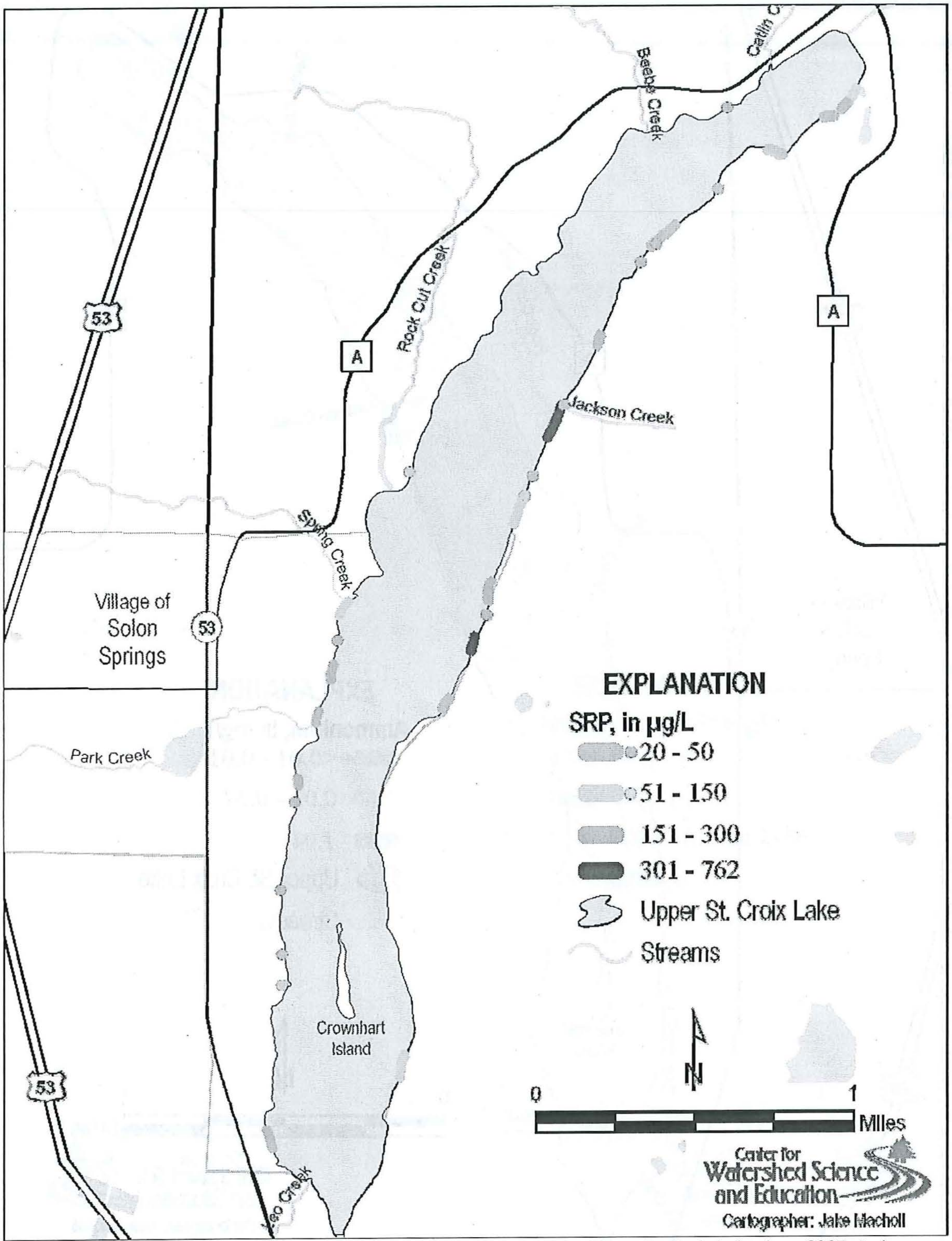

Figure A6. Soluble reactive phosphorus (SRP) concentrations from the Upper St. Croix Lake June 2007 study. Minipiezometers are represented as rectangles covering the approximate area of inflow, springs are represented as circles.

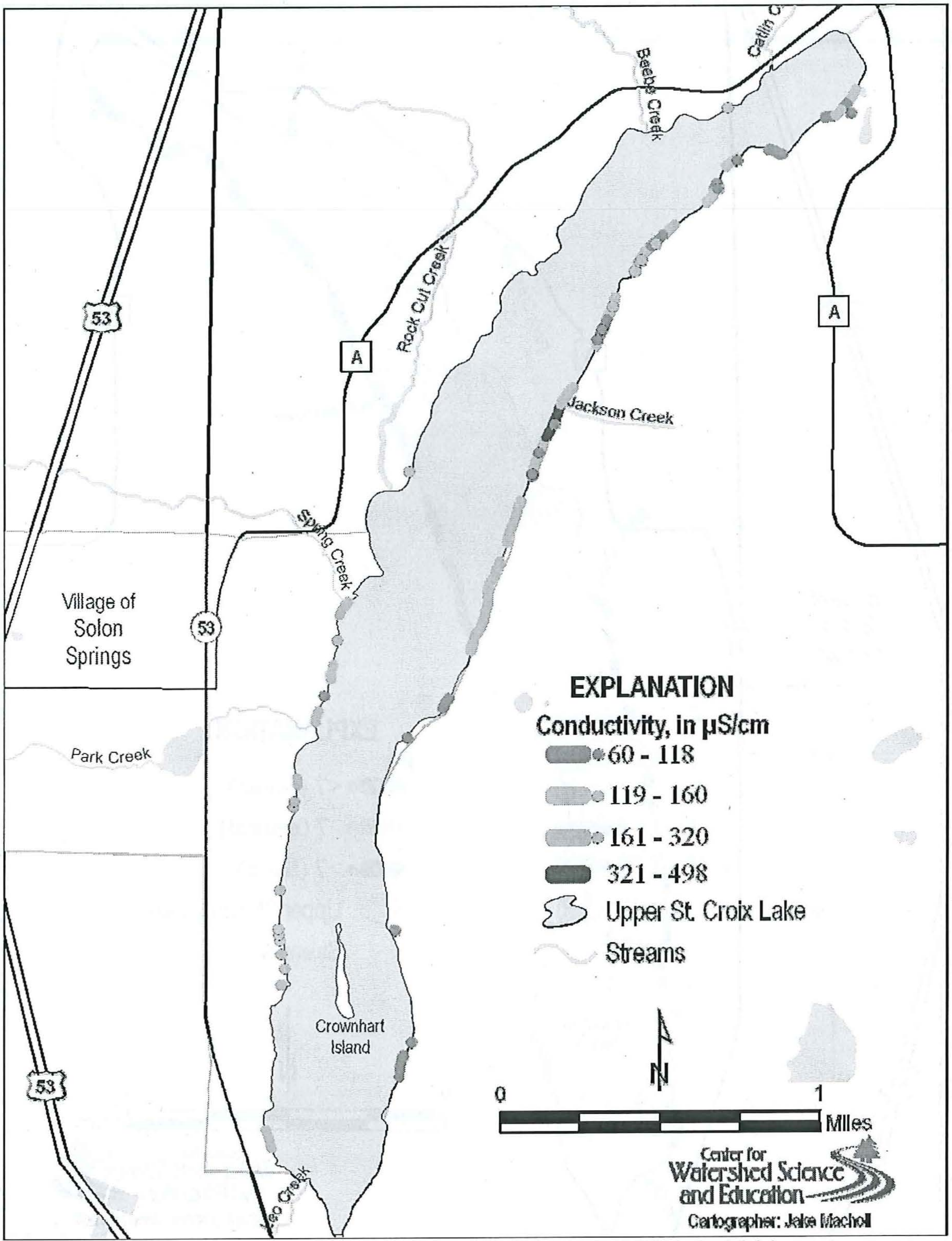

Figure A1. Conductivity measurements from the Upper St. Croix Lake June 2007 study. Minipiezometers are represented as rectangles covering the approximate area of inflow, springs are represented as circles.

Table A4. Physicochemical characteristics of nearshore groundwater springs not sampled for lab analysis, 06/27/08.
[°C, degrees Celsius; µS/cm, microSiemens per centimeter; L/s, Liters per second; n.d., no data]

Site ID	Water Temp. (°C)	Conductivity (µS/cm)	Field pH	Discharge L/s
SCLS8	n.d.	105	7.01	0.05
SCLS7	n.d.	114	6.98	.02
SCLS6	n.d.	97	7.0	.02
SCLS5	n.d.	111	7.0	.02
SCLS1	n.d.	n.d.	n.d.	.2
11c	n.d.	110	7.87	.34
11b	n.d.	n.d.	n.d.	.02
11a	n.d.	109	7.3	.02
159	9.5	n.d.	n.d.	n.d.
158	12.3	n.d.	n.d.	n.d.
157	12.3	n.d.	n.d.	n.d.
155	16.3	213	7.7	.08
150	13.9	131	7.7	.34
149	8.7	129	7.5	.17
148	10.4	150	7.9	.85
146	15.1	193	7.7	.87
143	17.3	66	7.9	1.0
142	13.8	102	7.9	.4
140	12.9	93	8.0	n.d.
135	n.d.	88	7.93	.4
130	19.9	101	7.48	.16
128	9.3	121	7.99	.06
128	9.3	121	7.99	.08
47	9.9	n.d.	7.8	1.0
20	9.4	133	7.84	.09
13	n.d.	n.d.	n.d.	1.0
13	n.d.	n.d.	n.d.	.1
12	11.9	117	7.72	18.06
144	14.1	n.d.	n.d.	n.d.

Springs 154, 153, 152, and 141 had no data collected.

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Unlike nitrate and nitrite, ammonium (NH_4^+) does adsorb to soil particles, effectively immobilizing it. Ammonium found in groundwater is primarily from sources such as wetlands, septic systems and wastewater infiltration ponds, and cattle holding areas (Muldoon et al., 1990; Bundy et al., 1994). Ammonium concentrations found during this study ranged from below detection limits (<0.01 mg/L) to 0.57 mg/L. A concentration of 7.04 mg/L (site SCL2) was detected near where Jackson Creek enters Upper St. Croix Lake. Further investigation is needed to determine if this is a continuous source of ammonium or a temporary situation.

3.4.5 Soluble Reactive Phosphorus

The primary concern of elevated phosphorus concentrations in groundwater is its potential impact on surface water in areas of groundwater discharge. Soluble reactive phosphorus (SRP) is a fraction of natural phosphorus which is easily dissolved in water and readily taken up by plants and algae. Concentrations of SRP measured during this study ranged from 20 to 762 µg/L with an average value of 107 µg/L. An extremely elevated SRP value of 1507 µg/L was detected at SCL34 which is located south of Park Creek. These concentrations are very high for groundwater, though research has identified geologic materials as a source of phosphorus in groundwater in some areas of northwest Wisconsin (Muldoon et al., 1990). Additional monitoring will be necessary to interpret whether sources of phosphorus in groundwater near Upper St. Croix Lake are natural or anthropogenic.

3.5 Groundwater Contribution to Upper St Croix Lake

The criterion used to define a groundwater sample was water temperature. Physicochemical data associated with the coldest minipiezometer water temperatures (<20° C) were considered to be representative of groundwater. Warmer water temperatures were deemed more representative of lake sediment interstitial water. When groundwater's nutrient contribution to Upper St. Croix Lake was calculated, the average concentrations of the coldest water samples were used.

Nutrient loads were calculated by multiplying the groundwater inflow volume by the nutrient concentration. The annual loads were found to be as follows: SRP, 149.8 kg; nitrate + nitrite, 2173.5 kg; ammonium, 53.9 kg; chloride, 69918.1 kg. This information will be utilized in water and nutrient modeling of Upper St. Croix Lake.

3.4 Physicochemical Characteristics

Groundwater inflow to the lake was measured in the field for temperature, conductivity, and pH. Random samples were taken for lab analysis of reactive phosphorus, nitrate + nitrite, ammonium, and chloride content. Shoreland springs were assessed similarly when possible and were interpreted as points of groundwater inflow during this study. Appendix A contains tables and maps of the groundwater chemistry.

3.4.1 Conductivity

The conductivity of water entering Upper St. Croix Lake is largely below or near the regional background conductivity of approximately 160µS/cm (Kammerer, 1995). Sites SCL2 (eastern shore) and SCL48 (western shore) had the highest measured conductivity with 320 and 498µS/cm, respectively. These locally elevated measures may be originating from the groundwater transport of contaminants such as road salts, septic system effluent, and fertilizers. Sites located on the western side of the lake had overall higher measures of conductivity. This may be attributed to the greater number of salted roads on the west side of the lake, to the longer groundwater flow paths from the west and the dissolving of minerals as groundwater interacts with subsurface materials, or a combination of both factors. Testing of groundwater from outlying wells would aid in pinpointing the source of the elevated dissolved ions.

3.4.2 pH

There are no health-based standards for pH in groundwater, though pH largely controls the amount and chemical form of many organic and inorganic substances dissolved in groundwater. Water with a pH outside the range of 6.5 to 8.5 (natural background concentrations) can lead to high concentrations of dissolved metals (Hem, 1985). Low pH (acidic) groundwater can cause some metals, which have drinking water standards, to leach out of sediments into the water. The movement of metals in groundwater with high pH (basic) is not yet completely understood. Field measured values for pH ranged from 6.47 to 8.70.

3.4.3 Chloride

At present, there are no health standards for chloride in groundwater. Chloride concentrations ranged from below detection limits (<0.1 mg/L) to 56.8 mg/L with an average concentration of 15.0 mg/L. Relatively high chloride concentrations were found on the west side of the lake, predominantly along the shoreline of the village of Solon Springs. This reflects the more developed nature of the west side of Upper St. Croix Lake. Human activity is often attributed to the presence of chloride as it is not commonly found in the geology or soils of Wisconsin (Shaw et al., 2002). Chloride is found in animal and human waste and commonly used in road salts.

3.4.4 Inorganic Nitrogen

The health based standard for nitrate in drinking water is 10 mg/L. Nitrates and nitrites (NO_2+NO_3-N) are very soluble and do not bind to soils, which allows them to readily leach to groundwater. Nitrate is the form of nitrogen most available for plant use. In the sandy soils that dominate the Upper St. Croix Lake watershed, nitrate not taken up by plants can leach to groundwater with relative ease. Nitrate concentrations in the mini-piezometer samples ranged from below detection limits (<0.1 mg/L) to 1.3 mg/L and averaged 0.5 mg/L. While these levels are not of a health concern, concentrations of nitrate above 0.3 mg/L in surface waters will support algae and weed growth (Shaw et al., 2002).

A total of 47 springs were found encircling the lake and were concentrated on the southwest and east shores (Figure 5). Discharge rates were largely measured using a bag technique, whereby the time required to fill a vessel of known volume was measured. Two larger springs were measured using a flow meter and the discharges at smaller or diffuse flow sites were estimated. Spring flow rates ranged from an immeasurable trickle to 21 gallons per minute, the average discharge being 6 gallons per minute. Assuming steady-state conditions, springs were found to contribute 5.6% (6.83×10^5 m^3/year) of the total water entering Upper St. Croix Lake on an annual basis.

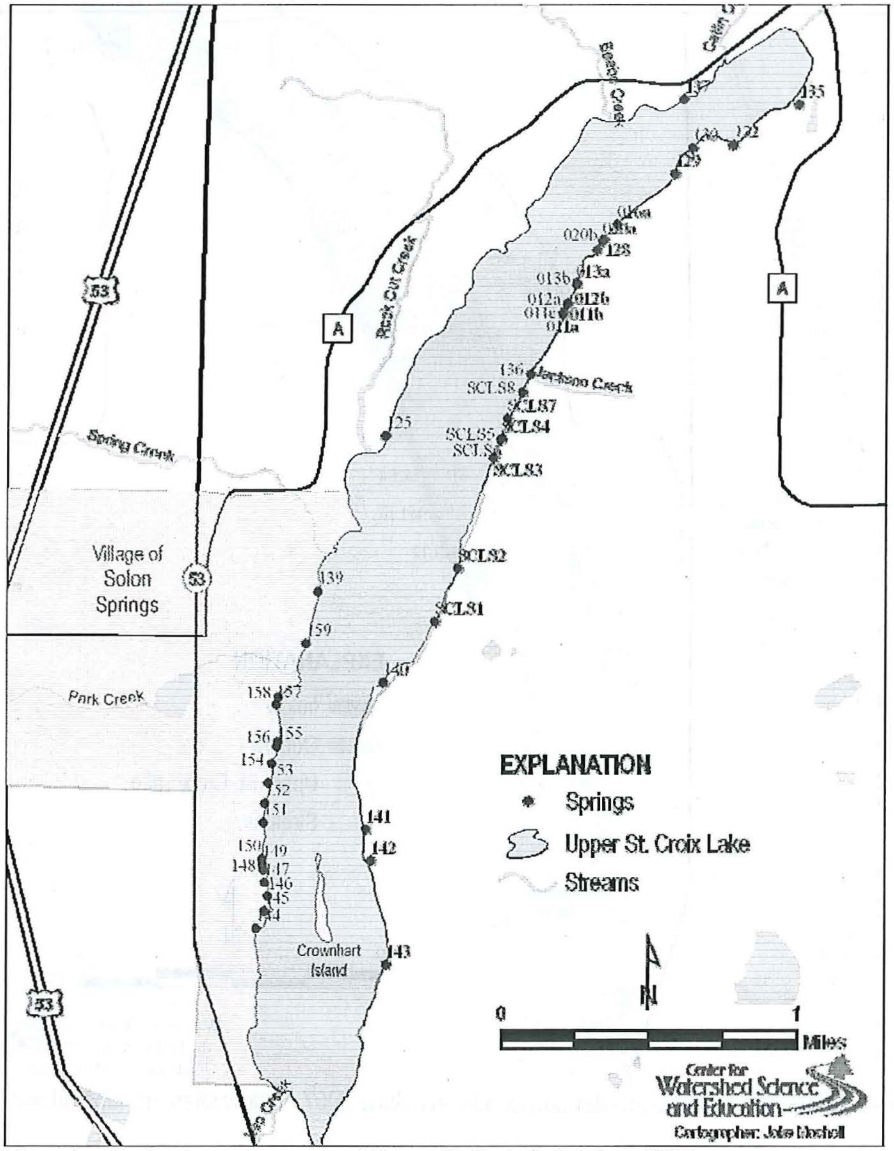

Figure 5. Location of groundwater springs around Upper St. Croix Lake, June 2007

The groundwater flux was calculated for each site using the average hydraulic conductivity and the site specific representative areas and vertical hydraulic gradients. These values were summed to determine a total estimated groundwater contribution to Upper St. Croix Lake of 4.12×10^6 m^3/year. This number represents 34% of the water contributed to Upper St. Croix Lake on an annual basis, indicating that groundwater has the potential to be a significant source of pollutants to the lake.

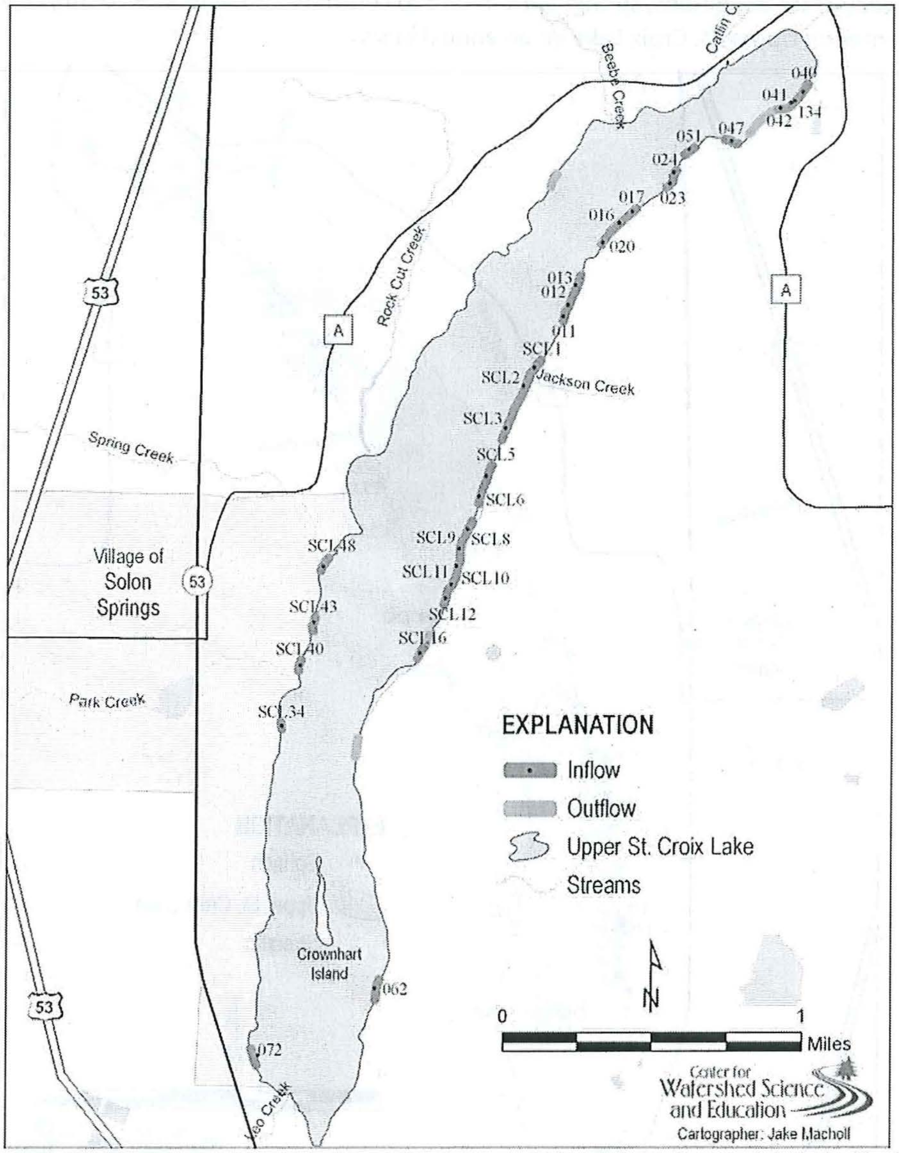

Figure 4. Upper St. Croix Lake groundwater flow conditions, June 2007. Inflow sites are labeled with site ID.

3.3.3 Springs

Shoreland springs were investigated and sampled in conjunction with the mini-piezometer study. Springs are points of groundwater discharge occurring where the water table meets the land's surface. Springs provide points to measure groundwater elevation and are sources for groundwater chemical analyses.

3.3 *Groundwater Contribution*

The hydrology of Upper St. Croix Lake can be described in terms of a water budget:

$$\Delta S = (P + SW_{in} + GW_{in}) - (ET + SW_{out} + GW_{out}),$$

where ΔS is the change in the volume of water in the lake and is equal to the volumes of water entering the lake minus the volumes of water leaving the lake. Water enters as precipitation (P), surface water inflow (SW_{in}), and groundwater inflow (GW_{in}). Water leaves the lake as evaporation and vegetative transpiration (ET), surface water outflow (SW_{out}), and groundwater outflow (GW_{out}).

The groundwater component of the Upper St. Croix Lake water budget was estimated using mini-piezometers in June 2007. A groundwater connection was established with 89% (157 out of 176) of the mini-piezometers. Measured hydraulic gradients ranged from -0.08 to 0.38, with the majority being zero indicating static, or no-flow, conditions. Groundwater inflow was found at 34 sites and was located primarily on the eastern lakeshore (Figure 4).

Six sites exhibiting recharge to groundwater (GW_{out}) were identified during the mini-piezometer investigation, suggesting Upper St. Croix Lake is acting as a groundwater discharge area. Recharge to groundwater from the lake was not measured. Water takes the flow path of least resistance, which, for Upper St. Croix Lake, is through the river channel at the southern terminus of the lake. Due to this, the recharge to groundwater component of the water budget was regarded as a negligible in this study.

3.3.1 *Hydraulic Conductivity*

The greatest source of error in groundwater seepage calculations is usually the hydraulic conductivity measurements. This study found values ranging over two orders of magnitude from 10^{-2} cm/s to 10^{-4} cm/s. The average hydraulic conductivity (0.01 cm/s) was used to calculate the groundwater seepage rate. This value is characteristic of the sediments in which the mini-piezometers were installed (Bear, 1988). The nearshore lake sediments noted during the investigation were sand and cobbles/sand for the majority of the lake with sand and muck dominating the nearshore substrate south of Crownhart Island.

3.3.2 *Groundwater Inflow*

The groundwater contribution to Upper St. Croix Lake was estimated using the Darcy relationship: $Q = -K \times A \times (\Delta h/\Delta l)$, where Q is the groundwater contribution or flux, K is the hydraulic conductivity, A is an area of the lake bed, and $(\Delta h/\Delta l)$ is the vertical hydraulic gradient.

Mini-piezometers provide a small sample in space and time and extrapolation of individual measurements to an entire lake is difficult. Generally, groundwater inflow decreases with distance from the shore (Shaw and Prepas, 1990). Mini-piezometer transects found groundwater inflow to be insignificant beyond 45 feet from the shore for much of Upper St. Croix Lake. The open water survey performed in the winter of 2007 confirmed this by noting only nearshore areas of open water. The area of inflow (A) that each mini-piezometer represented was estimated using this information. Thiessen polygons were created in ArcMap to estimate the area of inflow for individual sites (Harvey et al., 2000). The polygons were extended to 30 feet out from the shore, which is the average distance of maximum groundwater flux (Q) determined from the mini-piezometer transects.

3.2 *Groundwater Levels*

Data on the depth to groundwater are available for the area from the U.S. Geological Survey (USGS) archives (http://nwis.waterdata.usgs.gov/wi/nwis/gw). Since 1968, the USGS has been logging depth to groundwater measurements in a well south of Upper St. Croix Lake in Solon Springs, WI. The well is located just outside of the groundwatershed for Upper St. Croix Lake, but because of its proximity and because it is completed in the same sand and gravel aquifer, the data should be fairly representative of groundwater levels in the lake's groundwatershed.

The overall trend from May 1968 to November 2007 is a very slight decrease in the groundwater levels (Figure 3). The trend over the last ten years also indicates a very minor (approximately 0.3 ft) decrease in groundwater levels. The recent trend is greater than the trend for the overall record. This is representative of the below-normal levels of precipitation the area has been receiving, especially in 2006 and 2007 (NOAA, 2008). Groundwater levels fluctuate about one foot each year due to seasonal variations. The annual low generally occurs in late April, May or early June and the annual groundwater high occurs primarily in September or October.

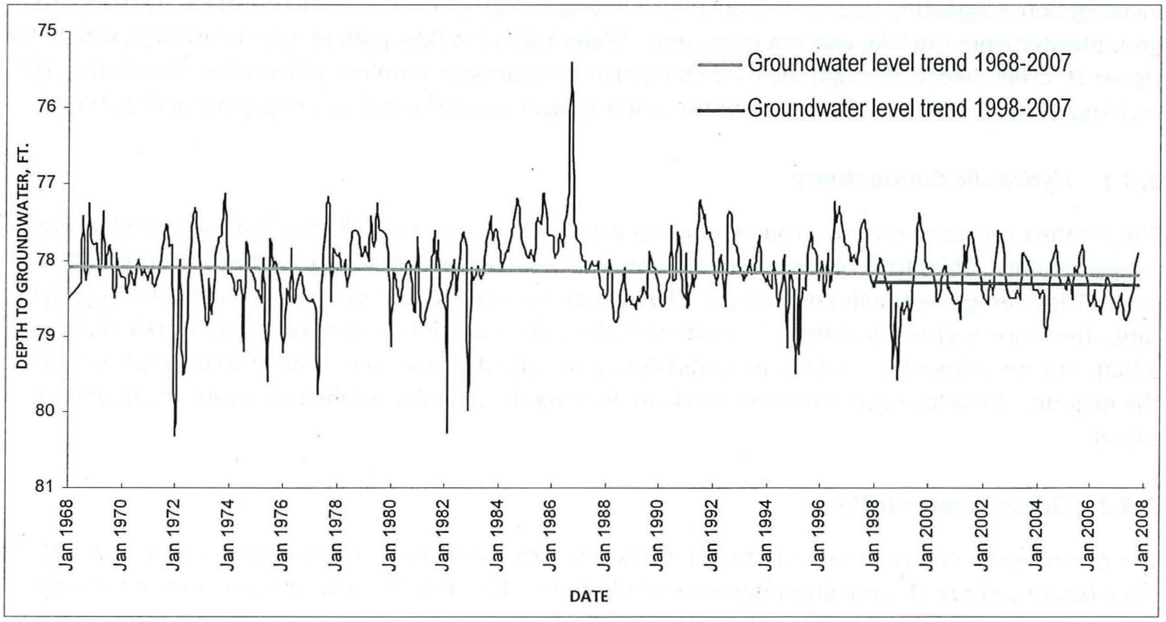

Figure 3. Depth to groundwater measurements in USGS monitoring well near Solon Springs, WI. The depth to groundwater 40-year trend is indicated by the green line; the groundwater level trend from 1998-2007 is indicated by the red line. The 40-year trend-line very closely matches the 40-year average depth to groundwater of 78.1 ft.

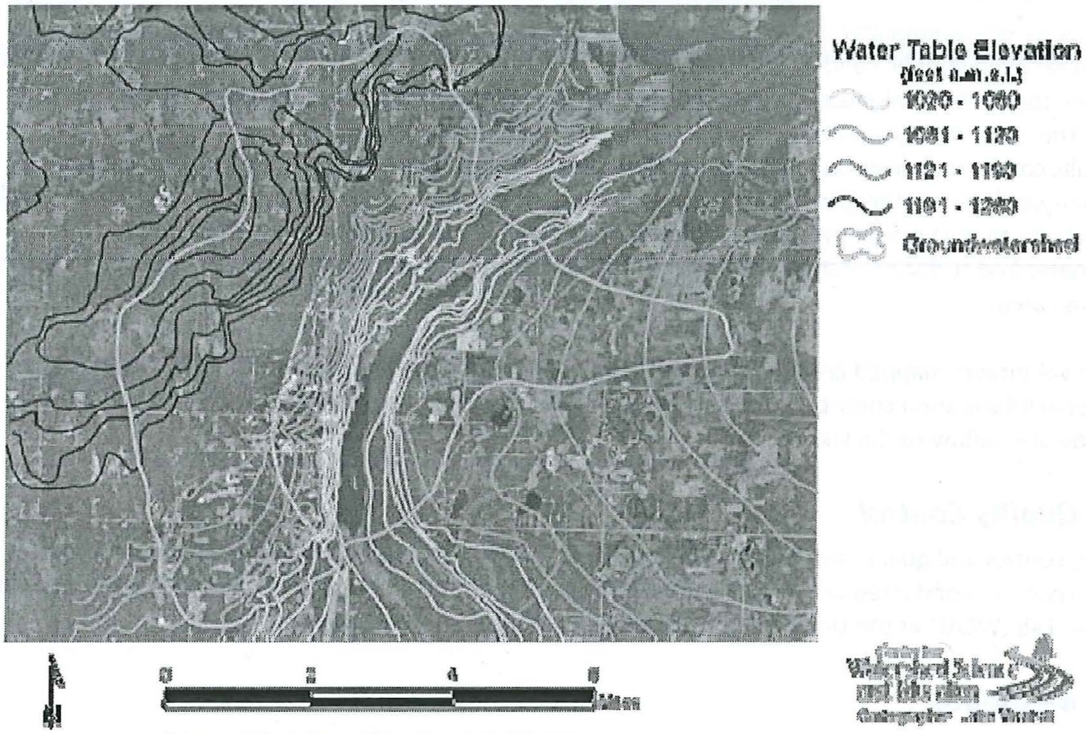

Figure 1. Groundwatershed and approximate water table elevations of Upper St. Croix Lake.

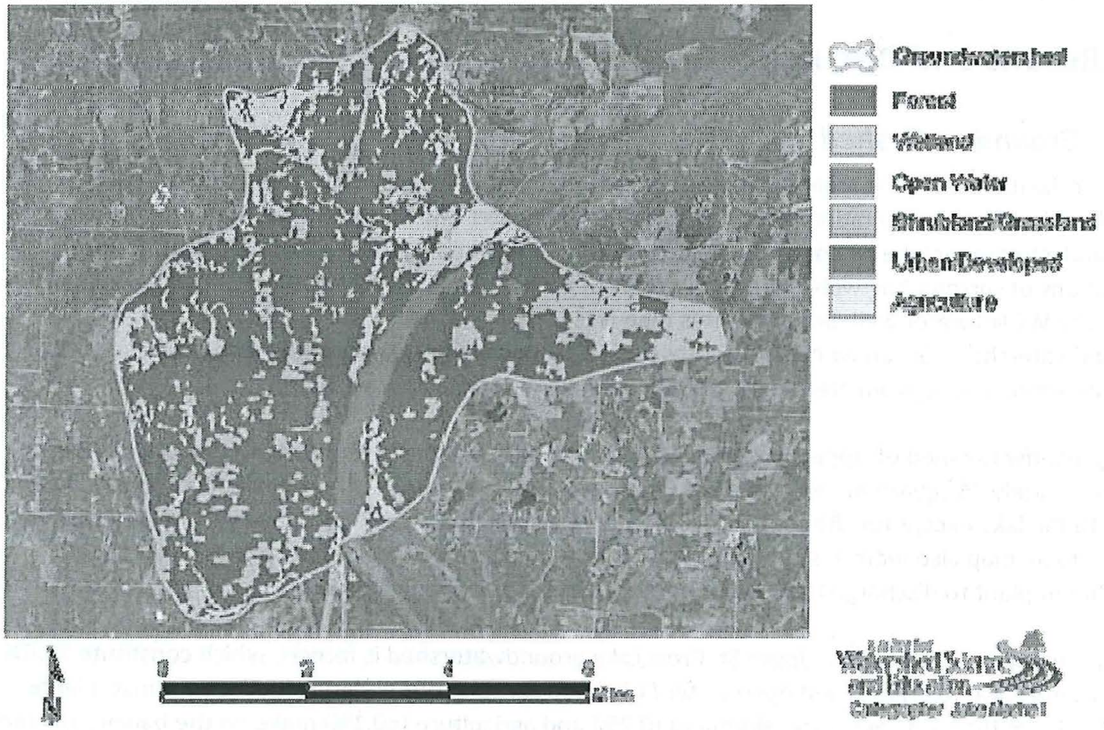

Figure 2. Land use within the Upper St. Croix Lake groundwatershed.

The velocity of groundwater inflow, or seepage rate, was estimated by conducting falling head tests to determine the hydraulic conductivity (Fetter, 2001). The test was performed by timing the fall of water from the top of the mini-piezometer to a black O-ring placed at 37% of the slug height above the static head. This procedure was repeated three times to determined an average falling head time. The hydraulic conductivity was calculated using the average falling head time and design specifications of the mini-piezometer. The groundwater seepage rate, or flux, was estimated by multiplying the hydraulic conductivity to the vertical hydraulic gradient (the difference in water levels between the mini-piezometer and surface water, divided by the depth from the sediment surface to the middle of the screened area).

Citizen volunteers mapped areas of open water and ice-melt on the lake in January 2007. This additional information contributes to a more complete understanding of the location and extent of groundwater inflow to the lake.

2.2 *Quality Control*

Quality control and quality assurance techniques were observed when performing field and lab work. All analyses not conducted in the field were completed at the WDNR certified Water and Environmental Analysis Lab (WEAL) at the University of Wisconsin-Stevens Point (UWSP).

2.3 *Metadata*

Land use coverages were obtained from the Wisconsin Initiative for Statewide Cooperation on Landscape Analysis and Data (WISCLAND). ArcMap 9.2 software was used with hydrology, road coverages, and political boundaries for data interpretation. Additional maps were digitized at UWSP.

3 Results and Discussion

3.1 *Groundwatershed*

A groundwatershed is the area of land (including both the overlying surface area and underlying aquifers) in which precipitation infiltrates to the groundwater and flows to a discharge zone such as a wetland, stream, or lake. A contour map of water-table elevations was created using the surface elevations of surrounding water bodies as points of water table elevation and water-table elevations from the WDNR water well data files. This map was used to delineate the Upper St. Croix Lake groundwatershed. Groundwater flow paths are perpendicular to equipotential (contour) lines, with groundwater flowing from areas of higher elevation to areas of lower elevation.

The groundwatershed of Upper St. Croix Lake is closely aligned to the surface watershed and covers approximately 34 square miles of land area (Figure 1). The vast majority of the lake has groundwater flow to the lake except for the southern terminus where groundwater flow is away from the lake. The water-table map also indicates the potential for groundwater from the Solon Springs wastewater treatment plant to discharge towards Upper St. Croix Lake and to Leo Creek.

The primary land cover in the Upper St. Croix Lake groundwatershed is forests, which constitute 70.6% of the land area. Wetlands and open water (17%) and shrubland/grassland (12.1%) comprise a large remainder of the land cover. Development (0.2%) and agriculture (<0.1%) make up the balance of land use (Figure 2).

1 Introduction

Upper St. Croix Lake is located in northern Wisconsin in Douglas County. The lake is an 855-acre natural impoundment that serves as the headwaters of the St. Croix River. The lake receives water from groundwater, seven tributaries, surface runoff, and direct precipitation. The Village of Solon Springs is located on the western shore of the lake. Many of the local businesses thrive by providing services to lake residents and recreational visitors. The concerns of local citizens and Upper St. Croix Lake Association members about blue-green algae blooms and reduced water clarity led to this study.

1.1 Study Goals and Objectives

The objective of this study was to better understand the role of groundwater in Upper St. Croix Lake's water and nutrient budgets. The data gathered will be used in lake nutrient models. Specific objectives of the UWSP study included:

- develop a water-table map and identify groundwater flow directions
- assessing the current water quality of groundwater entering the lake
- estimate groundwatershed nutrient contributions

2 Methods

2.1 Groundwater Measurements

In June 2007, groundwater flow conditions (inflow, outflow or static) of Upper St. Croix Lake were assessed using mini-piezometers (small, temporary wells) placed approximately every 100 yards around the perimeter of the lake. Well positions were marked using a handheld GPS and labeled on a map for future reference and investigation. Lab analyses were completed on 35 water samples for concentrations of nitrate-nitrite (NO_2+NO_3-N), ammonium (NH_4-N), soluble reactive phosphorus (SRP), and chloride from sites exhibiting groundwater inflow and from groundwater spring locations.

The mini-piezometers were constructed from 5 foot lengths of 3/16 inch inside diameter polypropylene tubing with a point formed on the bottom end. A small diameter ball-point sewing needle was used to perforate the bottom 9.5 cm of the tubing starting 7 cm from the point. A 1 ml pipette tip was attached to the pointed end to protect the mini-piezometer tip during installation.

Researchers installed the mini piezometers to shallow depths (11-19 inches) in the lake sediment in an average water column of 24 inches. A metal rod was inserted into the mini-piezometer to ease the insertion of the well into the lake sediment. After reaching an installation depth of approximately 18 inches, the metal rod was removed and the well was developed to ensure communication with the groundwater. Well development was performed by injecting two to three 60cc syringes of water into the well and drawing four to five full syringes back out until clear water, assumed to be groundwater, was found. The site was abandoned if communication with groundwater could not be established.

At each sample site measurements of water depth, installation depth, static head height, and slug height (length of tube above static head) were recorded. Static head identifies whether groundwater is entering the lake (inflow) or whether water is leaving the lake (outflow); a static head above the lake water indicates inflow and a static head below the lake water indicates outflow. A site where the head is level with the lake water is considered a no-flow or static site.

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Acknowledgements

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Groundwater Assessment of
Upper St. Croix Lake, Douglas County, Wisconsin

April 2008

University of Wisconsin – Stevens Point
Center for Watershed Science and Education
N. Turyk, J.A. Macholl