Jennie Lake Nutrient Budget

March 2022

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Prepared for:

Jennie Lake Improvement Association
Meeker County, Minnesota
March 2022

Prepared by:

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Table 1. MPCA designated impairment thresholds for water quality parameters by ecoregion. Lake Jennie (red star) falls at the edge of the NCHF Ecoregion and is classified as a shallow lake (see yellow highlight). During 2021 total phosphorus averaged 63 ug/l, chlorophyll a 39 ug/l and Secchi depth 3.7 feet.

Ecoregion	TP (ug/l)	Chl a (ug/l)	Secchi (ft)
Northern Lakes and Forests (NLF) - Lake trout (Class 2A)	< 12	< 3	> 15.7
Northern Lakes and Forests (NLF) - Stream trout (Class 2A)	< 20	< 6	> 8.2
Northern Lakes and Forests (NLF) - Aquatic Rec. Use (Class 2B)	< 30	< 9	> 6.6
North Central Hardwood Forest (NCHF) - Stream trout (Class 2A)	< 20	< 6	> 8.2
North Central Hardwood Forest (NCHF) - Aquatic Rec. Use (Class 2B)	< 40	< 14	> 4.6
North Central Hardwood Forest (NCHF) - Aquatic Rec. Use (Class 2B) Shallow Lakes	< 60	< 20	> 3.3
Western Corn Belt Plains (WCBP) & Northern Glaciated Plains (NGP) - Aquatic Rec. Use (Class 2B)	< 65	< 22	> 3.0
Western Corn Belt Plains (WCBP) & Northern Glaciated Plains (NGP) - Aquatic Rec. Use (Class 2B) Shallow Lakes	< 90	< 30	> 2.3

INTRODUCTION

Limnopro Aquatic Science, Inc. ("we") collected data and estimated nutrient budgets for phosphorus in years 2019 (an exceptionally wet year) and 2021 (an exceptionally dry year) on Jennie Lake. Using the model structure, we were also able to reconstruct potential nutrient conditions over years 2007-2018 and 2020 using historical weather information and flow data in nearby streams as model inputs even though we did not collect data during those same periods on Jennie Lake.

Conditions have been poor enough historically that the MPCA has listed Jennie Lake as an impaired water body with respect to recreational use (Table 1). This means that the MPCA has ruled that people seeking to swim, ski, or recreate in other ways in the lake either are reluctant from using the lake in such a way, or because of associated harmful algal blooms (HABs) it may not be safe. Generally, Jennie Lake has low water clarity, particularly during the summer months; however, 2021 was an exception to this rule as the lake exhibited the best water quality in the historical record of collecting data (Fig. 1).

Water clarity is a function of suspended particles that reflect and scatter sunlight penetrating through the water column. Suspended particles are measured as total suspended solids (TSS), which includes both living (e.g., algae, bacteria, zooplankton) and nonliving (e.g., mud and silt) particles. Nonliving particles get suspended during wind events and high boat traffic in shallow areas, while the living components, particularly algae, grow in the water column when provided sunlight and nutrients. While there is no way to control the impact of wind on the lake, users can help to keep nonliving suspended sediments down by using good judgment and keeping boat speeds low in shallow and nearshore areas.

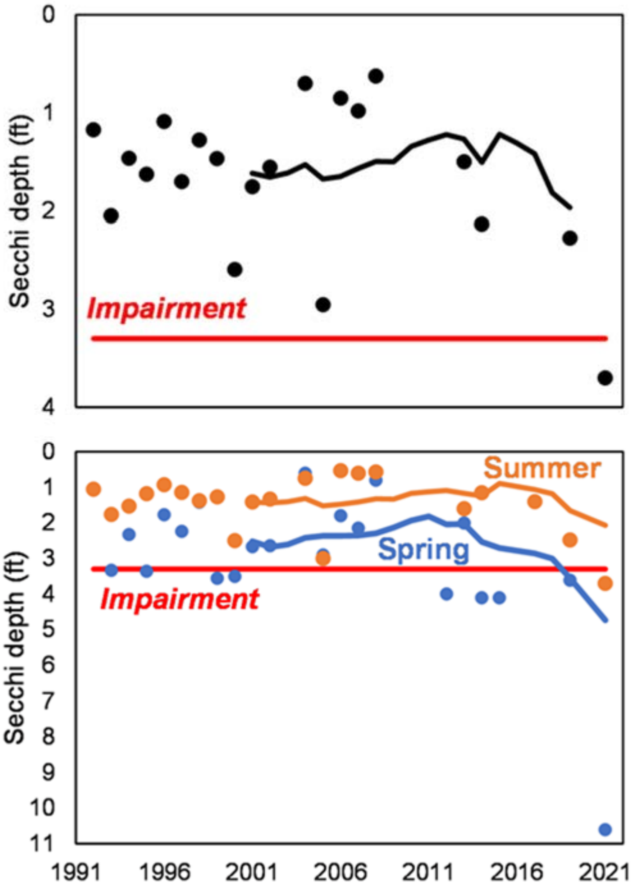


Fig. 1. Water quality as measured by Secchi disk readings in Jennie Lake annually (a) , including the period of June-September, which is what the MPCA uses to measurement impairment and separately (b) for the spring (< 6/21) and summer (>6/21). Historical data were obtained from the MPCA. The impairment threshold is for the NCHF shallow lake ecoregion and trend line is 10-yr moving average, which is what the MPCA uses to judge impairments.

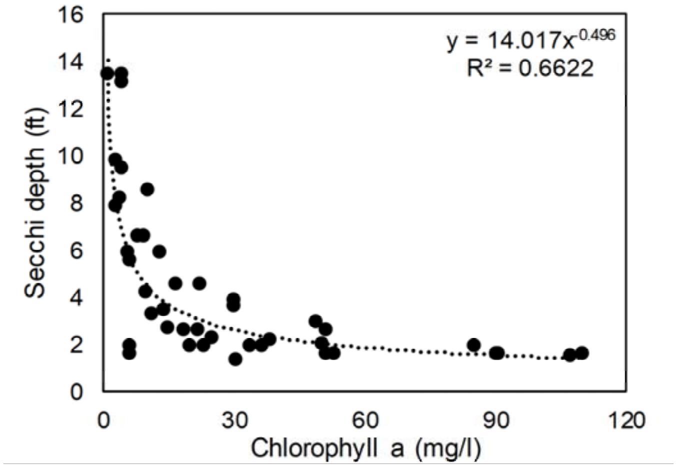


Fig. 2. Regression model showing the contribution of algae to water clarity as measured by Secchi depth for 42 measurements taken between 1981—2021.

This nutrient budget project focuses on the algae contribution to poor water quality. Algae are microscopic plant-like organisms that capture light in chlorophyll molecules and use that as energy to grow. Chlorophyll is proportional to algae biomass and is much easier and much less expensive to measure than directly counting individual algae cells.

We modeled Secchi depth water clarity as a function of chlorophyll with historical data and found over 66% of water clarity to be directly attributable to levels of chlorophyll in the water at any given time (Fig. 2). The remaining variability in Secchi depth water clarity can be attributed to nonmeasured factors such as mud, silt, and normal errors in measurements.

It is important to note that the relationship between Secchi depth and chlorophyll is not linear. Reductions of chlorophyll when concentrations are on the low end of the scale have a bigger impact on Secchi depth water clarity than would reductions at higher chlorophyll levels. For example, a change from 75 to 65 mg/l chlorophyll (10 units) would improve water clarity only by 1 inch while a change from 30 to 20 (10 units) would lead to an improvement of 7 inches. This means that initial efforts to reduce algae through nutrient reduction procedures may not produce large improvements in water clarity but that with persistent and sustained efforts over time, larger impacts will be more likely.

In general, for most lakes, the ultimate driver for high algae concentrations and associated poor water quality are nutrients, primarily phosphorus but sometimes nitrogen. These are said to be “limiting” factors or in highest demand relative to supply. For a limiting factor, we should see that as that factor increases so does the algae that depends on it. Historical data support a relationship for Jennie Lake between chlorophyll and total phosphorus but not necessarily nitrogen (Fig. 3). As phosphorus goes up, algae increase, and water becomes less clear (i.e., “turbid”). While we measured nitrogen during 2019 (but not in 2021), the focus on the report will be on phosphorus given the weak relationship between nitrogen and algae.

The Lake Jennie Improvement Association contracted with Limnopro Aquatic Science, Inc. in 2019 and again in 2021 to construct a nutrient budget as a first step in determining potential actions that can improve water quality. If we can determine major sources of phosphorus input to the lake and change such conditions so that less phosphorus gets into the water column that will reduce algae, that can translate to an increase in water clarity and higher desirability for recreating in the lake.

There are many management techniques that can mitigate phosphorus into the lake, but a first step pri-

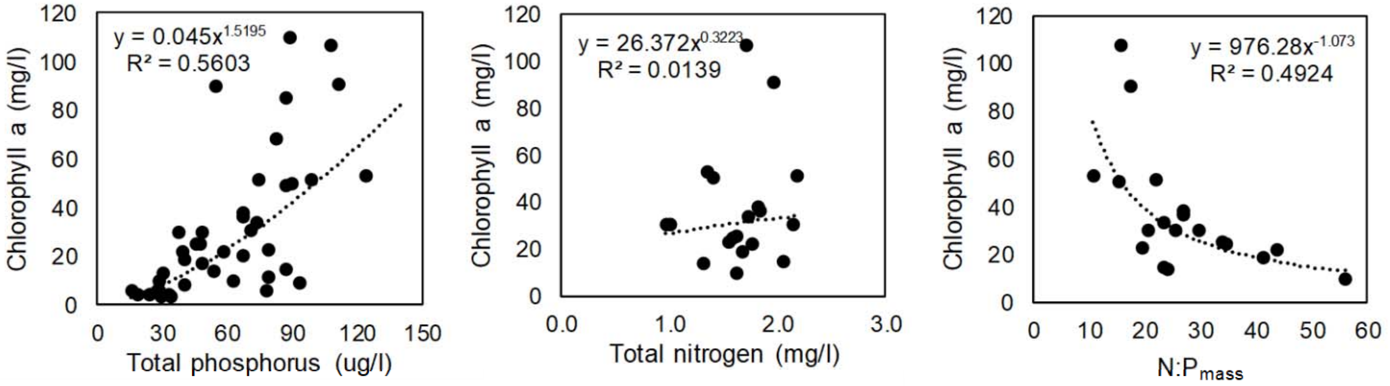


Fig. 3. Relationship between nutrients and algae in Jennie Lake as measured by chlorophyll a. A total of 19 measurements had full complements of phosphorus, nitrogen, and chlorophyll a were used in the analysis came from 1996, 2007, 2008, and 2019.

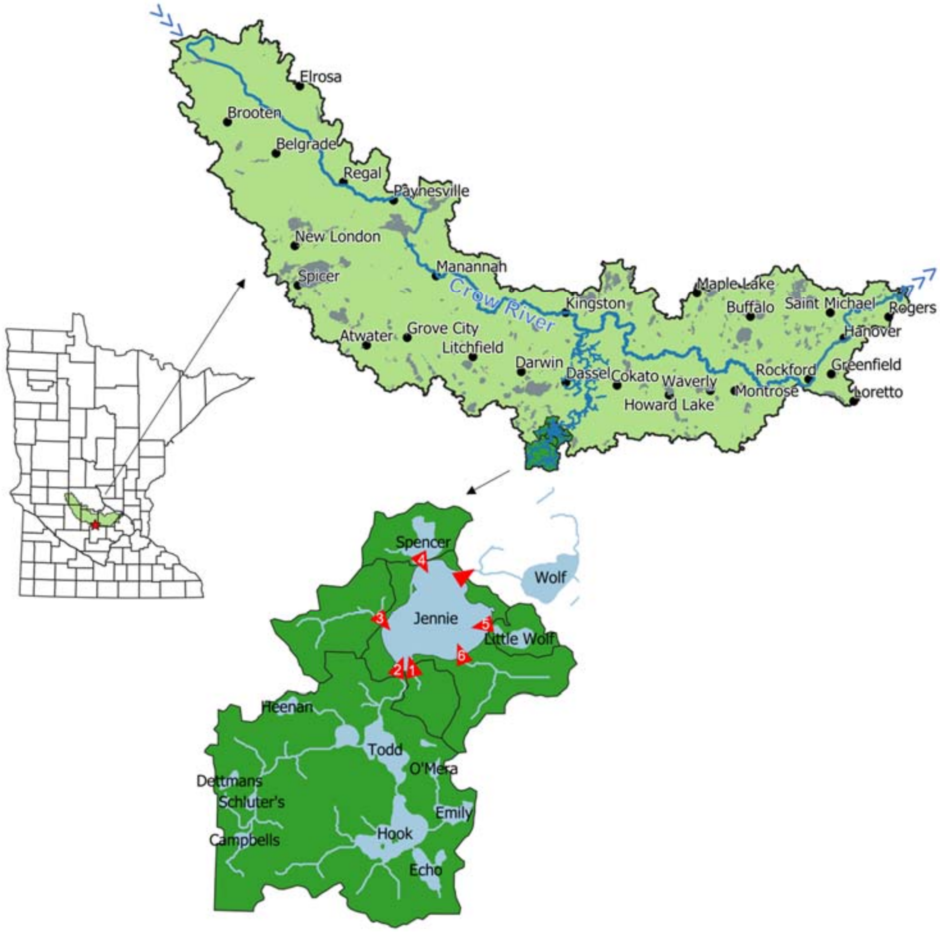


Fig. 4. Location of Jennie Lake within (a) Minnesota, (b) the North Fork Crow River major watershed, and (c) the total watershed area draining to Jennie Lake (i.e., Jennie Lakeshed). Red arrows in subplot c indicate numbered inlets for delineated areas draining to sampled points. The unnumbered arrow indicates the only outlet from the lake.

or to determining management is to determine what sources ought to be targeted. Additionally, many of the methods used to mitigate phosphorus to the lake are beyond the ability of most lake associations to fund and therefore rely on external funding. A sound nutrient budget is a first step at demonstrating to such funders that the lake has done its due diligence in coming up with solutions that have the highest probability of success possible.

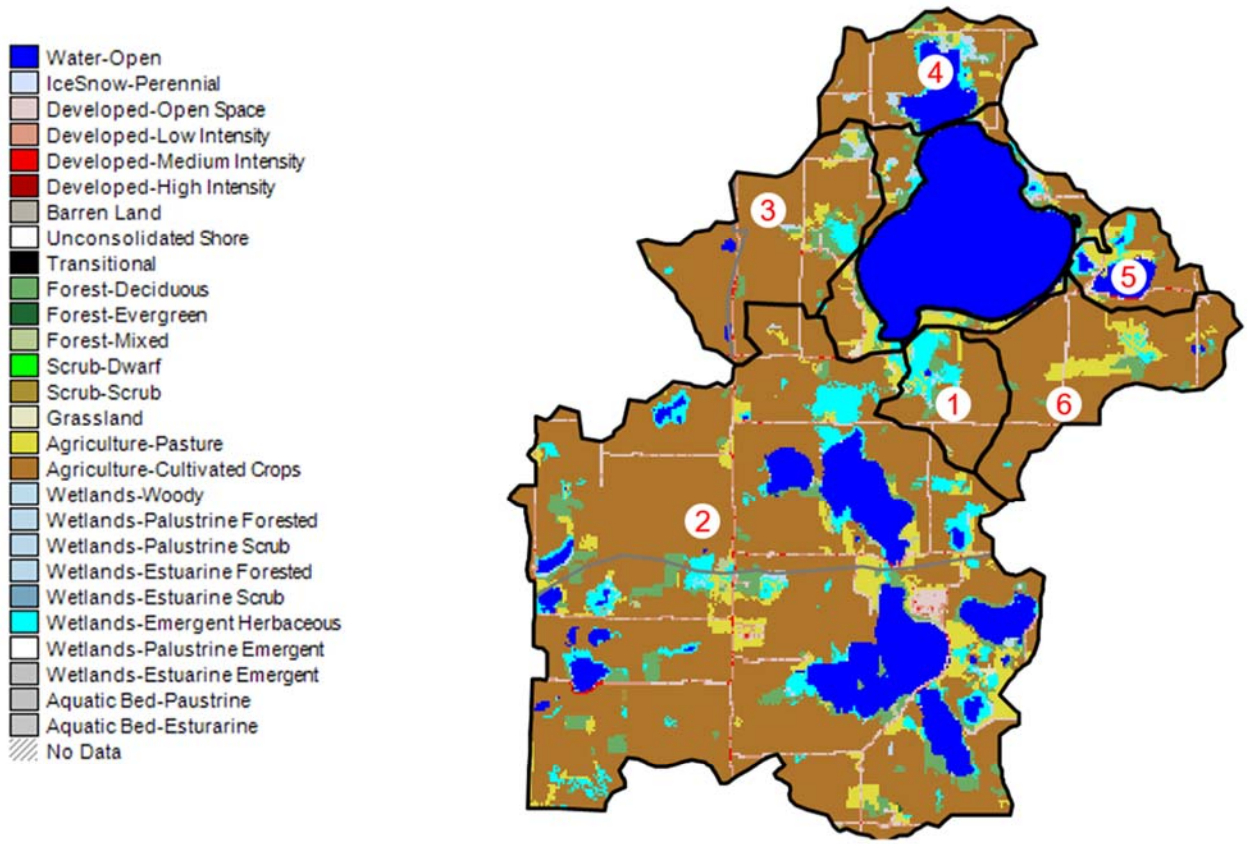
METHODS

Study Site

Lake Jennie is a shallow 1,058 acre lake with a maximum depth of 11.5 ft located 5 miles south of Dassel, MN within the North Fork Crow River watershed (Fig. 4). The lake has a 12,358 acres watershed (11:1 watershed to lake ratio) that is dominated by cultivated, water, and pasture land uses (Fig. 5). The shoreline is 50% developed into residential properties. Given its location within the larger watershed, the amount of land that directly drains into Jennie Lake is relatively small. Jennie Lake drains into Wolf Lake.

Field Sampling

Data were collected from Jennie Lake in 2019 and 2021 on the following dates: 5/24/2019, 6/24/2019, 7/24/2019, 8/22/2019, 9/14/2019, 9/26/2019, 10/26/2019, 11/24/2019, 7/28/2021, 5/25/2021, 6/302021, 7/20/2021, 8/30/2021, and 9/30/2021. A total of six inflows were identified as well as a single outflow. If flow was detectable during a sampling period grab samples were taken from a triple rinsed 250 ml poly bottle for total phosphorus analysis. During 2019 water samples were also collected for analysis of total nitrogen. At the same time, flow measurements were made with either a Geopacks Advanced Stream Flowmeter (Model ZMFP126-S), or, in the case flow was low, by timing distance traveled for a standard tennis ball. Flow measured in



Land Type	Inlet 1	Inlet 2	Inlet3	Inlet 4	Inlet 5	Inlet 6	Direct	TOTAL
				Total Acres				
Agriculture - Cropland	288	4,682	827	394	167	791	251	**7,400**
Agriculture - Pasture	22	438	33	20	37	90	80	**720**
Barren or Mining	0	2	0	1	0	0	0	**3**
Forest	36	406	69	33	10	30	76	**660**
Grass Land	1	12	0	2	4	0	8	**27**
Upland Shrub Land	1	8	0	0	2	0	2	**13**
Urban	13	325	53	36	27	44	53	**551**
Water/Wetlands	72	1,404	52	186	105	24	77	**1,920**
TOTAL	**433**	**7,277**	**1,034**	**672**	**352**	**979**	**547**	**11,294**
				Percentage				
Agriculture - Cropland	66.5	64.3	80.0	58.6	47.4	80.8	45.9	**65.5**
Agriculture - Pasture	5.1	6.0	3.2	3.0	10.5	9.2	14.6	**6.4**
Barren or Mining	0.0	0.0	0.0	0.1	0.0	0.0	0.0	**0.0**
Forest	8.3	5.6	6.7	4.9	2.8	3.1	13.9	**5.8**
Grass Land	0.2	0.2	0.0	0.3	1.1	0.0	1.5	**0.2**
Upland Shrub Land	0.2	0.1	0.0	0.0	0.6	0.0	0.4	**0.1**
Urban	3.0	4.5	5.1	5.4	7.7	4.5	9.7	**4.9**
Water/Wetlands	16.6	19.3	5.0	27.7	29.8	2.5	14.1	**17.0**
TOTAL	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Fig. 5. Jennie Lake subbasin characteristics based on NLCD 2016 land use layer.

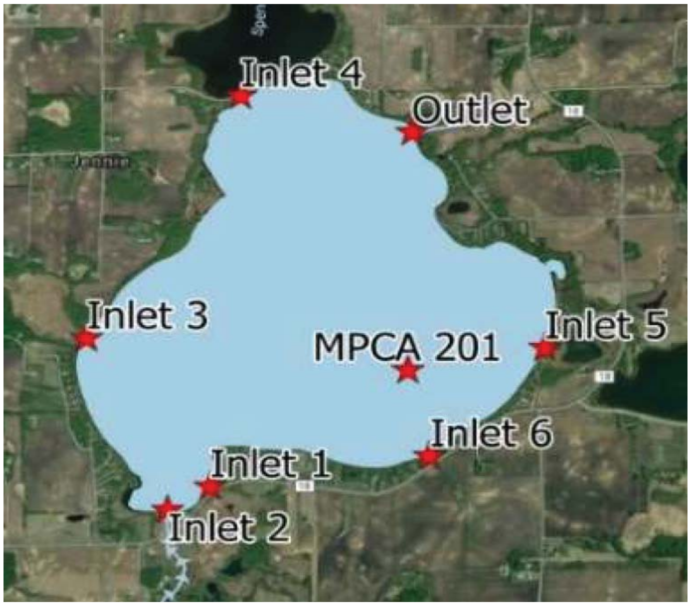


Fig. 6. Sampling locations, including established MPCA Citizen Lake Monitoring Program (CLMP) sampling site in one of the deeper areas of the lake.

the later case was adjusted by multiplication by 0.85 given flow at the surface is known to be faster than average discharge. Flow velocities were converted to discharges by measuring cross-sectional areas where flow would be measured during the first sampling occasion.

During sample periods water samples were collected at MPCA Citizen Lake Monitoring Program (CLMP) site for Jennie Lake using a 2-m integrated surface sampler and were analyzed for total phosphorus and chlorophyll a (Fig. 6). A temperature/dissolved oxygen profile was also collected at these sampling occasions as well as a biological sample for zooplankton and algae (2019 only) Zooplankton were sampled through a 183 micron plankton net with an 8 inch diameter lowered to 2.5 feet below the water surface. Algae were sampled as a grab sample using 150 ml amber poly bottle. Zooplankton were preserved in 50% ethanol and algae in 2% Lugol's solution. Additionally, sediment samples from this same location were taken to provide a profile of redox (i.e., oxygen sensitive) phosphorus in the sediment that could be used to estimate alum dosing.

Model Development

We used the data collected to build nutrient model using a two compartment model, the first consisting of "external" sources of nutrients that were directly dependent on hydrology (i.e., movement of water) and a second "internal" source of nutrients that was not directly depend on hydrology. Hydrology dependent sources of nutrients included nutrients added through the six inflows, direct precipitation to the lake (i.e., nutrients in rain water), dry deposition to the lake (i.e., particles containing nutrients in the air), and removal through flow to the outlet of Jennie Lake, and nutrients added or subtracted to the lake through groundwater movement. Precipitation falls directly on the surface of the lake and drives runoff directly from the basin. Precipitation also drives volume changes in the lake, which impacts elevation. The elevation of the lake, in turn impacts the flows in a predictive way via a stage-rating curve. The determination of groundwater inflow is the difference between all measured inflow and outflows.

Internal sources of nutrients included resuspended nutrients from lake sediments, leaching from senescent curlyleaf pondweed, and septic inputs. The model was built on a daily time-step over the average open water period of 4/15/2019 to 11/15/19 for a total of 214 days in 2019 and 4/15/2021 to 10/15/2021 or a total of 184 days in 2021. All measures are used in imperial notation with rates given as feet per day and volumes as acre-ft day. Lake volume measurements were given as acre-ft.

Hydrology Submodel

We used a standard mass-balance model to estimate water budget terms where the volume of water in Jennie Lake (*V*) could be simulated by a series of water input and outputs (Fig. 7). It is standard in hydrology models to symbolize discharge using the letter "*Q*". By discharge, we mean the volume of water flowing into or out of the lake assigned to a specific source over a given time

Water inputs included direct precipitation to the lake surface (Q_{DP}), runoff as overland or interflow from the land surrounding the lake (Q_{RO}), stream flow coming into Jennie Lake (Q_{SFi}) and inflow from ground water (Q_{GWi}). Water outputs from the lake include water lost as direct evaporation from the lake (Q_{DE}), stream flow out of the lake leaving through the fish gate, and groundwater outflow (Q_{GWo}). We can then model the daily change in lake volume (dV/dt) as,

where all discharge rates were modeled in acre-ft per day and lake volume was estimated in acre-ft.

$$\frac{dV}{dt} = (Q_{DP} + Q_{RO} + Q_{SFi} + Q_{GWi}) - (Q_{DE} + Q_{SFo} + Q_{GWo})$$

[EQ. 1]

Lake Volume

Lake volume could be indirectly measured with lake

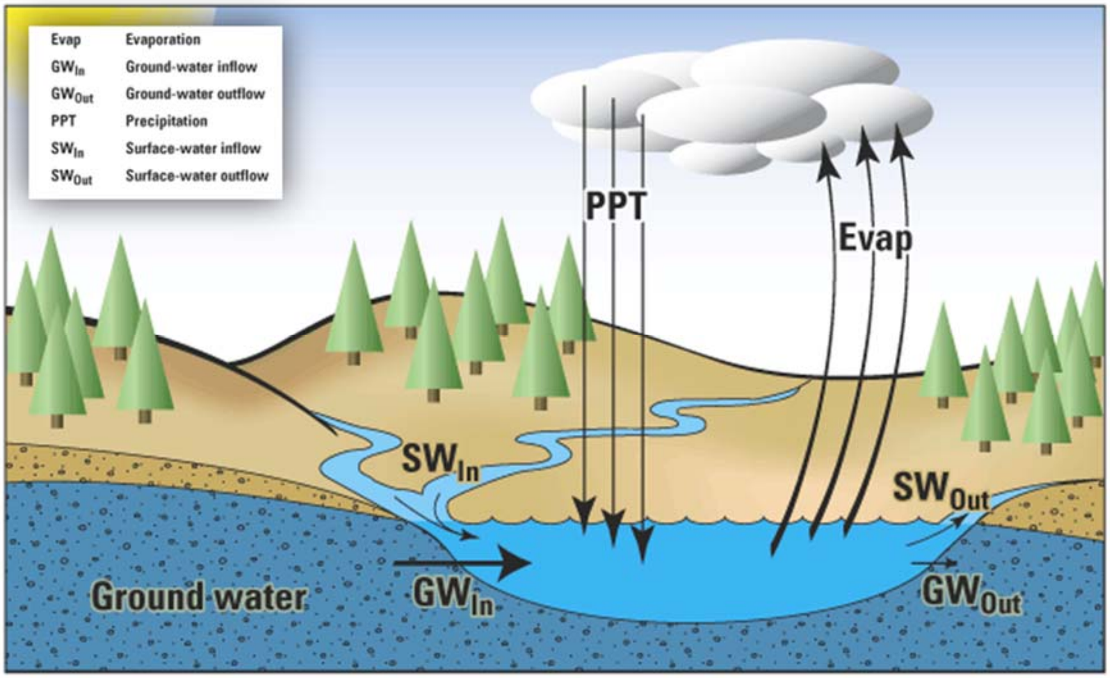


Fig. 7. Generalized water budget (from USGS).

elevation through construction of hypsographic and volumetric curves. A hysographic curve is an analytic method used to determine the surface area of the lake at each depth interval (Fig. 8). This information can be used to calculate the volume of water between every change in depth and then add those together to get the overall volume. We set surface depth of zero equal to the ordinary high-water level reported by the MN DNR at 1061.0 ft. In order to establish a functional relationship between lake level and volume, we pulled out depths from 0 – 5 ft (=1061.0 - 1056 ft) above sea level) and fit a linear function to these data, and we estimated volume as a result using the equation,

$$V = 119Z - 120{,}939 \qquad \text{[EQ. 2]}$$

Direct Precipitation

Next, to estimate direct precipitation to the lake (Q_{DP}), we needed to determine the precipitation rate (*PREC*) and the surface area (*A*) of the lake on any given day. Direct precipitation to the lake is the product of daily precipitation rate and area of the lake such that

$$Q_{DP} = PREC \times A \qquad \text{[EQ. 3]}$$

Precipitation rates (*PREC*) were used from records at the Dassel, MN weather station. We were able to use the hypsographic curve to generate a function that related the surface area (*A*) of the lake to water levels. Using depths from 0 to 5 ft, we used the same procedure to estimate surface area as we did to volume with the resulting function as

$$A = 23.8Z - 24{,}188 \qquad \text{[EQ. 4]}$$

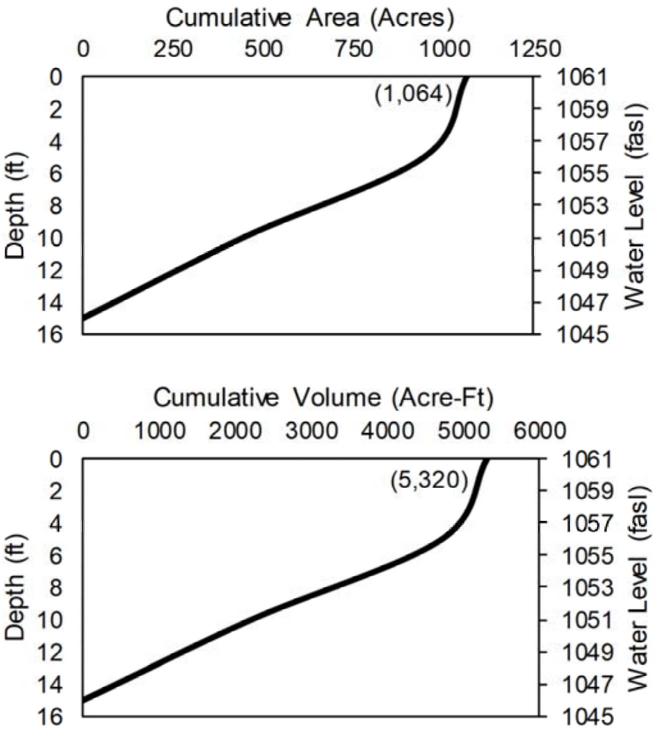


Fig. 8. Hysographic (above) and volumetric (below) curves relating water level to surface area and volume respectively for Lake Jennie. Number in parentheses are estimated values at ordinary high water mark of 1061.0 ft above sea level.

Runoff

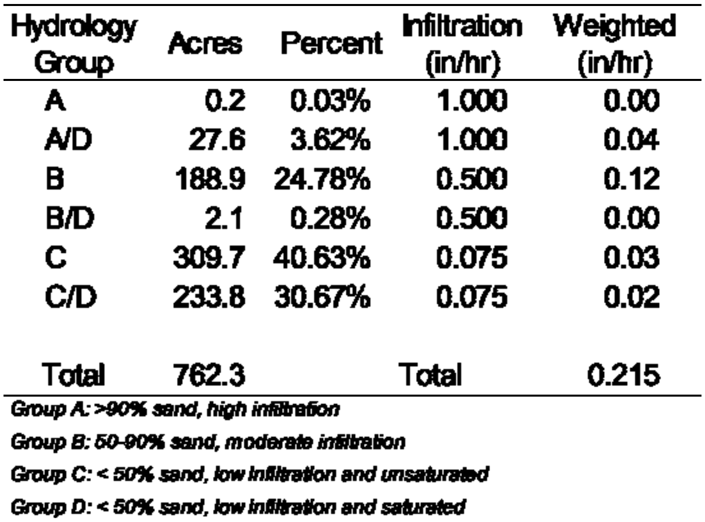
Generally, only a small portion of precipitation will enter a lake as runoff. The majority of precipitation leaves the landscape as evaporation after it is intercepted by plants, pools in depressions, or temporarily saturates soil. The water that is not returned to the atmosphere either moves into the lake through runoff or seeps through soils into the groundwater pool.

The proportion of precipitation making it to the lake, into groundwater, or returned to the atmosphere is in large part dependent on the nature of the soils in the watershed through which new rainfall moves. We use a measure called the “infiltration” rate to estimate how much water moves into the soil. Infiltration is the maximum rate that rain can soak into the ground, and it depends on sediment type. For example, sandy soils have a large particle size and associated large pore size. This allows water to quickly move through it. In sandy soils, rain can soak into the ground at rates of up to 1 inch/hour. Clay soils, on the other hand, have small particle sizes and small pore size and subsequently it takes longer for rain to soak in. In heavily clayed soils it may take up to 13 hours for the same inch of rain to soak into the soil. During that time, the rain on the surface of the land can either be evaporated or runoff into the lake.

The Meeker County Ground Water Survey (2019) gives expected infiltration rates for different soil hydrology types in Meeker County (Fig. 9). In order to determine the soil hydrology types in the Jennie Lake lakeshed, we mapped them using GIS layers available through the NRCS web soil survey tool. Once we knew the area of the lakeshed for each of the soil hydrology group, we estimated the infiltration rate by finding the weighted average. This gave a single infiltration rate of 0.215 in/hr for the Jennie Lake lakeshed (Table 2).

Runoff (Q_{RO}) was calculated in inches per hour by subtracting the weighted infiltration rate (0.215 in/hr) from the measured hourly precipitation in inches per hour and multiplying that value by 762 acres, which is the area directly surrounding the lake that we estimate contributes interflow or sheetflow rather than intercepting tributary. If hourly precipitation was lower than the weighted precipitation rate, then all rain would soak up into the ground and runoff would be equal to zero for that hour. Using this method yielded an estimate of 4.6 inches of runoff for the period 4/15/2019-11/15/2019 and 30.17 inches of precipitation over the same period. During the period of 4/15/2021-10/15/2021 this method estimates 3.8 inches of runoff and 14.7 inches of precipitation.

Table 2. Soil hydrology group and infiltration rates used to estimate runoff as sheet flow in the area directly surrounding the lake. Raw data were obtained from NRCS Soil Survey and infiltration rates from Meeker County Groundwater Atlas.



Hydrology Group	Acres	Percent	Infiltration (in/hr)	Weighted (in/hr)
A	0.2	0.03%	1.000	0.00
A/D	27.6	3.62%	1.000	0.04
B	188.9	24.78%	0.500	0.12
B/D	2.1	0.28%	0.500	0.00
C	309.7	40.63%	0.075	0.03
C/D	233.8	30.67%	0.075	0.02
Total	762.3		Total	0.215

Group A: >90% sand, high infiltration

Group B: 50-90% sand, moderate infiltration

Group C: < 50% sand, low infiltration and unsaturated

Group D: < 50% sand, low infiltration and saturated

The runoff coefficient can be computed as R/P and in this case is equal to 15% in 2019 and 25% in 2021, which is consistent with other Minnesota measurements. In other words, approximately 15% of precipitation that falls over the year ends up as runoff to the lake as interflow. Interflow is water that moves through the shallow subsurface to the lake or potentially through tiles. We assume that the 85% of the precipitation that does not get the lake is eventually returned to the atmosphere as evapotranspiration (ET). Subsequently, we do not add ET from the watershed as a separate term. Groundwater will be treated as the residual term of the equation such that any infiltration that percolates to the groundwater pool will be captured by that term.

Tributary Flows

Flow measurements were made at four sites directly from culverts. Stage-discharge rating curves were developed to estimate flow during the time where direct measurements were not collected by using a regression of lake level data against measured discharge. Initial plot visualizations were inspected, and apparent outliers were removed prior to estimating the standard stage-rating curve fitted to a logistic model (Fig. 10). If during the sample period there was no detectable flow a given site no samples were taken. During 2021 the only sampling periods with flow were 4/28/2021 (inlets 1, 2 & 6) and 5/25/2021 (inlets 2 & 3).

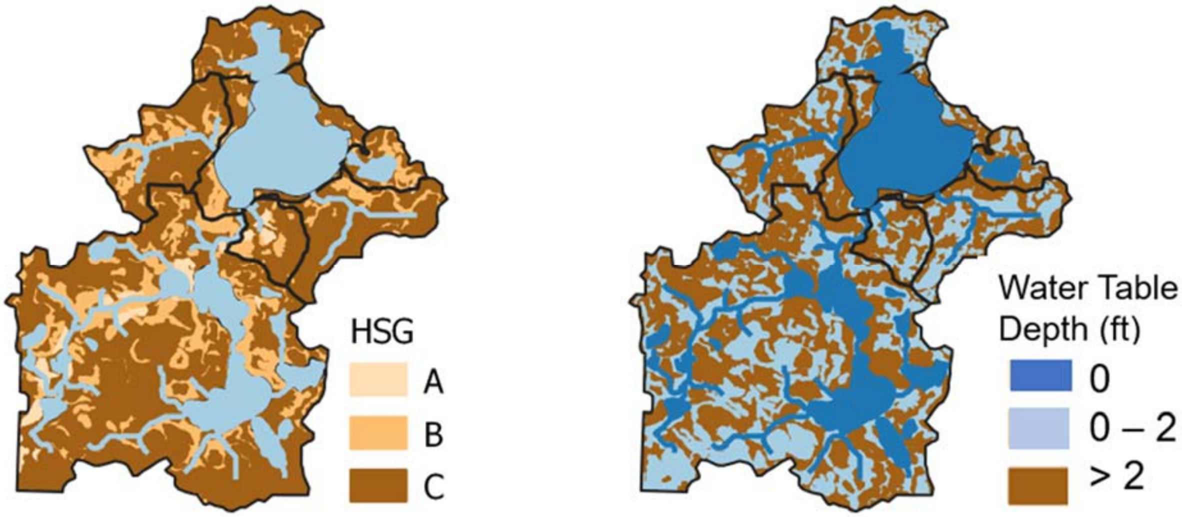


Fig. 9. Soil characteristics including Hydrological Soil Group (HSG; see Table 2) left and average depth to water table right.

Direct Evaporation

Direct evaporation (Q_{DE}) is water lost from the surface of the lake and can be calculated as the measured evaporation rate multiplied by the surface area of the lake. Evaporation measurements are notoriously difficult, and in fact, there are only two weather stations in Minnesota that attempt to do so on a continual and long-term basis, one in St. Paul and the other in Waseca, Minnesota. Pan evaporation is recorded monthly at two sites in Minnesota, including one in St. Paul, MN and the other in Waseca, MN. Pan evaporation is known to overestimate evaporation from a lake surface, and as such many pan coefficients have been developed to convert them to evaporation. Without direct measurements, most researchers use a pan coefficient of 0.745 and we do so here. We adjusted from Baker (1979), based on the location of Jennie Lake, the monthly evaporation relative to both the St. Paul and Waseca readings, which are the only publicly available ongoing records available. These monthly records were converted to a daily value by dividing by 30 and then setting that reading to the 15th of each month. Linear interpolation was used between readings to estimate daily evaporation.

Nutrient Submodel

Having estimated waterflow, we used a standard mass balance model for estimating nutrient fluxes to and from the lake (Fig. 11).

External Loading

Total phosphorus was monitored during both 2019 and 2021 with total nitrogen additionally being monitored in 2019. Water samples were collected simultaneously and sent to AW Research, Inc., Brainerd, MN, for chemical analysis. In general, nutrient loading was estimated by multiplying the modeled discharge at each source by the measured nutrient concentrations at the times when samples were collected. For estimation of nutrient concentrations between sampling events, we the flow weighted mean modeled through the use of Flux32 software.

Constant concentrations for direct precipitation (14.7 ug/l) and dry deposition (0.170 kg/ha/year) were used from Barr (2007) averages for the Upper Mississippi Major Watershed. While no wells are included in MN DNR database from Meeker County, there are 127 records from Pope and Stearns Counties, for which portions exist within the North Crow River Watershed. The total phosphorus for these wells was 68 ug/l, which is what we used to account for groundwater flux of nutrients in the lake.

Internal Loading

Sources and sinks for internal nutrient dynamics include septic tank inputs, curlyleaf pondweed senescence, and within lake storage. Septic tank inputs were taken as reported by Barr (226) at 1.53 grams of phosphorus per day per capita. Curlyleaf pond-

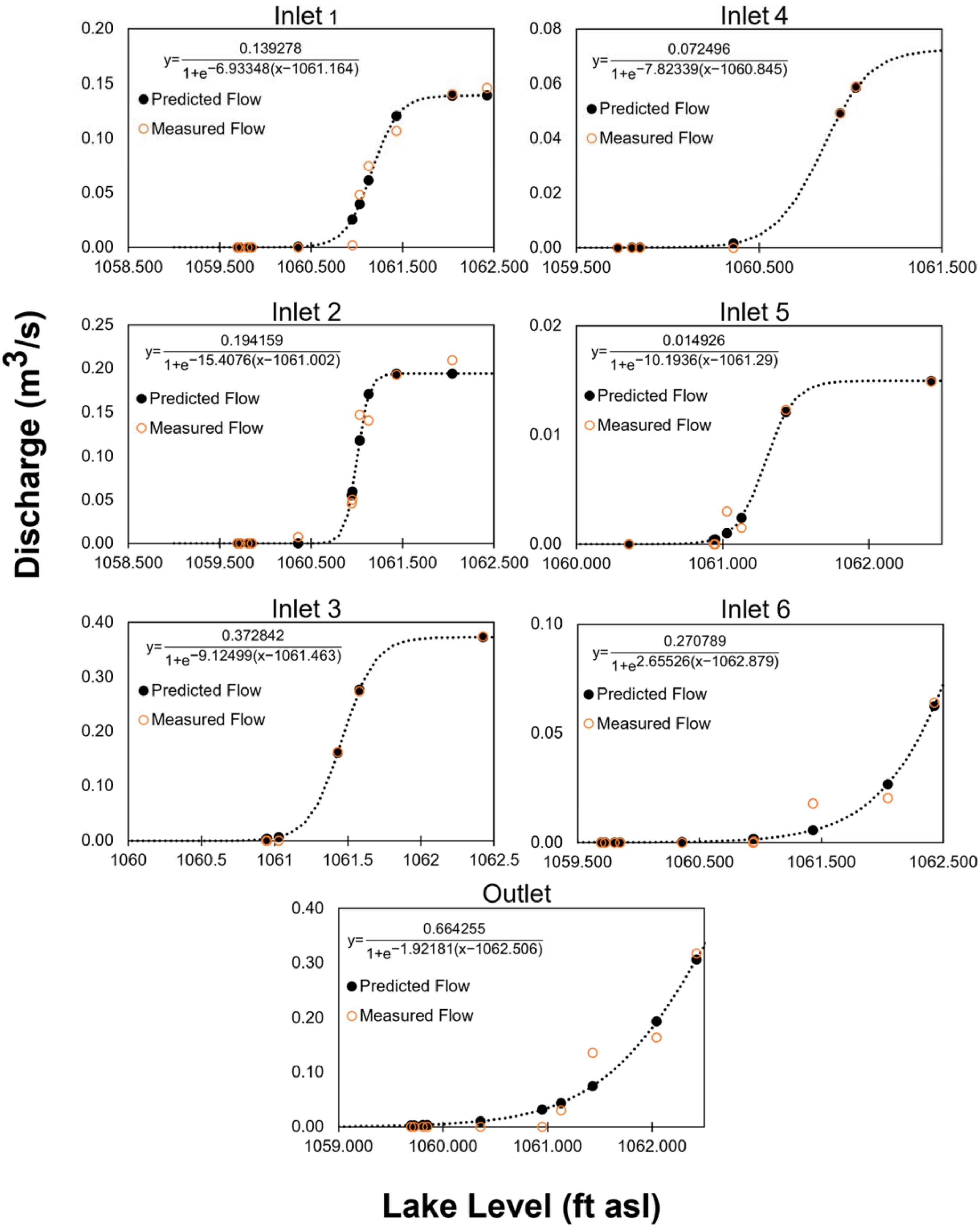


Fig. 10. Stage rating curves for each of the six inlets and single outlet to Jennie Lake for flow measurements made in 2019 and 2021. Points indicate measurements and dashed line indicates modeled flow.

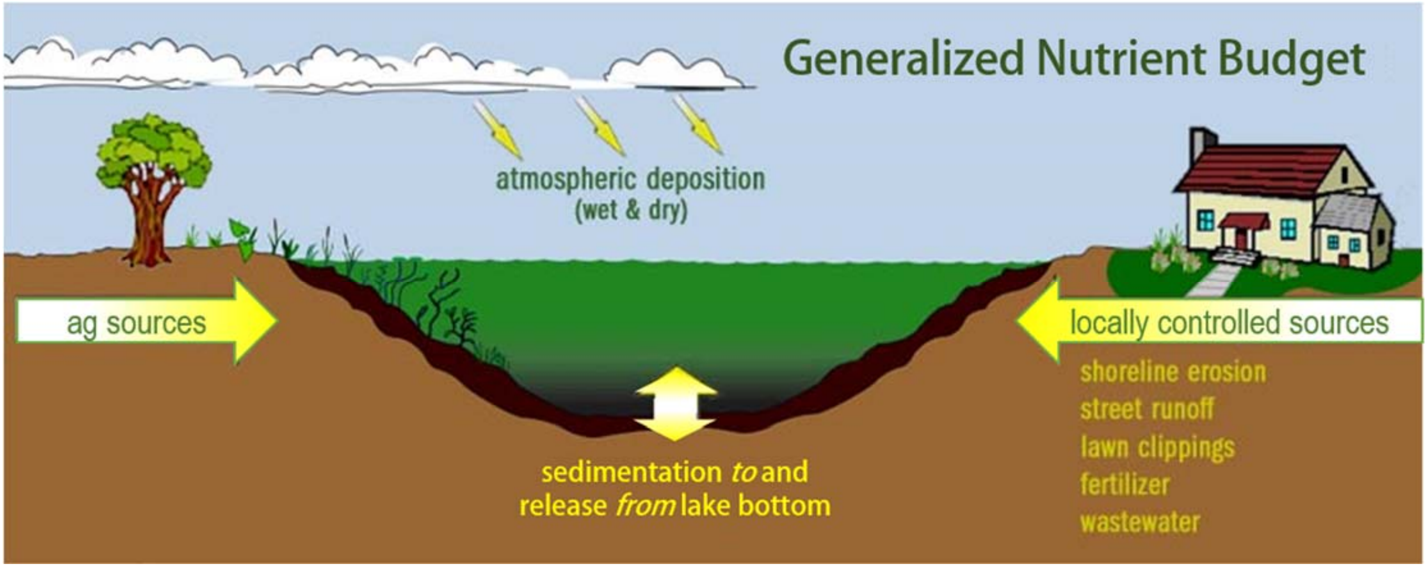


Fig. 11. Generalized nutrient budget to a lake. Not shown are sources to the lake from biological recycling, including death and decay of plant material, nor groundwater nutrient flow through. Diagram adapted from lakeaccess.org.

weed biomass and senescence for release of phosphorus was based on a series aquatic point intercept surveys and sonar mapping of biovolume during 2020-2021. For estimation of phosphorus content and senescence we used available published references. Lake storage was calculated by multiplying the volume of the water by the deep open water nutrient concentration samples collected during five events. These five samples collected at approximately one month intervals were used as a basis for linear interpolation to fill in missing days. Once daily values were obtained we derived an estimate of the change in storage from one day to the next by taking the difference (i.e., N_{t+1}- N_t where N_t is the nutrient load for phosphorus and nitrogen respectively at time t and N_{t+1} is the nutrient load in time t+1) Once the change of storage was estimated we could solve for the internal load (i.e., LOAD) as the difference sedimentation to and release from lake sediments, between the change in storage of nutrients within the lake from all other sources of nutrient flux such that

$$\boldsymbol{LOAD = (TP_{t+1} - TP_t) - (RUN + PREC + ATM + SEP) \pm INFLOW \pm GW - OUT} \quad \textbf{[EQ. 5]}$$

RESULTS

Average lake volume during 2021 (5,168 acre-ft) was lower than 2019 (5,392 acre-ft). The water level fluctuated by 1.6 feet with the highest water levels in the spring with a steady decline the rest the monitored period (Fig. 12).

Total water movement through Jennie Lake was approximately four times the value in 2019 than it was in 2021. These two years present relative extremes in precipitation years with 2019 being the wettest year on record back through the past 30 years and 2021 being one of the driest (Table 3). During 2021, there was less than 1 acre foot of flow in nearly all of the inlets and the outlets. Notably, the outlet likely would not have been flowing much even if it would have been a wetter year as it was blocked by a natural bog-like dam that had developed. On average, Inlet 2 provides the greatest amount of water from watershed precipitation events, followed by Inlet 2. None of the other inlets look to provide a good deal of water during most years. The open channel that is Inlet 3 flows in both directions during the year depending on conditions at any given time.

We note that values here for 2019 are slightly different than those presented in the 2019 write up. This is because with the collection of additional data in 2021, models were improved. The primary flow during most years is groundwater movement by the lake. The position of the lake high in the watershed and depth of water table support its characteristic as a seepage lake.

In 2021 an estimated 1,602 pounds of phosphorus moved into Lake Jennie (Table 4). The largest con-

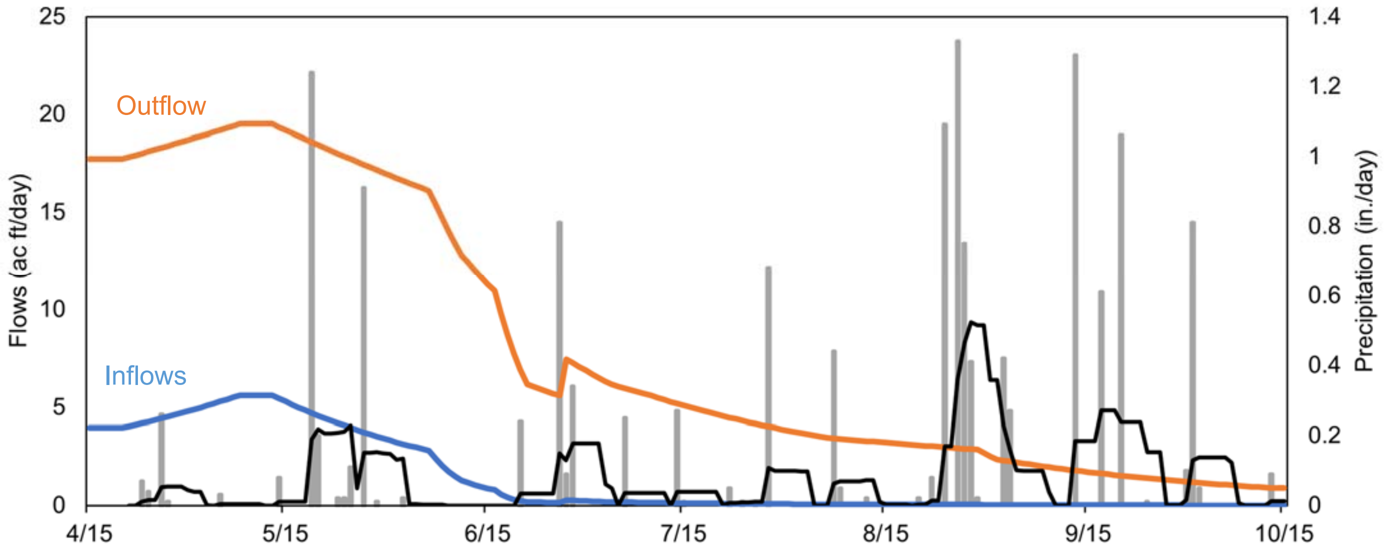


Fig. 12. Modeled hydrology for Jennie Lake 4/15-11/15/2021. Inflows (blue line) are combined from Inlets 1-6. Precipitation data come from Dassel, MN. Black precipitation lines show 7-day moving average.

tributor to phosphorus in the lake during this year was groundwater followed by curlyleaf pondweed die off. Because there was virtually no flow from any of the six tributaries all of the phosphorus entering the lake had to come either internally or from precipitation and dry deposition. Nitrogen was not monitored in 2021.

During an average year, total internal loading over the five years modeled averaged 38% with the total tributary inflow adding up to 15%. Of the tributary flows, Inlet 2 provided the highest phosphorus load in the amount 11%.

Table 3. Hydrology (i.e., water flow) data for Jennie Lake. Asterisked (*) years had directly measured data while additional years were estimated based on model built. Average reflects contributions for each source over the full five years shown.

Source/Loss	Acre-feet per year						
Year	2007	2008	2013	2019*	2021*	Average	
Inputs							
Inlet 1	172	342	469	1,595	0	516	7%
Inlet 2	437	709	927	3,197	0	1,054	14%
Inlet 3	-751	-663	-402	1,166	0	-130	-2%
Inlet 4	266	266	228	266	0	205	3%
Inlet 5	8	18	26	102	0	31	0%
Inlet 6	55	91	123	415	0	137	2%
Runoff	197	205	199	287	243	226	3%
Precipitation	1,810	1,902	1,852	2,717	1,262	1,909	26%
Groundwater	3,508	7,183	2,956	2,354	1,409	3,482	47%
Total Inputs	5,702	10,054	6,377	12,100	2,914	7,429	100%
Outputs							
Outlet	2,341	5,520	1,454	3,022	1	2,468	31%
Evaporation	2,513	2,411	2,399	2,037	1,864	2,245	28%
Seepage	2,115	2,896	3,226	6,749	1,233	3,244	41%
Total Outputs	6,969	10,828	7,079	11,808	3,098	7,956	100%
Storage Change	-1,267	-774	-702	291	-184	-527	

**Model building years*

DISCUSSION

There are two ways that phosphorus in the lake can be managed. One is through the use of "Best Management Practices (BMPs)" in the watershed to control phosphorus coming into the water from the landscape. BMPs mostly focus on engineered solutions to slow water down as it travels over the landscape prior to getting into the water into depressional areas where nutrients can settle out prior to getting into the lake. The second way to control nutrients is through within lake controls, primarily by plant management, nutrient interception at the mouth of an inlet, and locking up nutrients to sediments of the lake.

Osgood (2017) indicates by review of past efforts that eutrophic lakes require >80% reduction in sub-basin phosphorus source to lakes must occur by BMP's to potentially create a discernable positive impact in water quality. This is virtually impossible, and efforts at a lesser scale will be expensive and likely not impact phosphorus concentrations.

The two years monitored (ie., 2019 and 2021) represent two climate extremes in the region with 2019 being the wettest year in over 30 years and 2021 being one of the driest. These climate differences were reflected in flow regimes. In 2019, there was abundant flow and increased tributary phosphorus loading relative to average years. In 2021, there was very little precipitation and tributary flows were

Table 4. Hydrology (i.e., water flow) data for Jennie Lake. Asterisked (*) years had directly measured data while additional years were estimated based on model built. Average reflects contributions for each source over the full five years shown.

Source/Loss	Phosphorus pounds per year						
Year	2007	2008	2013	2019*	2021*	Average	
Inputs							
Inlet 1	30	60	83	211	11	79	2%
Inlet 2	181	326	426	902	0	367	11%
Inlet 3	-139	-120	-87	191	0	-31	-1%
Inlet 4	32	32	32	32	34	32	1%
Inlet 5	2	5	8	25	0	8	0%
Inlet 6	25	46	63	178	9	64	2%
Precipitation	67	68	74	103	50	72	2%
Dry deposition	137	137	138	140	157	142	4%
Groundwater	580	1193	547	416	576	662	20%
Septic	204	204	204	204	205	204	6%
Runoff	54	55	60	82	6	51	2%
Curlyleaf pondweed	410	410	410	410	410	410	12%
Internal Load	2,020	743	1,980	1,525	145	1,283	38%
Total Inputs	3,603	3,159	3,935	4,419	1,602	3,344	100%
Outputs							
Outlet	531	1259	366	635	404	639	30%
Sedimentation	1149	664	2261	360	460	979	46%
Seepage	349	486	596	1008	194	527	25%
Total Outputs	2029	2409	3223	2003	1057	2,144	100%
Storage Change	1,574	751	712	2,416	545	1,200	

**Model building years*

reduced to near zero.

One of the unexpected outcomes for 2021 was a very low amount of internal loading. We might have hypothesized that internal loading should be independent of precipitation patterns but in fact it was much lower during 2021 relative to average. The most likely hypothesis for the observation is the reduced mixing that occurred during the dry year from a lack of storm and wind events that would be more frequent than in wet years.

One of the pieces of evidence that supports this hypothesis is the degree of stabilization and thickness of the anoxic area of the lake in Jennie relative to prior years. While prior years showed anoxic depth to 13 feet, in 2021 it was 8 feet and persisted from the beginning of June through the remainder of the year (Fig. 13). There was even some degree of thermal stratification that setup in 2021 that is not common in lakes as shallow as Lake Jennie.

The virtual lack of tributary flow, along with stable water led to the lowest phosphorus on record for a year and overall best water quality.

We agree with his conclusion that BMP's are not a good strategy to control phosphorus in lakes and also agree that the primary way lake water quality can improve is through internal load management. Efforts focusing on phosphorus interception strategies (e.g., at the mouth of inlets) and removal efforts by chemical precipitation, which are much less expensive and have removal efficiencies of up to 90%.

Mobilization of phosphorus in shallow lakes is thought to follow three different pathways (1) bacterial mineralization of phosphorus from lake sediments, (2) iron-phosphorus redox conditions under temporary anoxia brought on by high BOD, particularly un-

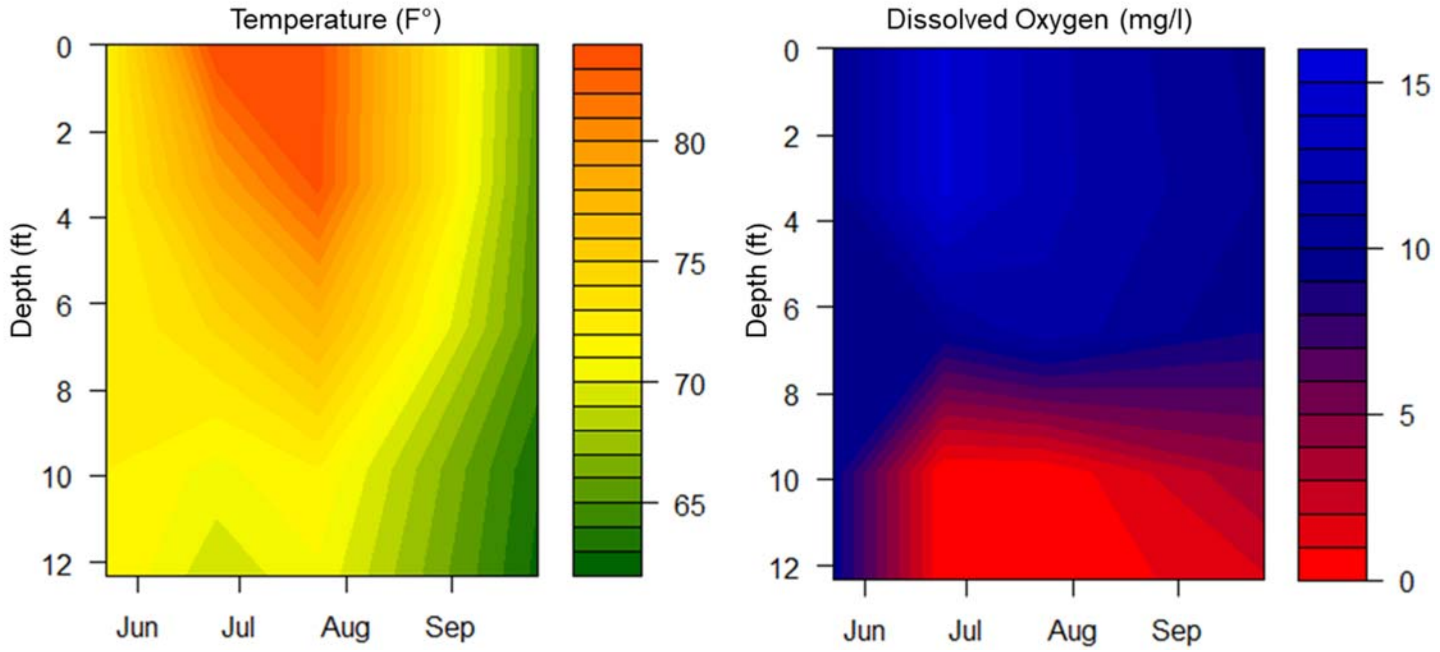


Fig. 13. Jennie Lake isopleths for temperature and dissolved oxygen profiles collected during 2021.

der warm water and calm condition with wind mixing, and (3) exchangeable cation activity at high temperatures that occurs in the upper water column at high rates of photosynthesis.

Aluminum sulfate is widely used in unstratified shallow lakes effectively; however, most applications are in small lakes where cost is more manageable. The total cost of an alum treatment for a lake the size of Jennie could be between 1 – 3 million dollars (i.e. \$2,000—\$3,500 per acre), but it is not unusual for treated lakes to cut phosphorus in the lake in half with results lasting more than 5-10 years.

Considering the high cost of such a treatment given the size of the lake, we are proposing treating the lake as if its stratified. This lower cost option would be not to treat the entire lake but only areas where wind is most likely to push liberated phosphorus into the water column and restricting alum treatment to those areas.

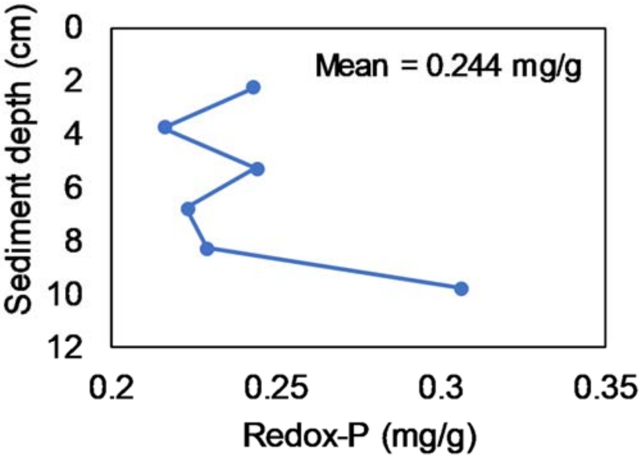
Based on dissolved oxygen profiles during average years and Jennie Lake bathymetry, we set an anoxic area at the 13 foot depth, which represents an area of 84.9 acres. At an average cost of \$3,000 per acre, a treatment of this area cost approximately \$254,700. The reduction goal of phosphorus to the lake is 1,629 lbs/yr. Reducing this source of phosphorus yields a cost benefit of approximately \$152 per pound of phosphorus removed per year, which is considerably less than most traditional BMPs which often have cost effectiveness of \$1,000 lbs TP/yr or more.

Exact dosing was determined by digitizing a data from James and Bischoff (2015) that estimates Alum dosage using sediment redox-phosphorus using the equation,

$$y=159.23x^{0.3607} \qquad \text{[EQ. 6]}$$

Their approach, and most approaches to dosing for alum, uses only a portion of the phosphorus in the sediments that is reactive to oxygen conditions at the bottom. This portion of the phosphorus is called the “redox-P”. It is typical to attempt to control the upper 5-10 cm of sediment. In 2021, we collected a sediment and had it analyzed for sediment redox conditions. we estimated that in order to inactivate the redox-P in the first 10 cm of sediment (Fig. 14).

Huser et al (2011) set a load reduction goal of 50% for four lakes in Minneapolis and concluded that this was a reasonable target. They found in all lakes a 20 ug/l reduction in measured TP. Other studies indicate load reductions of 90%. Given we are targeting only a portion of the water body, we are aiming for a 50% reduction of loading and a reduction of the in lake TP to below 60 ug/l.



Sediment Depth (cm)	Redox-P (mg/m^2)	Alum dosage (g/m^2)
0-5	0.7	138
0-8	1.1	167
0-10	1.7	192

Fig. 14. Redox-Phosphorus at sediment depths based on sediment core collected in 2021 and the estimated alum dosage based off James and Bischoff (2015).

In addition to treating anoxic areas of the lake, we are also advocating a feasibility analysis of installing a flow controlled alum dosing station at Inlet’s 2 and 3 or potentially a sand iron filter. These controls together have a good chance of improving water quality as measured by clarity.

There is a risk in improving water clarity that will lead to an increase to macrophyte growth. Macrophyte growth was a primary concern and motivated current work on the nutrient budget to the lake. Lake residents were concerned about plants washing up on shore. We hypothesize that this may be due to late season poor water quality that weakens plants. Improvements in water quality may strengthen plants allowing them to remain in sediment. Strategic management of curlyleaf pondweed will also help improve water quality and nuisance plant proliferation. A thoughtful and long-term plant management plan that focuses on replacing curlyleaf pondweed with low growing native species will be important, particularly as part of an overall plan that includes improving water clarity. Improving water clarity will increase plant habitat and lead to greater coverage of plants on the lake. This is unavoidable. A good plant management plan will seek to decrease early spring matting plants in favor of later and lower growing native plants and being vigilant of new invading AIS.

Huser et al (2016) provided one of the most comprehensive assessments of the longevity of alum treatments to lakes. They looked for patterns across 114 lakes and found a range of 0-45 years of water quality reduction with a mean of 11 years. Factors that lead to greater longevity included higher alum dosing, stratification scheme, and watershed to lake area ratio. Based on their model Jennie Lake would be included in a group of lakes that should be expected to have persistent improvement of water quality for at least five years. While Jennie Lake should be considered polymictic due to its shape, our own work indicates that the lake at least weakly stratifies for the summer. This is important because in their assessment the difference between longevity in polymictic or unstratified and stratified lakes is 5 years versus 17 years. For these reasons we would estimate that the longevity of a properly applied and dosed alum treatment should persist between 5-17 years.

Finally, while the impaired waters threshold for the NCHF Lakes Ecoregion is 3.8 ft for Secchi depth, the average annual Secchi depth over all measured points is almost never bellow that level for Jennie Lake (review Fig. 1a) which leads to the conclusion that it would be extremely difficult to make changes to bring the lake off of the impaired waters list, at least in the short term. A more realistic target for the short term would be to improve the water quality so that it stays above the 75th percentile for Secchi depth over all periods which is 2.76 feet.

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