JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 55, No. 2 AMERICAN WATER RESOURCES ASSOCIATION April 2019

Further Development of a Specific Conductivity Approach to Measure Groundwater Discharge Area within Lakes

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Research Impact Statement: Lakebed seepage index (LSI) expands specific conductivity point measurements to lake-wide assessment of groundwater discharge areas within a lake.

ABSTRACT: Groundwater exchanges with most lakes are rarely quantified because there are many technical challenges to quantification. We investigated a lakebed mapping approach to infer the relative areas of groundwater exchange in 12 prairie shallow lakes and five Laurentian mixed forest shallow lakes in Minnesota, USA in 2011. We used a relatively common approach (seepage meters) to provide baseline information on the magnitude and direction of flow at four locations in each lake. To expand from point measurements to the whole-lake scale, we explored use of specific conductivity as a cheaper and more time efficient proxy for groundwater discharge to lakes. We validated the approach at near shore stations in each lake where seepage meter measurements and specific conductivity surveys overlapped. Specific conductivity surveys provided a similar assessment of groundwater discharge compared to seepage meters for 50% of the lake-sampling period combinations. The lakebed mapping approach, when validated for a lake with a limited number of seepage meter (or alternative methods) measurements, offers the advantages of being more time and labor efficient over the use of a similar number of seepage meter monitoring locations; seepage meters (or piezometers, for example) are costlier in terms of equipment and labor, even for single-lake studies. We show the combined approach could provide useful baselines for understanding and mapping groundwater exchange in shallow lakes.

(KEYWORDS: groundwater; seepage meter instrumentation; specific conductivity; shallow lakes.)

INTRODUCTION

Surface water in shallow lakes is affected by many factors, such as land management, surface water connections, biological communities, and interactions with underlying groundwater. Climate, geomorphic setting, and groundwater exchange are often key determinants of water budgets and the ecology of wetlands and shallow lakes (Lodge et al. 1989; LaBaugh et al. 1995; Hagerthey and Kerfoot 1998; Rosenberry et al. 2000; Euliss et al. 2004; Sebestyen and Schneider 2004). While many factors influencing surface waters are well-studied, groundwater exchange remains among the most cryptic variables in all but a few well-studied lakes (e.g., Cottonwood Lake Area, ND; Kantrud et al. 1989; Winter and Rosenberry 1995). Better knowledge of extent, type (recharge, discharge), and location of groundwater movements is needed to allow aquatic scientists to assess

Paper No. JAWRA-17-0165-P of the *Journal of the American Water Resources Association* (JAWRA). Received December 19, 2017; accepted December 19, 2018. **Discussions are open until six months from issue publication**.

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Citation: Bischof, S.M., B.R. Herwig, S.D. Sebestyen, M.A. Hanson, K.D. Zimmer, J.B. Cotner, and T.J. Kroeger. 2019. “Further Development of a Specific Conductivity Approach to Measure Groundwater Discharge Area within Lakes.” *Journal of the American Water Resources Association* 55 (2): 485–496. https://doi.org/10.1111/1752-1688.12730.

the importance of groundwater exchange and geomorphic settings, and to integrate these hydrodynamics with other factors that affect shallow lake waters.

Groundwater interactions vary greatly over space and time (McBride and Pfannkuch 1975; Winter 1976, 1981; Sebestyen and Schneider 2001) and are difficult to study especially in larger lakes (Brock et al. 1982). At any point in a lake, there are two possible directions of flow, though there may be times and places of no water flow through a lakebed. Water upwelling through the lakebed is discharge or inseepage of groundwater to a lake. Water downwelling through the lakebed is recharge or outseepage to groundwater.

Monitoring efforts require intensive instrumentation (piezometers, nests of groundwater wells, seepage meters, etc.) as well as frequent field measurements to document groundwater interactions for even one water body (Winter 1981, 1989; Lee and Welch 1989; Sebestyen and Schneider 2001). Variation in groundwater sources affect lake chemistry and specific conductivity (Brock et al. 1982; LaBaugh 1989; Riera et al. 2000; Hayashi and Rosenberry 2002). Calcium, magnesium, carbonates, and silicon concentrations increase as minerals are chemically weathered along groundwater flowpaths (Freeze and Cherry 1979; Hem 1985) and enter lakes where and when groundwater discharges through lakebeds. It is reasonable to expect solute concentrations, and specific conductivity, which is a proxy of total dissolved inorganic solutes, to be higher in lakes that have more groundwater inflow relative to surface water inflow (LaBaugh 1989; Winter 1989; Riera et al. 2000) in humid climates.

Discharging groundwater with high solute concentrations leads to greater ionic strength and higher specific conductivity in freshwater wetlands and lakes (LaBaugh 1989; Harvey et al. 1997). Mapping specific conductivity along a lakebed has been used to infer areas of groundwater discharge (Hawkinson and Verry 1975; Harvey et al. 1997). In a related approach, Hanson et al. (2005) applied specific conductivity as a proxy variable to rank relative magnitudes of groundwater discharge among 45 shallow lakes in Minnesota and North Dakota.

In our study, we used traditional groundwater instrumentation (seepage meters and piezometers) to determine lake water sources in two study regions. We augmented these approaches with mapping of specific conductivity in water at the sediment surface across entire lakebeds. Using results from colocated specific conductivity measurements, seepage meters, and piezometers, we compared these three methods and evaluated their utility for quantifying whole-lake groundwater discharge.

METHODS

Site Description

We studied groundwater exchange in shallow lakes, defined as having depths of <5 m, within two ecological regions in Minnesota, USA; five lakes were located in a forested Itasca State Park (ISP) study area and 12 lakes were in a prairie region of West Central (WC) Minnesota (Figure 1; Table 1). ISP is a heavily visited park, with undeveloped lands that are managed for mature and old-growth forests. Surface geology is dominated by coarse and gravelly till of the Itasca moraine with calcareous loamy soils. Glacial drift ranges in thicknesses from 60 to 180 m (Almendinger et al. 2000). WC Minnesota had prairies before European settlement but has largely been converted to agriculture. Study lakes here were mostly in public ownerships (nine lakes were within Waterfowl Production Areas administered by the U.S. Fish & Wildlife Service and two lakes were within Wildlife Management Areas administered by the Minnesota Department of Natural Resources). The land around one lake was privately owned. The adjacent uplands support grasses within surrounding landscapes of row crops. This prairie region has gently rolling ground moraines with glacial drift thicknesses between 30 and 122 m (Almendinger et al. 2000). Soils are loamy and formed in gray calcareous till.

Study lakes lacked major surface water contributions from inflows (inlets); only 2 of the 17 lakes had small inlets, which in both cases were connections to similar upstream lakes. About 41% of the study lakes had outlets and were connected to downstream water bodies. Three of the seven lake outlets formed connections with like lakes, and four outlets formed connections with much larger, downstream lakes. Solute concentrations in our lakes were likely influenced most strongly from inputs from the immediate lake watershed as well as from groundwater sources. Due to shallow water depths, nutrients and surface water are well mixed.

Monitoring Groundwater Flow

During 2011, lakes were sampled once in mid-summer between June 14 and July 27 and a second time in late summer between August 11 and September 1. Groundwater was monitored at four near shore stations in each lake, and stations were located in northeast, northwest, southeast, and southwest quadrants. Sampling stations, which were chosen randomly in each lake quadrant, consisted of one seepage meter

FIGURE 1. Location of Itasca State Park and West Central study areas in Minnesota.

and one piezometer that were equidistant from the shoreline and separated from one another by a 50–100 cm buffer (Sebestyen and Schneider 2004). Stations were 2–10 m offshore where the water was 50–90 cm deep.

Seepage meters were used to measure the volume of groundwater discharge or recharge at the four locations in each lake (Figure 2). The seepage meter design (Lee 1977) was modified as per Rosenberry (2008). Meters were bottomless high-density polyethylene cylinders, approximately 58 cm in diameter, and fitted with a 1.27 cm diameter nozzle on the top side near the edge of the cylinder. Open ends of cylinders were pressed or driven into the lakebed until the tops were about 3 cm from the sediment and the nozzles on the cylinders were elevated to allow gas escape. Seepage meters were installed and sampled from a canoe to minimize disturbance. Following a stabilization period of at least 30 days, a 3-m hose was attached to the top nozzle and stretched parallel to the shoreline (Rosenberry 2008). The hose provided a buffer distance to minimize lakebed disturbance in the immediate vicinity of a seepage meter. A 4-L bag (filled with 1.5 L of water and expelled of air) was secured to the hose with a shutoff valve (left open when the meters were not being measured). The seepage bag was enclosed in a perforated rigid box to protect against wave action (Rosenberry 2008; Rosenberry and LaBaugh 2008). The time when the shutoff valve on a seepage bag was opened was recorded. After approximately 24 h, shutoff valves were closed, bag volumes were measured, and time was again

TABLE 1. Lake information including Lake identifier (and Abbr.), Surface area, and Geographical location.

Lake identifier	Abbr.	Surface area (m^2)	Latitude	Longitude
West Central Lake 1	WC1	114,741.6	46°04′50.19″N	96°09′49.82″W
West Central Lake 2	WC2	87,463.6	46°03′58.95″N	96°09′58.26″W
West Central Lake 3	WC3	72,331.7	45°59′35.02″N	95°53′06.47″W
West Central Lake 4	WC4	33,305.5	45°58′22.42″N	95°52′28.26″W
West Central Lake 5	WC5	120,117.0	45°55′55.85″N	95°51′25.13″W
West Central Lake 6	WC6	30,334.9	45°53′29.36″N	95°45′25.35″W
West Central Lake 7	WC7	91,508.5	45°42′53.31″N	95°53′24.19″W
West Central Lake 8	WC8	56,560.1	45°34′54.88″N	95°32′02.60″W
West Central Lake 9	WC9	141,847.9	46°15′49.20″N	96°03′08.40″W
West Central Lake 10	WC10	146,136.1	46°07′53.85″N	95°53′34.36″W
West Central Lake 11	WC11	153,165.6	45°47′15.88″N	95°44′26.49″W
West Central Lake 12	WC12	80,969.9	45°51′02.60″N	95°53′42.05″W
Itasca State Park Lake 1	ISP1	19,712.2	47°11′43.73″N	95°17′49.19″W
Itasca State Park Lake 2	ISP2	63,823.2	47°12′07.20″N	95°17′58.74″W
Itasca State Park Lake 3	ISP3	96,528.5	47°08′33.48″N	95°09′23.21″W
Itasca State Park Lake 4	ISP4	37,086.9	47°11′13.30″N	95°11′04.36″W
Itasca State Park Lake 5	ISP5	12,970.3	47°11′25.49″N	95°10′50.80″W

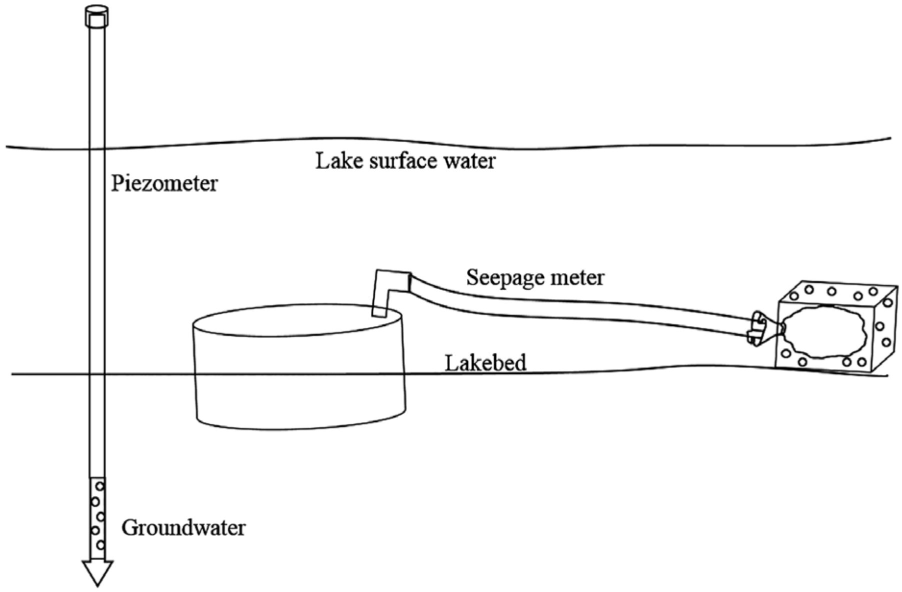

FIGURE 2. Schematic of sampling methods: seepage meter to measure seepage flux, piezometer to collect groundwater samples and measure Groundwater$_{sc}$, Lakebed$_{sc}$ was measured directly above the sediment surface, and Surface water$_{sc}$ was measured just below the water surface.

recorded. A decrease in volume indicated groundwater recharges and increases indicated groundwater discharge. Seepage flux was calculated using the formula:

$$Q = \frac{V_f - V_o}{\Delta t \times A}, \tag{1}$$

where V_o represents initial bag volume, V_f was volume after bag removal, Δt indicates collection time (duration of time when the shutoff valve was open), and A represents surface area beneath the seepage meter.

Groundwater and Surface Water Sampling

Groundwater samples were collected from piezometers constructed of PVC pipe with an inside diameter of 1.9 cm connected to a 10 cm perforated PVC tube that contained a polyethylene porous filter (Figure 2) (Kalbus et al. 2006; Toran et al. 2010).

Each piezometer had a polyethylene internal sampling line that was connected to a hand pump for extraction of groundwater samples. Piezometers were hand driven into the lakebed, until the top of the filtered tip was 30 cm below the sediment–water interface. Before being sampled, piezometers were left undisturbed for at least a month.

Different methods were used to sample water depending on direction of groundwater exchange. When a seepage meter indicated recharge, a tube was connected with a hand suction pump to the internal line of the piezometer for extraction of groundwater. Prior to collection of a groundwater sample, water was evacuated from the piezometer one hour before sampling. Immediately before taking the sample, the piezometer's sample volume was purged three times using the hand suction pump. Eight piezometers took greater than one hour to refill, and were purged of all water just once before a sample was collected for laboratory analysis. When seepage meters showed discharge, piezometers were sampled differently to ensure that surface water had not leaked through the perforated section of the shallow piezometers. We measured specific conductivity in 100 mL increments as water was pumped from a piezometer until values changed by <100 μS/cm or 10% of the previous measurement. That volume of water was then collected for solute concentration measurements. After sampling, a 20.3 cm diameter tube was placed around each piezometer and these devices were gently pushed a few cm into the sediment surface. A salt solution was then added to the water between the 20.3 cm tube and piezometer and specific conductivity was measured. Additional 100-mL increments, ranging from a total volume of 1,000–50,000 mL, were pumped from a piezometer to detect increased specific conductivity values that would have been indicative of surface water leaking into a piezometer. Surface water contamination in discharging groundwater samples occurred in <13% of piezometers. There was no distinguishable pattern in the occurrence of surface water contamination in the groundwater samples. If specific conductivity did not change after addition of the salt tracer, samples were considered valid for chemistry analysis.

Surface water samples were collected 0.3 m below the water surface at the middle of each lake. All samples were transported back to the laboratory on ice, filtered through 0.45 μm polypropylene membrane filters, and frozen until subsequent chemical analyses. Water samples were thawed and analyzed for chloride (Cl^-), nitrate (NO_3^-), nitrite + nitrate ($NO_2^- + NO_3^-$), phosphate (PO_4^{-3}), sulfate (SO_4^{-2}), ammonium (NH_4^+), aluminum (Al^{+3}), calcium (Ca^{+2}), total iron, potassium (K^+), magnesium (Mg^{+2}), manganese (Mn^{+2}), sodium (Na^+), silicon (Si), strontium (Sr^{+2}), specific conductivity, and dissolved organic carbon and detailed laboratory methods can be accessed in Supporting Information. Reference standards and analytical duplicates of samples were analyzed after every tenth sample. A relatively small percentage of samples analyzed for Al, Fe, Mn, Sr, nitrate, or nitrite + nitrate (range = 1.3%–8%) had recorded values that fell below the method detection limit (MDL), and were replaced with MDL/2 following the guidance of USEPA (2000). All chemical analyses were performed at United States Department of Agriculture (USDA) Forest Service Forestry Sciences Laboratory in Grand Rapids, Minnesota. Although detailed water chemistry patterns were not our focus, there were some regional and water source patterns that may be useful to some readers. Data analysis methods and findings are reported in Supporting Information.

Conductivity Mapping

A handheld YSI EC300 meter (YSI Inc., Yellow Springs, Ohio, USA) was used to measure specific conductivity at 30–39 lakebed locations, depending on lake size. Due to the wide range of surface areas, a mathematical method was devised to designate the number of locations. At a range of 10,000–19,999 m^2, the increment was divided by 500 m^2, averaging 30 specific conductivity sample locations. To determine the number of sample locations for larger lakes, lake area increments increased by 10,000 m^2 and the dividing factor increased by 250 m^2 to determine the number of specific conductivity sample locations. Lake surface areas ranged from approximately 12,970 m^2 (30 measuring points) to 153,165 m^2 (39 measuring points). A Garmin GPSmap76csx (Garmin International Inc., Olathe, Kansas, USA), with position error of <10 m, was used to record the coordinates of each measurement location.

We assessed whether high relative specific conductivity, within 1.0 cm above the sediment surface ($Lakebed_{sc}$), could be used to indicate areas of groundwater discharge in our study lakes (Harvey et al. 1997). Extending this idea, we surmised that lower values of $Lakebed_{sc}$ compared to surface water ($Surface\ water_{sc}$) indicated groundwater neutral or recharge areas. We calculated a lakebed seepage index (LSI) of relative discharge magnitude for each lakebed specific conductivity measurement location.

$$\frac{(Groundwater_{sc} - Lakebed_{sc})}{(Groundwater_{sc} - Surface\ water_{sc})} = LSI \qquad (2)$$

We assigned $Groundwater_{sc}$ as one value for all LSI calculations within an individual lake, taken as a mean specific conductivity value of all piezometers indicating discharging groundwater (Figure 2). We assigned Surface water$_{sc}$ as one value for all LSI calculations taken from 0.3 m below the lake surface at the center of an individual lake. We assigned Lakebed$_{sc}$ as an individual measurement directly above the sediment surface for the 30–39 locations within an individual lake. In the first round of sampling, 10 lakes showed specific conductivity in surface water that differed from groundwater, while seven lakes showed no difference. In the second round of sampling, nine lakes showed specific conductivity in surface water that differed from groundwater, while eight lakes showed no difference. In lakes that showed no difference between Surface water$_{sc}$ and Groundwater$_{sc}$, Lakebed$_{sc}$ at sampling stations where discharge was shown by seepage meters was used to distinguish the threshold between discharging groundwater and non-discharging groundwater.

LSI indicated groundwater discharge, but does not provide enough information to further differentiate between the conditions of recharge or no flow. An LSI below 1.0 indicated a Lakebed$_{sc}$ associated with discharging groundwater, while an LSI > 1.0 indicated a Lakebed$_{sc}$ associated with a neutral or recharging groundwater zone. Measuring specific conductivity directly above the lakebed measured either groundwater just after passing through the lakebed into the lake or lake water just before passing though the lakebed into groundwater (recharge). Lakebed$_{sc}$ values from point measurements were interpolated using kriging to estimate the total area of lakebed area discharging groundwater to each lake. These maps allowed us to visualize patterns in groundwater discharge across the entire lakebed for each study lake. Maps were generated from Lakebed$_{sc}$ values in ArcGIS 10.5.1, with ordinary kriging interpolation using the spatial analyst tool available within the ESRI software package (ESRI 2018). Kriging has been found to provide the best linear unbiased estimates of specific conductivity in groundwater analyses (Kumar 2010).

We performed a Pearson correlation analysis of LSI values and seepage flux calculated at seepage meter locations to link traditional groundwater sampling equipment to specific conductivity and LSI. The correlation analysis of LSI values and seepage flux was computed with SYSTAT 13 software (SYSTAT 2009). Lakes were analyzed individually for each sampling round to minimize uncontrollable variables that varied seasonally and geographically.

RESULTS

Specific conductivity was much higher in all water sources from the WC area (compared to ISP lakes) during both sampling periods ($p < 0.05$; Figure 3). Specific conductivity was consistently higher in discharging groundwater samples than in surface water samples, lending support to the notion that specific conductivity was useful as an indicator of discharging groundwater along lakebed surfaces. Specific conductivity levels in recharging groundwater were often lower than those in discharging groundwater, but in some cases specific conductivity levels were comparable between discharge and recharge sites.

Seepage flux measured at each seepage meter indicated either discharging groundwater or non-discharging groundwater at the LSI value associated with the meter. The Pearson correlation between seepage flux and LSI showed varying results, ranging from a strong positive correlation to a strong negative

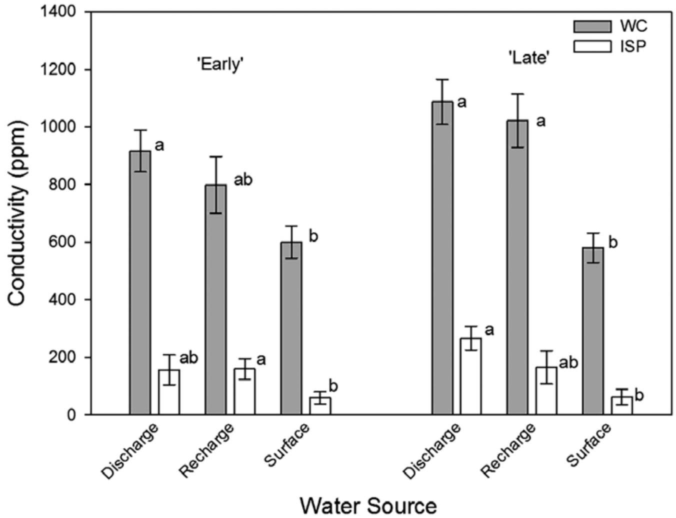

FIGURE 3. Mean specific conductivity (±1 SE) in discharging groundwater, recharging groundwater, and surface water in "early" (left panel) and "late" (right panel) sampling periods for the West Central (WC) study lakes (gray bars) and Itasca State Park (ISP) study lakes (open bars). Small case letters indicate differences among water sources (groundwater discharge, groundwater recharge, and surface water) within a study area. Water sources that do not share a letter are significantly different. Specific conductivity values were significantly higher in WC compared to ISP lakes for all water sources in both sampling periods.

TABLE 2. Pearson correlation results between seepage flux measured from seepage meters and lakebed seepage index (LSI) calculated from specific conductivity.

Correlation strength	Number of lakes	Correlation coefficient
Strong positive	8	1.0 to 0.5
Moderate positive	2	0.5 to 0.3
Weak positive	7	0.3 to 0.1
No correlation	4	0.1 to −0.1
Weak negative	1	−0.1 to −0.3
Moderate negative	2	−0.3 to −0.5
Strong negative	10	−0.5 to −1.0

TABLE 3. Percent of sediment surface area contributing to discharging groundwater during 2011.

WC			ISP		
Lake	Percent	Seepage meter results	Lake	Percent	Seepage meter results
WC2	7/74	↑↑↑↑/↑↑↑↑	ISP2	15/5	↓↑↓↓/↓↓↑↑
WC8	24/99	-↑↓↑/↑↑↑↑	ISP1	33/38	↑↓↓↓/↑↓↓↓
WC3	NA/79	↓↓↓↓/↓↑↓↓	ISP3	54/57	↓↑↑↑/↑↓↑↑
WC6	44/11	↓↑↑↓/↑↓↑↓	ISP5	88/94	↓↑↑↓/↑↑↑↑
WC7	46/43	↑↑↑↓/↓↓↑↓	ISP4	92/NA	↑↑↑↓/↓↓↑↑
WC9	75/17	↑↑↑↓/↑↑↓↑			
WC5	98/87	↑↑↑↑/↑↑↑↓			
WC11	99/99	↑↑↑↑/↑↑↑↑			
WC12	99/4	↑↑↑↑/↓↑↑↑			
WC10	99/96	↑↑↑↑/↑↑↓↑			
WC4	NA/NA	↓↑↓↑/↓↓↓↑			
WC1	NA/39	↓↑↑↑/↑↓↑↑			

Note: For each sampling station (NE, SE, SW, and NW) and each sampling period, groundwater discharge is indicated with ↑ and groundwater recharge is indicated with ↓. Percent area discharging data ("percent") displayed as mid-summer (June 14, 2011 through July 27, 2011) value/late-summer (August 12, 2011 through September 1, 2011) value.

correlation (Table 2). Four lakes (WC3, WC12, and ISP4 during the early period, and WC4 during the late period of sampling) showed no correlation between seepage flux and LSI.

LSI values were used to distinguish between Lakebed$_{sc}$ values associated with discharging groundwater and Lakebed$_{sc}$ values associated with non-discharging groundwater. Lakebed$_{sc}$ values associated with groundwater discharge were subsequently used to calculate the percentages of sediment surface area with discharging groundwater in the study lakes (Table 3). ISP lakes showed a wide range, with 5%–94% of individual lakebed surface areas associated with discharging groundwater. The pattern in the WC Minnesota lakes was also highly variable, with seasonal differences in lakebed areas discharging groundwater ranging from 0% to 95% (Table 3). We did not observe consistent directional changes in lakebed discharge areas between the two different sampling dates but several lakes exhibited dramatic changes between these periods, for example, WC2, WC9, and WC12 (Table 3). Percent lakebed areas discharging groundwater could not be calculated for four lake-sampling period combinations: WC1 during the early period, ISP4 in the late period, or WC4 for both sampling periods because either the seepage meters only showed groundwater recharge or the seepage meter results were contradicting the specific conductivity values measured above the lakebed (Table 3). A kriged map of specific conductivity values is provided for WC2 as an example of relative intensity of groundwater discharge across the lakebed (Figures 4 and 5). Additional maps of all other study lakes and sampling period combinations are provided in Supporting Information.

DISCUSSION

We combined Lakebed$_{sc}$ measurements with results from traditional groundwater monitoring techniques using seepage meters and piezometers to characterize groundwater exchange in shallow lakes within two different ecological regions of Minnesota. Our method of mapping specific conductivity indicated that areas of groundwater input could be quantified and visualized from mapping spatial variability in Lakebed$_{sc}$, though the approach should be validated for a particular lake given negative correlations that we observed between seepage flux from seepage meters and LSI. This approach has the potential to offer a quick and inexpensive means to compare or even rank shallow lakes based on inferred magnitude of groundwater inputs. Lakebed$_{sc}$ monitoring in shallow lakes allows lake-scale estimates, rather than "snap-shot" views of groundwater exchange from a handful of points such as wells and piezometers. Relationship strength between seepage flux and LSI ranged from no correlation to strong correlation. A strong correlation indicates that specific conductivity measured in lake surface water, discharging and recharging groundwater, and on lakebed surface can be used to calculate a LSI that distinguishes between discharging groundwater areas and non-discharging groundwater areas. Findings of a weak or no correlation indicates that there was poor spatial agreement between LSI and Lakebed$_{sc}$ measurements compared to measurements from traditional groundwater monitoring equipment. Higher resolution temporal and spatial measurements may need to be conducted in future assessments to understand and validate more fully these alternative approaches.

Water sources of wetlands and lakes largely depend on landscape setting and vary from precipitation to groundwater-dominated (Romanov 1961). Directionality and magnitude of groundwater interactions also vary and predominant groundwater directionality may be mostly recharge, discharge, both recharge and discharge (flow through), or none as some basins have no apparent exchange with underlying groundwater (Kantrud et al. 1989; Winter 1989; Winter and Rosenberry 1995; Kratz et al. 1997; Fetter 2001). Chemical composition of wetlands and shallow lakes reflect predominant groundwater exchange, along with characteristics of soil and underlying parent materials along groundwater flow pathways

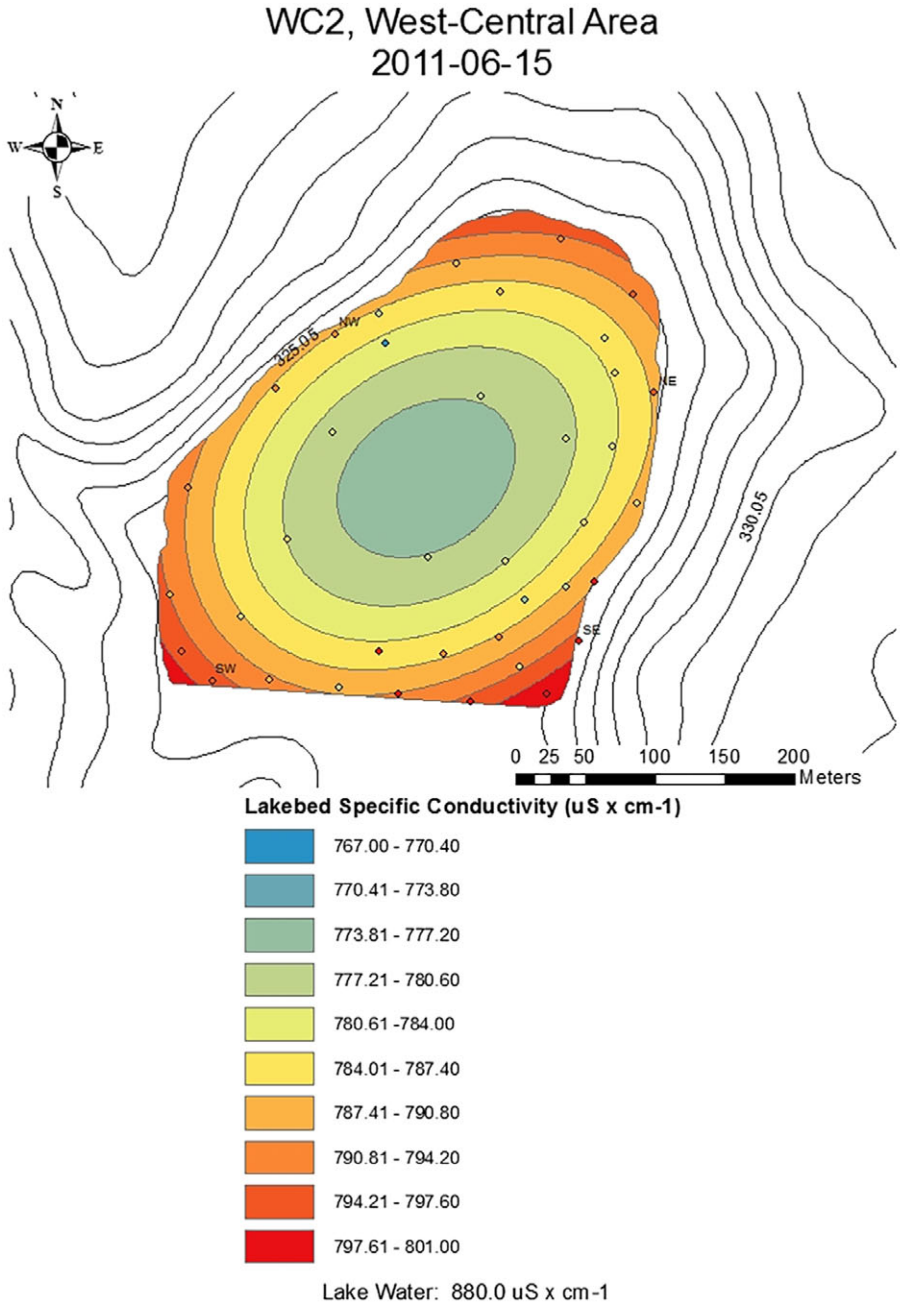

FIGURE 4. Map of WC2 with contours depicting the variations of specific conductivity throughout the lake bottom, early summer. The noncolor class contours are local elevation of the surrounding landscape.

(LaBaugh 1989). Longer flowpaths provide more opportunity for accumulation of solutes. Combined influences of long flow pathways, thick glacial till, and predominant discharge sometimes produce hypersaline condition in shallow lakes, especially in arid landscapes such as those within the North American Prairie Pothole Region (Kantrud et al. 1989; Euliss et al. 2004). Given the major chemical and biological influences of groundwater exchange in shallow lakes, and the extreme variability among these waters, investigators need simple, less costly methods for assessing groundwater exchange, and the approach described here may offer practical advantages especially for studies of multiple lakes.

Our study suggests that lakebed specific conductivity mapping is a much cheaper, and more time efficient proxy for estimating groundwater discharge to lakes compared to seepage meters. Our method also allowed us to expand from point measurements to the whole-lake scale. Lake-wide assessment of discharge

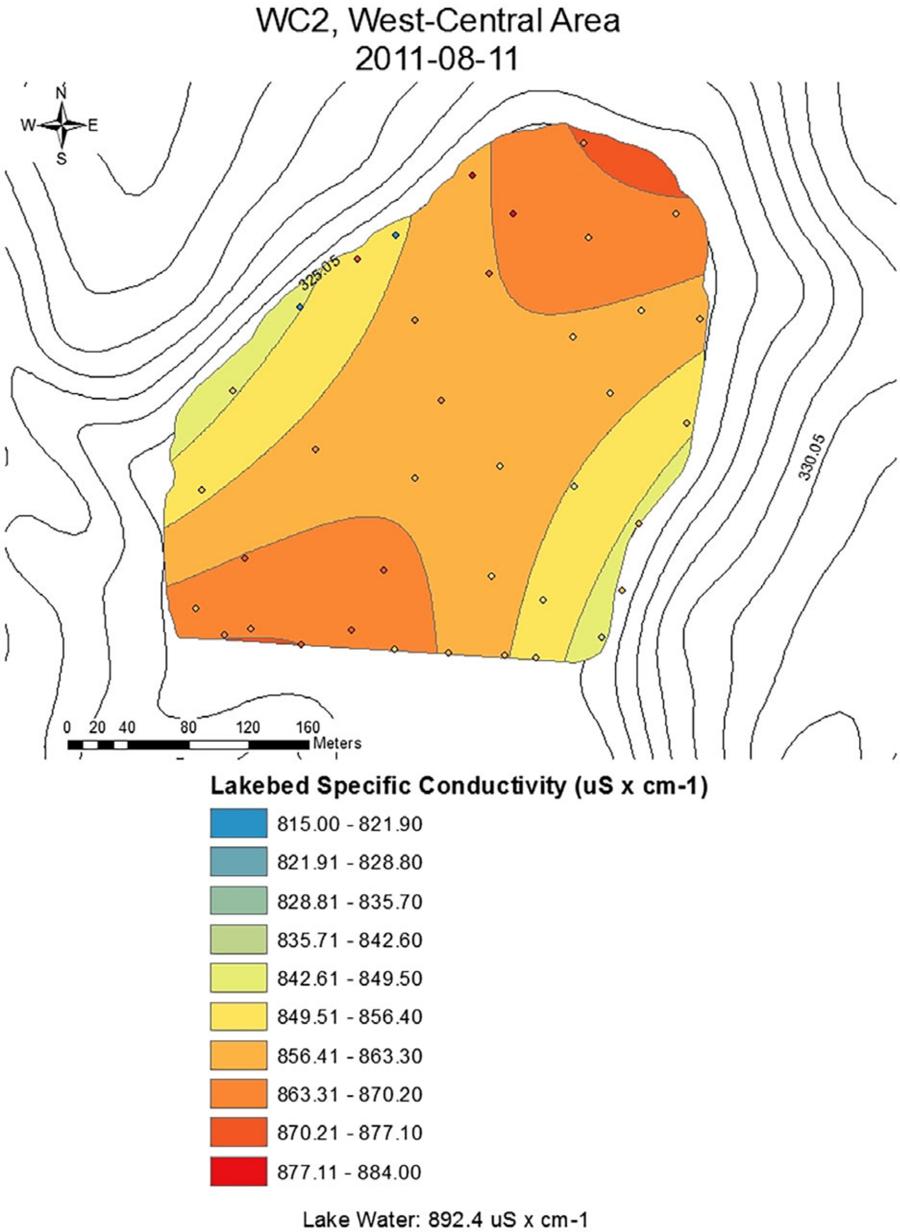

FIGURE 5. Map of WC2 with contours depicting the variations of specific conductivity throughout the lake bottom, late summer. The noncolor class contours are local elevation of the surrounding landscape.

areas is an ideal scale for advancing groundwater science, and for understanding how local and regional water resource management decisions affect individual lakes. Using our method, it was possible to map several lakes in a single day. Collecting comparable information with a similar number of seepage meter monitoring locations is likely to be cost and time prohibitive. Depending on the number of seepage meters deployed, one or more days are required to install the equipment, weeks to months are required for equilibration, and two additional return trips are required; one to place a bag and a second to make a measurement (i.e., collect and measure bag volume). For the conductivity mapping approach, we have described here, piezometers have a similar installation and equilibration commitment, but piezometer and Lakebed$_{sc}$ measurements can be done in a day. Revisits to seepage meters always require two days, whereas conductivity mapping revisits can occur in a day, with multiple lakes per day achievable. In terms of equipment cost-efficiency, both methods require a boat, but seepage meters have a higher initial labor cost and have higher costs to take measurements (i.e., two trips) compared to piezometers and specific conductivity mapping (one trip). Specific conductivity mapping requires the one-time purchase of a meter/ sensor plus the initial cost of piezometers, which are relatively inexpensive. Moreover, compared to piezometers and specific conductivity mapping, the time required to collect and process samples from seepage meters in a massive whole-lake seepage meter deployment scenario would likely be prohibitively expensive.

We also explored whether groundwater exchange differed between study regions and sampling periods. For lakes in ISP, lakebed areas receiving discharging groundwater appeared to be uniform from mid-summer to late summer. In contrast, inferred areas of groundwater discharge changed markedly in most lakes in our WC area. For instance, WC2 showed 7% of the lakebed surface area receiving discharging groundwater during mid-summer and 74% during late summer (Table 3). All seepage meters in WC2 during both sampling periods only indicated discharging groundwater. The lakebed mapping and LSI method indicated discharging and non-discharging groundwater and also determined the extent of groundwater exchange in WC2 during both sampling periods (Figures 4 and 5). These findings are consistent with other studies that have shown areas in a lake where the direction and magnitude of seepage have been stable over time, and other areas in the same lake where seepage changed in direction and magnitude over several months (Sebestyen and Schneider 2001). Similar to Kratz et al. (1997) and Winter (1998), we expected and observed ISP headwater lakes to have local groundwater flow with little inflow from deeper intermediate to regional groundwater sources. We attribute the more stable groundwater flow here to predominantly localized groundwater flow and the influence of the old-growth forest surrounding these lakes creating a stable groundwater environment by regulating soil water levels through transpiration (Franklin et al. 1981; Bormann and Likens 1994). Furthermore, we sampled during summer months, which may also minimize fluctuations in localized groundwater flow systems that could be caused by seasonal transitions. Lakes in ISP also had lower specific conductivity and solute concentrations (see Supporting Information), which is also characteristic of local groundwater flow (Winter 1998). More gradual topographic relief is prevalent in WC Minnesota and the shallow lakes here had higher specific conductivity and solute concentrations, which suggests greater connection to intermediate and regional groundwater flow systems. Shallow lakes in WC Minnesota also lie lower in the landscape, and this landscape setting is consistent with higher intermediate to regional groundwater flows.

CONCLUSIONS

We mapped Lakebed$_{sc}$ linked to LSI and calculated lakebed areas where groundwater discharged into lakes. Using a proxy variable such as Lakebed$_{sc}$ offers methodological advantages over sole reliance on seepage meters and piezometers at a handful of shoreline stations (as noted by Harvey et al. 1997). Detailed basic research on groundwater exchange in shallow lakes is urgently needed, but we think that there is also a place for economical strategies to gather data from multiple lakes over relatively short time periods. Given concerns over both surface water and groundwater quality, as well as excessive groundwater removal, we think relationships between watershed land use and groundwater need additional study despite the logistical challenges. Studies are needed to clarify whether relationships exist among land use practices and concentrations of various constituents in groundwater, and whether groundwater interactions with lakes and wetlands are affected by management or land cover attributes in adjacent source areas of water and solutes.

The lakebed mapping approach appears to provide a spatially comprehensive baseline for understanding groundwater exchange in shallow lakes, but may be most useful when used in conjunction with limited application of traditional seepage meter and piezometer monitoring. Such a combined approach has potential to increase understanding of how anthropogenic activities affect groundwater dynamics and ecological characteristics of shallow lakes.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Water chemistry results, laboratory methods, and maps for all of the study lakes with contours depicting the variations of specific conductivity throughout lake bottoms.

ACKNOWLEDGMENTS

We thank the Fergus Falls and Morris Wetland Management Districts of the U.S. Fish and Wildlife Service, Minnesota DNR Parks and Trails, and Minnesota DNR Glenwood Area Wildlife Office for access and use of study sites. We thank Matthew Bischof, Markus Bischof, and Winston Allen for assistance with field work. We sincerely appreciate efforts of John Larson and Doris Nelson from the Northern Research Station (NRS) of the USDA Forest Service (Grand Rapids, Minnesota) for guidance on water chemistry analyses. Core funding for this research was provided by the Minnesota Department of Natural Resources, Minnesota Space Grant Consortium, and a Bemidji State University mini-grant. The NRS funded the contributions of SDS and NRS laboratory staff to this project as well as chemical analyses.

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