed Area

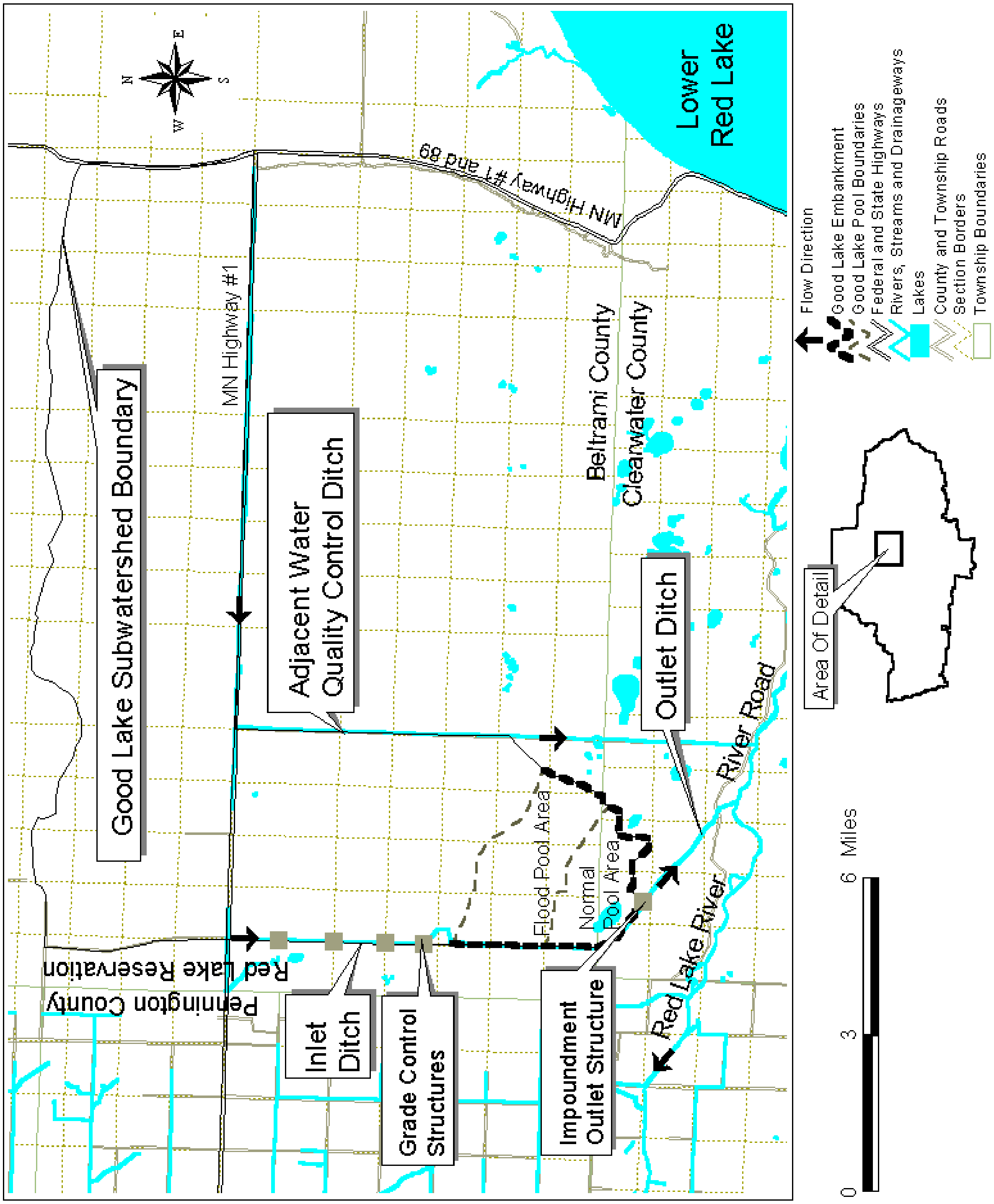


Table 1. Good Lake Impoundment Morphometry Information

Contributing Drainage Area (square miles)	81.5
Normal Pool Surface Area (acres)	1,800
Normal Pool Mean Depth (feet)	1.8
Normal Pool Depth Range (minimum – maximum in feet)	0 to 8
Flood Pool Surface Area (acres)	4,780
Flood Pool Mean Depth (feet)	2.8
Flood Pool Storage (acre-feet)	13,100
Flood Pool Depth Range (minimum – maximum in feet)	0 to 11.1
Draw-down Time Once Full (days)	Variable
Flood Pool to Normal Pool (days)	68
Normal Pool to Empty (days)	23.5
Fall Draw-down (Y/N)	Yes

Methods

Hydrological Methods

Hydrologic budgets for Good Lake includes: a) surface water inflow/outflow; b) evaporation; c) precipitation; d) change in lake storage; and the e) groundwater inflow/outflow.

a) RLWD staff measured the depth of water, using transducers and data recorders, above stop logs and rock weirs. The weirs served as the primary flow control structures in the Good Lake Impoundment system. In order to calculate the surface water inflow and outflow, a specific weir equation was used to convert the measured depth to a flow. The specific weir equation was determined by varying a weir coefficient, values from 1.0 to 3.3, depending on the roughness of the weir.

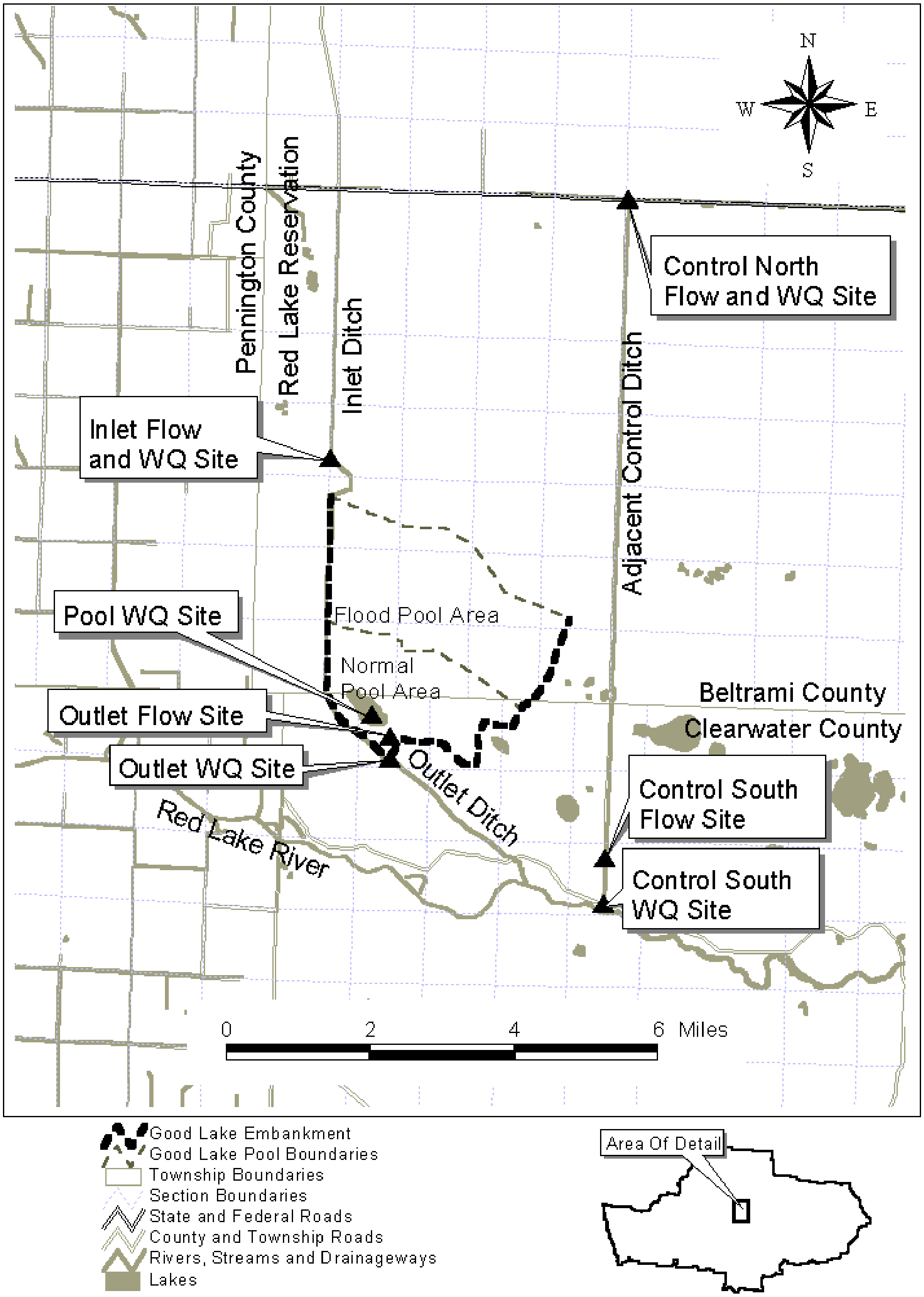
   Stage measuring instruments were installed at four sites (Figure 3):
   1) above the grade transition rock weir on the inlet channel drainage ditch (designated Good Lake Inlet);
   2) adjacent to a nesting island near the outlet structure (designated Good Lake Outlet);
   3) near a bridge over the adjacent ditch on Minnesota State Highway #1 (designated Control North);
   4) upstream of the River Road on the adjacent ditch (designated Control South).

   Runoff coefficients used in conjunction with assumed rainfall data were utilized to determine surface runoff for the ungaged sections of the watershed. This method was also applied to periods without recorded water level stages within the primary inflow channel (Deutschman and Erickson, 1999).

b) Evaporation was estimated using the mean annual lake evaporation rate provided by the Soil Conservation Service Hydrology Manual. (Deutschman and Erickson, 1999)
c) Rainfall data was provided by the Minnesota State Office of Climatology Volunteer Network, since rain gages were not set up within the watershed. (Deutschman and Erickson, 1999)
d) The net change in impoundment storage was assumed to be negligible, since no independent measurements of impoundment stage were obtained.
e) Groundwater inflow/outflow was assumed to be the difference between the calculated and mean inflows and outflows of the impoundment. Because groundwater inflow/outflow was not actually measured, the calculated groundwater inflow/outflow incorporates this error term.

The hydrological information is presented in two ways, an annual water budget basis for 1998 and a calculated hydrograph for the particular period from April to August 1998. The accuracy and error of each estimation is discussed in the "Quality and Limitations of Data" section later in this report.

Figure 3. Good Lake Flow and Water Quality Monitoring Sites



Water Quality Methods

Water quality samples were collected from five locations. Three corresponded to the stage measurement sites listed above: Good Lake Inlet, Control North and Control South. The measurements on the outflow from Good Lake Impoundment were taken on the outlet structure culvert. The other site was located in the deepest part of the impoundment pool which was designated Good Lake Pool (Figure 3).

Water quality parameters included:

- total phosphorus;*
- orthophosphorus;*
- ammonia;*
- total kjeldahl nitrogen;*
- nitrates + nitrites;*
- alkalinity;
- chemical oxygen demand;*
- dissolved oxygen;
- pH;
- specific conductance;*
- total dissolved solids;*
- total suspended solids;*
- turbidity;
- water temperature.

(* - depicts parameters used to determine mass balances)

The parameters listed above display water quality characteristics of the Good Lake Impoundment. Laboratory testing of total dissolved solids measurements was determined during some of the sampling events. During the remaining sampling events total dissolved solids measurements were found by multiplying the specific conductance measurement by a coefficient of 0.68. This coefficient was found by plotting values of existing laboratory measurements of total dissolved solids and finding the slope of the line (coefficient used in Hydrolab, 1997) Secchi disk, chlorophyll-a and dissolved oxygen/water temperature profiles were taken at the in-pool site, to try to determine trophic status of the impoundment.

The "Standard Operating Procedures for Field Samplers" manual from the RLWD (SOP, 2000) was written after this study and, with a few minor exceptions, describes the methods used for collection and analysis of water quality samples. During 1997, the laboratory analysis was performed for ammonia, total kjeldahl nitrogen, nitrates + nitrites, orthophosphorus, total phosphorus, chemical oxygen demand, total suspended solids and alkalinity at the water quality laboratory at the University of Minnesota Crookston (UMC). During 1998, lab analysis of chemical oxygen demand was performed there. Analysis of the remaining parameters in 1998 was performed by RMB Environmental Laboratories, Inc. in Detroit Lakes, MN. Both laboratories were certified by the Minnesota Department of Health. Both also had quality assurance/quality control

(QA/QC) procedures outlined in their separate QA/QC manuals. No statistical difference between the labs was found within the 95% level of confidence.

Water quality and calculated flow data was entered on Excel spreadsheets, then formatted for entry into the FLUX program (Walker, 1996). FLUX provides screening for outliers, which were deleted from the analyzed data set. Measurements found to be below detectable limits (BDL) were set to values of half the reporting limit (FLUX information found in Appendix B).

Results

Hydrologic Results

The principal sources of water to the Good Lake Impoundment were found to be precipitation and surface runoff. The surface runoff was channeled to the impoundment through a drainage ditch, which was measured at the inlet to the impoundment and results from a drainage area of 48.6 square miles. Another component of surface runoff results from the ungaged watershed directly adjacent to the impoundment, from a drainage area of 32.9 square miles. The annual 1998 hydrologic budget of Good Lake is displayed in Table 2. (Deutschman and Erickson 1999)

Assuming there was no change in the storage of the Good Lake Impoundment throughout 1998, the total outflow volume was therefore equal to the total inflow volume, i.e. 17,500 acre-feet. The predominant losses of water from the impoundment resulted from surface outflow and evaporation. Groundwater outflows and error accounted for the remainder of the total outflow volume. (Deutschman and Erickson, 1999)

Graphical representations of the hydrologic budgets in absolute terms as well as percentages of the total volume of water passing through the hydrologic system are shown (Appendix C). Also included are plots of the surface inflow/outflow hydrographs, as well as the daily rainfall hyetograph representing the impoundment system.

Table 2. Annual (1998) Hydrologic Budget
(Houston Engineering, Inc.)

Hydrologic Budget Element	Inflow		Outflow	
	Volume (acre-feet)	Percent of Total Inflow Volume	Volume (acre-feet)	Percent of Total Outflow Volume
Surface Outflow			10,700	61%
Surface Inflow (Gaged)	11,900	68%		
Surface Inflow (Ungaged)	1,800	10%		
Total Surface Inflow	13,700	78%		
Evaporation			3,900	22%
Precipitation	3,800	22%		
Change in Storage	0	--	0	--
Groundwater and Error			2900	17%

Water Quality Results

Pool Results

The depth of the Good Lake Impoundment is not sufficient for identification of stratification or depth based gradients in the dissolved oxygen profile. The impoundment also contains areas of dense emergent and submergent vegetation. The growth of this vegetation out-competes algae for nutrients. Evidence of this is displayed by secchi disk readings of the Good Lake Impoundment Pool which were clear to the floor of the impoundment. Therefore, trophic state indices, which are based on water clarity and nutrients, were not determined for the Good Lake Impoundment.

Inflow/Outflow (Mass Balances)

The total phosphorus, total nitrogen, total solids and total suspended solids mass balances are reported over the time period from April 9, 1998 to August 31, 1998 when accurate flow monitoring occurred. The mass balances are only reported on the Good Lake outlet and Good Lake inlet sites, and did not include the control ditches, which did not have accurate flow information recorded. For reference, the hydrologic budget for this time period is shown in Table 3. As in Table 2, it is assumed there is no change in impoundment storage and therefore the total inflow volume is assumed to be equal to the total outflow volume.

Table 3. Hydrologic Budget, April 9– August 31, 1998

Hydrologic Budget Element	Inflow		Outflow	
	Volume (acre-feet)	Percent of Total Inflow Volume	Volume (acre-feet)	Percent of Total Outflow Volume
Surface Outflow			7600	70%
Surface Inflow (Gaged)	7600	70%		
Surface Inflow (Ungaged)	1050	10%		
Total Surface Inflow	8650	80%		
Evaporation			2600	24%
Precipitation	2170	20%		
Change in Storage	0	--	0	--
Groundwater and Error			620	6%

Table 4 lists the mass balance for some water quality parameters, which includes amount of load retained or released and whether water quality was improved at the outlet by the impoundment system. Release is defined as the mass load released from storage in the impoundment pool itself and retention as the amount stored in the impoundment pool. The mass load values in Table 4 does not include the mass loading from atmospheric deposition.

The mass balance shows more organic phosphorus, ammonia, organic nitrogen, and suspended solids in the outflow than in the inflow. Only the orthophosphorus load displayed retention by the impoundment pool (11% decrease). The effect of the impoundment on the mass loads of nitrates and nitrites, dissolved solids and chemical oxygen demand were relatively neglible (2% and less).

Table 4. Good Lake Mass Balances*

Parameter	**Inlet Load** lbs/day (lbs/acre-ft)	**Outlet Load** lbs/day (lbs/acre-ft)	**Release** (-)/ **Retention** (+) **Load** lbs/day (lbs/acre-ft)	**Improved Water Quality at Outlet** (Y/N)
Total Phosphorus	3.9 (0.075)	6.8 (0.13)	-2.9 (-0.055)	N
Orthophosphorus	2.7 (0.052)	2.4 (0.046)	0.3 (0.006)	Y
Organic Phosphorus	1.5 (0.03)	4.7 (0.09)	-3.2 (-0.06)	N
Nitrates + Nitrites	1.4 (0.03)	1.4 (0.03)	0	--
Total Kjeldahl Nitrogen	135 (2.6)	188 (3.6)	-53 (-1.0)	N
Ammonia	3.3 (0.06)	5.1 (0.1)	-1.8 (-0.04)	N
Total Nitrogen	136 (2.6)	189 (3.6)	-53 (-1.0)	N
Chemical Oxygen Demand	6,150 (117)	6,020 (115)	130 (2.0)	Y (about 2% difference)
Total Suspended Solids	187 (3.6)	285 (5.4)	-98 (-1.8)	N
Total Dissolved Solids	24,900 (476)	24,700 (470)	200 (6.0)	Y (about 1% difference)
Total Solids	25,100 (480)	25,000 (475)	100 (5.0)	Y (less than 1% difference)

*Values do not include atmospheric deposition.

In comparison to Table 4 mass balances, Table 5 mass balances includes atmospheric deposition values. The atmospheric deposition values were taken from the National Atmospheric Deposition Program results at site MN16 in Itasca County, Minnesota (Appendix D).

With the atmospheric deposition mass added to the inflow mass load: the Good Lake Impoundment pool retained nitrogen during the period from April 9 to August 31, 1998. The mass load of phosphorus is still larger in the outflow than in the inflow. The affect of atmospheric deposition is relatively negligible on the total dissolved solids and total solids mass loads. There is less than a 2% difference between the inflow and outflow mass loads, nearly the same as in Table 4.

Due to the nature of the atmospheric data, individual components of the phosphorus and nitrogen budgets could not be calculated. The atmospheric data was not collected in conjunction with this study and the collection occurred over 100 miles away from the study site. The mass balance budgets with atmospheric data are of unknown accuracy.

Table 5. Good Lake Mass Balances Including Atmospheric Deposition

Parameters	**Inlet Load** lbs/day	**Outlet Load** lbs/day	**Release** (-)/ **Retention** (+) **Load** lbs/day	**Improved Water Quality at Outlet** (Y/N)
Total Phosphorus	4.9	6.8	-1.9	N
Total Nitrogen	201	189	12	Y
Total Dissolved Solids	25,100	24,700	400	Y (1.6% difference)
Total Solids	25,200	25,000	200	Y (less than 1% difference)

Seasonal Variations

Dissolved Oxygen

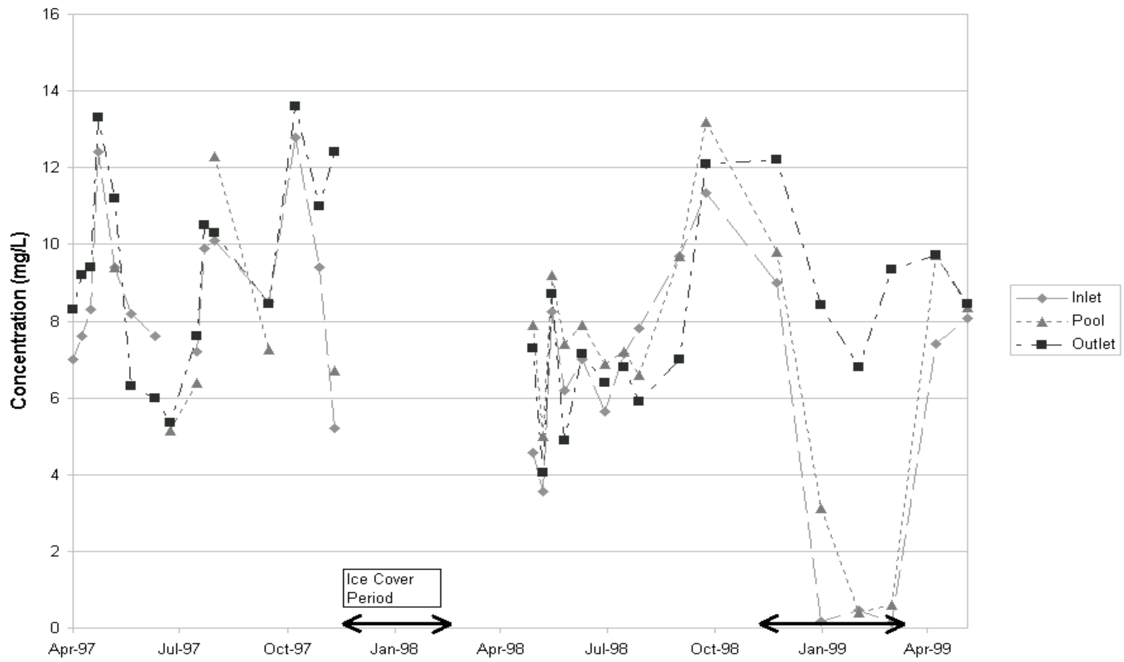
Time series graphs display information collected at the inlet, outlet and pool of the Good Lake Impoundment (Appendices E and F). The most notable feature in seasonal dissolved oxygen levels is the virtually anoxic period in middle to late winter, under ice and snow cover, recorded in 1999 (Figure 4). These conditions correspond to increased levels of total phosphorus, ammonia and total kjeldahl nitrogen. During the same time period, dissolved oxygen levels at the outlet were much higher. Samples from the outlet were taken at the culvert after water spilled over stop logs on the outlet structure, allowing reaeration, particularly in cold temperatures.

Dissolved oxygen levels at the inlet and outlet of Good Lake were in the range of 6 to 8 parts per million during the summer of 1998. Higher levels occurred during the fall and spring (approximately 10 to 13 parts per million) corresponding to lower water temperatures.

Phosphorus Parameters

Levels of orthophosphorus fluctuated during the summer period in 1998 with the inlet and outlet showing similar fluctuations possibly due to rainfall events. Organic phosphorus levels also displayed similar fluctuations, though the levels at the outlet were consistently higher at the outlet than at the inlet. The total phosphorus level also remained higher at the outlet than the inlet. The inlet, outlet and pool displayed a considerable increase in phosphorus levels during the middle to late winter months in 1999.

Figure 4. Good Lake Field Dissolved Oxygen



Nitrogen Parameters
Levels of total kjeldahl nitrogen remained fairly constant throughout the summer of 1998 at the outlet, but at the inlet some fluctuations are noted during the summer, again possibly responding to rainfall events. Ammonia remained at low levels in both the inlet and outlet until the winter months when both the inlet and outlet displayed much higher levels. Total kjeldahl nitrogen also corresponded with a marked increase during the winter months of 1999. Nitrates and nitrites remained near or below minimum detectable limits throughout the study period.

Solids Parameters and Specific Conductivity
Total suspended solids remained at low levels in both the inlet and outlet of Good Lake during the summer of 1998. The levels at the inlet to Good Lake recorded some higher levels during the late winter period and spring of 1999. Specific conductivity levels, which corresponds to the total dissolved solids levels, also show low levels in the spring of 1998 and 1999. However, levels increased throughout 1998 and into 1999 with the highest levels being recorded during the late winter months, but dropped dramatically from March to April of 1999 (while spring snow melt and runoff occurred).

pH
pH at the inlet and outlet of the impoundment remained between 7 and 8 during most of the study period. Although, during the winter of 1999, the pH levels at both sites were below 7. The pH levels in the pool remained between 7 and 8.3 during the monitoring period, with one exception on March 22, 1999 where a level of 6.9 was recorded. This measurement corresponded to near anoxic conditions at the time.

Discussion

The seasonal trends in water quality show a definite lack of oxygen both in the impoundment pool and the inflow into the pool during winter months. This lack of oxygen in the water (and possibly along with lower levels of available light and lower pH) may contribute to release of other chemical parameters such as nitrogen (including ammonia and organic nitrogen) and phosphorus. This may occur through some unknown chemical or biochemical process. Orthophosphate levels also show a definite increase during these anoxic conditions.

Most of the contributing drainage area for the Good Lake Impoundment has peat soils, which may have slow lateral flow of groundwater (Bidwell, Winter and Maclay, 1970). This flow likely continues during ice and snow cover periods in middle and late winter. This may have an impact on the dissolved oxygen levels.

During the study period field observations noted large floating masses of peat and vegetation near the Good Lake outlet structure. The floating masses often clog the Good Lake outlet structure and field personnel have had to remove them (Picture Appendix C). Some of these events were noted on observations taken on June 24 and August 12, 1997 and August 5 and 18, 1998. This action may have some unknown impact on the total suspended solids, phosphorus and nitrogen components of water quality.

Quality/Limitations of Data

The precipitation data used for the Good Lake system was obtained from a rain gage located approximately 24 miles south of the 81.5 square mile watershed (Clearwater County, Township 147, Range 38, Section 6). Because of the distance between the rain gage and this watershed, as well as normal spatial variation in rainfall, it is likely that the recorded rainfall is not completely representative of that within this watershed. Over an annual period, however, it seems likely that the total depth of precipitation recorded at the nearby rain gage will be similar to the actual rainfall which fell within this watershed.

Evaporation was estimated for the Good Lake system using long-term mean annual lake evaporation rates provided by the Minnesota Soil Conservation Service Hydrology Manual. The estimated evaporation rate assumed for the Good Lake system was 25.75 inches per year (Deutschman and Erickson, 1999). Because meteorological conditions were considered average for 1998, it is likely that the assumed annual evaporation rate is representative of the actual annual evaporation rate.

A few factors affected the quality of the estimation of surface inflow and outflow for Good Lake. The first factor was the operation of the Good Lake Impoundment. During 1998 the impoundment operation was maintained within normal levels until early September when the impoundment was quickly drained to a much lower level. The system discharge during this time period was not accurately recorded since the water level fell below the transducer during drawdown.

The second factor was a developing beaver dam immediately downstream of the inflow transducer, submerging the weir slightly. A third factor is segments of missing data resulting from equipment malfunction, etc. The three factors are the significant reasons that the mass balance equations have been estimated only during the time period from April 9 to August 31, 1998. Fourth was the ungaged sections of the this watershed. The Good Lake system had a gaged primary inflow; however, significant portions of the total contributing drainage area was ungaged. Good Lake had 32.9 square miles (approximately 40%) of its total contributing watershed which was ungaged. The ungaged section of the watershed contributes significant uncertainty to the determination of the hydrologic budget. Surface runoff was therefore determined for the ungaged section of the watershed using runoff coefficients and the assumed watershed precipitation data.

Similar problems along with the presence of backwater from the Red Lake River rendered the flow data unusable at the sites on the adjacent ditch (sites control north and control south). Intensive independent impoundment stage data was not collected and this lack of stage data forced an assumption of no change in storage. Groundwater inflow/outflow data was not collected and, therefore, will not be discussed.

A few factors influenced the water quality data and computation of mass balances. The mass balances were obviously affected directly by errors in flow as discussed above. Analysis of water quality samples took place at two laboratories (UMC water quality laboratory during 1997 and RMB Environmental Laboratories, Inc. in 1998). Due to other factors, which could affect water quality measurements from year to year, differences in analysis results from 1997 and 1998 are unknown. Personnel changes at the Red Lake Watershed District resulted in no record of water quality and flow measurements during the winter months of 1998. This data would have given more insight into the seasonal variances, which occur during this time period. The water quality results show a large difference between winter and summer levels and an accurate annual mass balance could not be computed for 1997.

Atmospheric deposition data utilized by this study was collected over 100 miles from the Good Lake system. Mass balance computations, utilizing this information, contain an unknown amount of error. Coefficients of variance (CV) for the calculation methods in determining mass loading of organic phosphorus, total kjeldahl nitrogen and total suspended solids were high (between 0.2 and 0.3, on a scale of 1). For the purposes of this study these values were accepted. CV values in this range point to a need for a more intensive data set to insure accuracy.

Recommendations Developed from this Study

The following recommendations are presented, based on meeting the original technical goals of the project:

- Continuous rain gages should be installed within the contributing drainage area. The gages should be strategically placed to allow for the development of drainage area specific rainfall-runoff relationships. The number of gages needed is approximately one gage per 5 square miles of watershed;

- Because seepage into or out of the impoundment through the peat soils seems to play an important role in the hydrology of Good Lake, monitoring this source of water would decrease the error in the hydrology budget. However, no economical method of study of this groundwater has been suggested;

- Stream gaging should be performed at each location 5-6 times during the ice-free period. The data can be used to adjust the rating curves developed using engineering equations;

- Improved record keeping (in the field) would enhance the ability to reduce and interpret the hydrologic data;

- Flow information should be collected the whole year (ice and ice-free periods) in order to obtain an accurate annual mass balance;

- Analysis of water quality samples should be performed at the same laboratory throughout the study;

- Consistent records of operational changes of the impoundment should be maintained and coordinated with the water quality study.

- Water quality data should be collected above a culvert rather than below due to aeration of water and gas transfer over a weir and through a culvert;

- Include more statistical design of the sampling plan before data collection.

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