LIMNOLOGY AND OCEANOGRAPHY
Letters

ASLO
Open Access

Limnology and Oceanography Letters 4, 2019, 105–112

doi: 10.1002/lol2.10110

LETTER

Headwater lakes and their influence on downstream discharge

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Scientific Significance Statement

There are an estimated 110 million small lakes (surface area less than 10 ha) in the world and little is known about how these lakes influence downstream discharge and water quality. We show that streamflow contributions from these small lakes can persist at least 4.2 km downstream and be detectable when the lake makes up as little as 0.5% of the catchment area. In addition, lake influences on downstream discharge can vary considerably over time; therefore, it is important to consider the influence of small lakes when interpreting water quality observations made downstream of these waterbodies.

Abstract

Small headwater lakes are common water features in northern environments. These small lakes are often reported to have an influence on downstream water quality; however, few studies have addressed the underlying hydrology of these systems and how small lakes influence downstream discharge or how far downstream these influences persist. We show that catchments with small lakes sustain baseflows compared to catchments without lakes. In addition, small lakes have limited influence on the magnitude and timing of peakflow events, except for immediately downstream of the lake where peakflow hydrographs are characterized by low magnitude and long duration. The relative contribution of lake water to downstream discharge can vary widely in time (between 0% and 75%) and be detectable when lakes make up as little as 0.5% of catchment area. This variability and persistence of lake water in stream networks may have important implications for how we interpret water quality patterns downstream of small lakes.

Climate change, forest disturbance, and urbanization are having a profound impact on the health of streams and their aquatic ecosystems (Bixby et al. 2015; Navarro-Ortega et al. 2015). Developing a process-based understanding of how these environmental changes are impacting streamflow regimes and water quality is critical for effective management of our water resources. A glaring knowledge gap in our understanding of how catchments respond to environmental change is the role of lakes on downstream discharge and water quality (Jones 2010; Baker et al. 2016).

Lakes are common features in northern landscapes, and there are an estimated 117 million lakes in the world, most under 10 ha in size (Downing et al. 2006; Verpoorter et al. 2014). Although lakes and streams have been studied extensively as separate systems, surprisingly little research has focused on lake–stream networks (Jones 2010; Pépino et al. 2016). Larger lake–stream systems have received most of the attention although it has been suggested that small lakes (surface area < 1 km^2), which are the

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Associate editor: Jordan Read

Author Contribution Statement: J.A.L. and H.L. conceived the study. H.L. coordinated and supervised data collection. J.A.L. conducted the analysis. J.A.L. led and H.L. contributed to interpretation of the data and writing of the manuscript.

Data Availability Statement: Data used in this manuscript are available from the B2SHARE data portal: http://doi.org/10.23728/b2share.60c1acf4ec7c4623889f6b1a0ded68f2.

Additional Supporting Information may be found in the online version of this article.

most abundant lake sizes in most northern regions, may have a disproportionately large influence on aquatic ecosystems (Downing et al. 2006). Most research on lake–stream networks has primarily been focused on statistical relationships between lake metrics, such as percent lake cover and landscape water quality patterns (Moore 2006; Buffam et al. 2007; Goodman et al. 2011), although some recent work has focused on hydrologic processes controlling evaporation rates and nutrient export from lakes (Kalinin et al. 2016; Spence et al. 2018*b*).

Most hydrologic research on lake–stream networks has been conducted in Arctic catchments and focused on the role of lake storage capacity and how it controls hydrologic connectivity at landscape scales (Spence 2006; Woo and Mielko 2007; Spence et al. 2010; Baki et al. 2012). In these cold and arid environments, streams draining lakes are prone to intermittent flows due to lake levels falling below the outlet elevation as a result of evaporation from the lake. In contrast, lakes in mountainous regions typically help sustain flows during summer months (Dorava and Milner 2000; Arp et al. 2006). In addition, it is commonly assumed that lakes attenuate peakflows (Dorava and Milner 2000; Jones et al. 2014); however, in some cases when antecedent lake storage capacity is small, such as during spring freshet, lakes can have a negligible influence on peakflows (Arp et al. 2006; Goodman et al. 2011).

Existing studies on lake–stream networks have primarily focused on hydrologic response immediately downstream of lakes (i.e., within 100 m of the lake outlet); therefore, it is unclear how far downstream the influences of headwater lakes on streamflow can persist. In this study, we use 9 yr of stream discharge and water isotope measurements from nested catchments with a headwater lake and a catchment without a headwater lake to address the following questions: (1) What are the influences of a headwater lake on downstream discharge patterns? and (2) how far downstream do the hydrologic influences of a headwater lake persist?

Methods

Study site

This study was conducted within the Krycklan Catchment Study located approximately 50 km northwest of the city of Umeå in northern Sweden (Laudon et al. 2013). The region is underlain by Svecofennian gneissic bedrock with metasediments and metagraywacke covered by a layer of quaternary deposits of glacial till that varies in thickness up to tens of meters. The climate of Krycklan is defined as cold temperate humid with persistent snow cover during the winter season (Laudon and Ottosson-Löfvenius 2016). The 30 yr (1981–2010) mean annual air temperature and precipitation are 1.8°C and 614 mm, respectively (Laudon et al. 2013). Forests in the catchments are dominated by mature Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*). Well-developed iron podzols dominate the forest soils.

The study focused on five monitored catchments located within Krycklan (Fig. 1). Four of the catchments (C5, C6, C9, and C13) are nested and have outlets located downstream of a small headwater lake (Stortjärnen Lake). The lake has a surface area of about 4 ha and a maximum and mean depth of 6.7 m and 2.7 m, respectively (Denfeld et al. 2018). Water enters the lake from a mire complex located northwest of the lake and by a small stream along the northeastern boundary of the lake. The outlet of C5 is located 100 m downstream of the lake, has a catchment area of 65 ha, and is also referred to as the lake outlet site. The next downstream catchment outlet is C6, located 1.4 km downstream of the lake with a catchment area of 110 ha, followed by C9, located 3.4 km downstream of the lake with a catchment area of 288 ha. The most downstream catchment outlet used in this study is C13 which is located 4.2 km downstream of the lake and has a catchment area of 700 ha. Stortjärnen Lake comprises 6%, 4%, 1%, and 0.5% of the total catchment area for C5, C6, C9, and C13, respectively. The lake outlet catchment (C5) makes up 51%, 19%, and 8% of the C6, C9, and C13 catchment areas, respectively. In addition to the lake–stream sites, we also used data collected at a nearby catchment without a lake (C1). The C1 site has a catchment area of 48 ha and the land cover is dominated by forest (98%) and a small amount of mire cover (2%). All five of the study catchments are outfitted with a weir or flume and hourly discharge records are estimated from water level observations and site-specific stage-discharge rating curves (Karlsen et al. 2016).

Field measurements and analyses

Lake influence on downstream discharge patterns

To address the first objective of this study, we examined streamflow patterns at seasonal and event scales and compared conditions for the catchments with the headwater lake with the catchment without the headwater lake. Field measurements consisted of hourly discharge records from C1, C5, C6, C9, and C13 for the summer and autumn periods (01 June–30 September) of 2008–2016 (Leach and Laudon 2019). We restricted our analyses to rain-dominated flow conditions (i.e., the open water period outside of the spring snowmelt flood). Winter flow was not examined since there were data gaps during this period. We compared summer–autumn (01 June– 30 September) hourly stream discharge flow duration curves for C1 and C6 catchments. We focused on C1 and C6 catchments since they are comparable in size. Indeed, the catchment area of C6, if the lake and its contributing area were removed, would be around 45 ha. This catchment area is similar in size to C1, the catchment without a lake (48 ha). We did not consider C9 and C13 in this analysis since the larger catchments, and associated water transit times, begin to confound the ability to isolate the influence of the lake. The C1 and C6 catchments are in close proximity to each other and receive similar timing and magnitude of rainfall inputs.

In addition to looking at the seasonal discharge patterns, we also explored discharge response at C1, C5, and C6 to individual rainfall events. Rainfall measurements logged every 10 min were collected with a tipping bucket gauge at the Svartberget meteorological station (Laudon et al. 2013). This station is

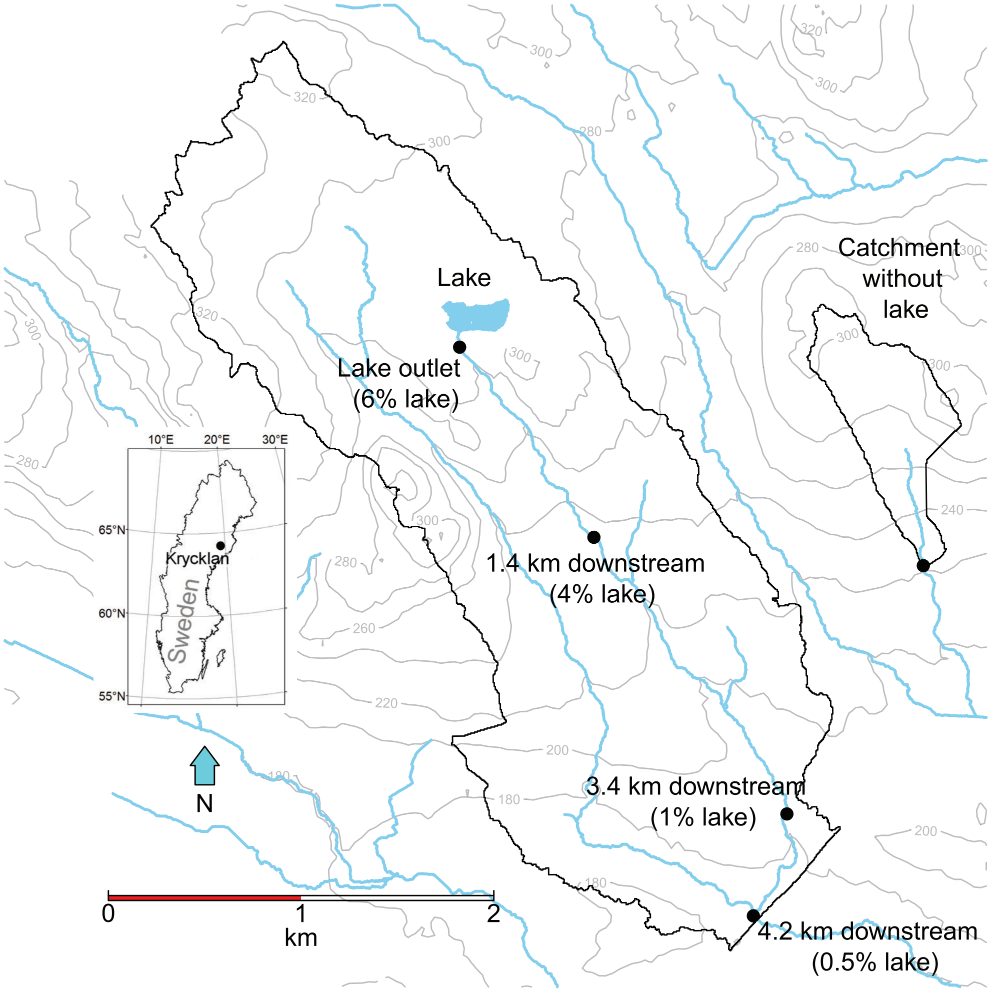

Fig. 1. Map showing the catchment with the lake–stream network and the catchment with no lake used in this study. Hydrometric station locations are indicated by the black circles: Lake outlet (C5), 1.4 km downstream (C6), 3.4 km downstream (C9), 4.2 km downstream (C13), and the catchment without a lake (C1). Contour lines are in 20 m intervals. The location of the Krycklan Catchment Study within Sweden is shown in the inset.

located about 1 km from the C6 site. The 2008–2016 summer–autumn streamflow record was partitioned into distinct rainfall events. Events were considered distinct if at least 4 mm of rainfall was separated by at least 12 h without rainfall. For each rainfall event, we computed the peakflow response magnitude (i.e., the difference between the event peakflow and the initial flow at the start of the event) and time between the initial rainfall and time of peakflow occurrence.

Downstream persistence of lake water

To address the second study objective, we estimated how much water sourced from the lake contributed to stream discharge at three distances downstream of the lake (1.4, 3.4, and 4.2 km). We estimated this using two methods. First, we assumed a maximum potential contribution by simply dividing the mean daily lake outlet discharge by the discharge at the respective downstream gauging stations. This approach will overestimate lake contributions as it does not account for gross water exchanges between stream and subsurface systems along the channel reach (Payn et al. 2009). Accounting for these gross water exchanges is important for considering lake water influence on downstream water quality. Therefore, we constrained these maximum estimates by using $\delta^{18}O$ water isotope measurements. Grab water samples have been routinely collected weekly to biweekly at the hydrometric stations for the 2008–2016 period following the water isotope collection and water sample analysis methods outlined in Leach et al. (2017). For every occasion when water isotope samples were made at C5 and one of C6 (n = 187), C9 (n = 154), and C13 (n = 149), the fraction of streamflow comprised of water sourced from the lake (F_{lake}) was estimated as:

$$F_{\mathrm{lake}} = \frac{C_{\mathrm{stream}} - C_{\mathrm{hillslope}}}{C_{\mathrm{lake}} - C_{\mathrm{hillslope}}} \qquad (1)$$

where C_{stream} is the isotope composition at C6, C9, or C13; C_{lake} is the isotope composition at C5 lake outlet; and $C_{\mathrm{hillslope}}$ is the isotope composition of hillslope runoff water from combined groundwater, forest soil water, and mire water sources. We did not have measurements of hillslope runoff water; therefore, we estimated this component using water isotope observations from two small, nearby catchments dominated by forest soils (C2 catchment) and a mire (C4 catchment), respectively, coupled with a Monte Carlo approach (Peralta-Tapia et al. 2015). The C2 catchment drains an area of 12 ha with 100% forest cover. The C4 catchment drains an area of 18 ha and is heavily influenced by a mire which covers 44% of the catchment but is located such that 98% of all water leaving the catchment has to pass through the mire complex (Lidman et al. 2013). Water isotope samples from these two catchments and the lake outlet generally bracket the values observed from the downstream sites (Supporting Information Fig. S1), which suggests that C2 and C4 may be reasonable proxies for combined hillslope water sources. We fit and compared a number of probability distributions (normal, logistic, log-normal, Weibull, gamma, and exponential) to the combined isotope measurements from C2 and C4 ($n = 169$). Based on Akaike's information criterion, a logistic distribution provided the best fit (Supporting Information Fig. S2 and Table S1) and we generated 500,000 random values from this fitted distribution to use in the above mixing equation. We then removed any of the 500,000 F_{lake} realizations that predicted implausible estimates (values below 0 and above the maximum contribution estimated from the hydrometric approach outlined above). From the remaining values, we computed mean and 95% confidence limits.

Results

Lake influence on downstream discharge

Stream discharge for the lake–stream network increased downstream and all sites were responsive to rainfall events (Fig. 2). Event hydrographs for the lake outlet site (C5) were relatively smooth whereas event hydrographs for the other downstream sites showed a more flashy response to rainfall inputs to the catchments.

A comparison of flow duration curves for June through September at C1 (no lake) and C6 (lake) sites highlights that moderate and peak flows at the two catchments were generally

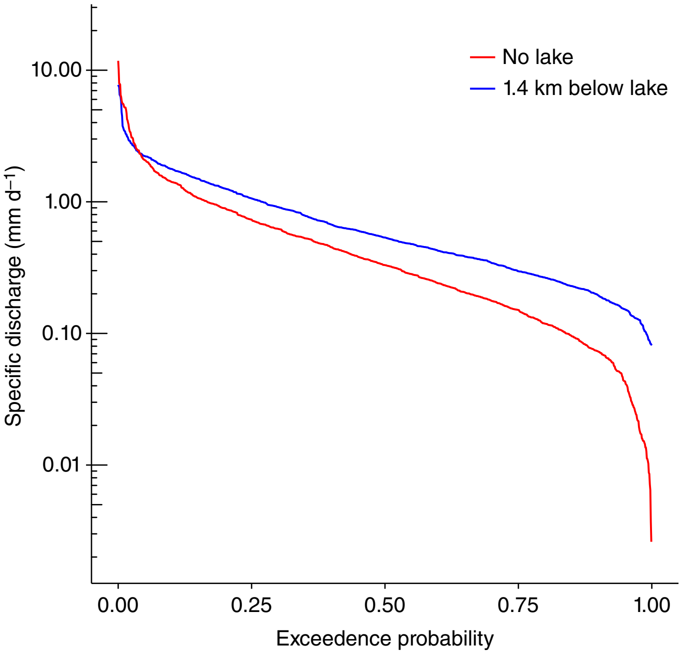

Fig. 3. Flow duration curves using specific discharge (mm d^{-1}) for June to September from 2008 to 2016 at the no lake (C1) and 1.4 km below the lake sites (C6). Note that the y-axis is in logarithm scale.

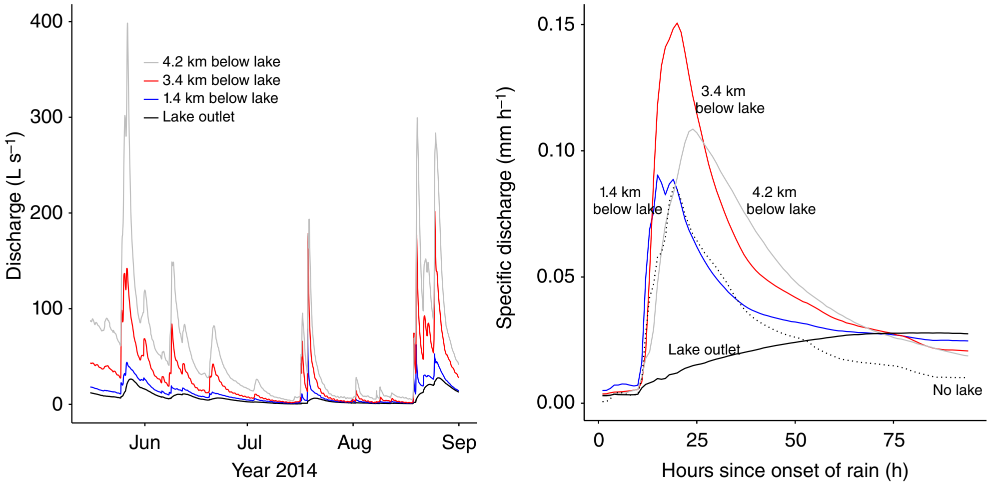

Fig. 2. The left panel shows an example hydrograph for the lake outlet (C5), 1.4 km below lake (C6), 3.4 km below lake (C9), and 4.2 km below lake (C13) sites during 2014. The right panel shows an example event hydrograph displayed in specific discharge and including the catchment with no lake (C1) in addition to the lake catchments.

similar; however, the lake influence sustained higher baseflow conditions (Fig. 3).

There were 191 rainfall events identified during the 9 yr data record that met the conditions of having at least 4 mm rainfall and complete hourly streamflow records for C1, C5, and C6. Examining hydrograph properties for the rainfall events highlights that the lake reduces peakflow response and increases time to peakflow immediately downstream of the lake, as indicated by the differences between C1 and C5 (Fig. 4). However, those influences appear to be lost by 1.4 km downstream of the lake since the no lake (C1) and 1.4 km below lake (C6) show similar peakflow response and time to peakflow across event rainfall magnitudes.

Downstream persistence of lake water

Estimated lake water contributions to catchment outlet flow for C6, C9, and C13 were highly variable across lake outlet discharge conditions (Fig. 5). The isotopic mixing approach estimates were, on average, about half the value estimated by the hydrometric approach. In addition, the isotopic estimates show that lake water contributions ranged between approximately 1% and 75% for C6, 0% and 50% for C9, and 0% and 25% for C13. Periods of greatest lake water contribution appear to be associated with moderate lake outflow; however, there is considerable spread around this relationship.

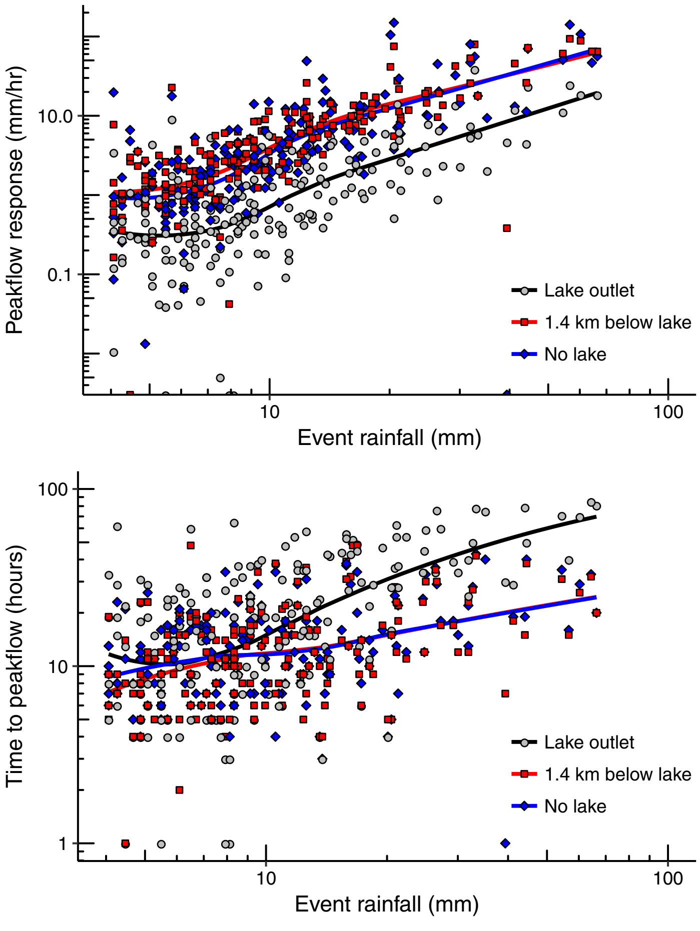

Fig. 4. Scatterplots in log-log space showing peakflow response (top) and time to peakflow (bottom) against event rainfall (mm) for no lake (C1), lake outlet (C5), and 1.4 km downstream of lake (C6). Smoothed lines of best fit using local regression are included to provide visual aids.

Discussion

Influence of a headwater lake on downstream discharge

Our results suggest that the small headwater lake had only a localized impact on the downstream peakflow regime, but a more persistent downstream influence on baseflow conditions. The lake influences on downstream discharge seen at our study site are similar to those observed in mountainous regions (Dorava and Milner 2000; Arp et al. 2006), but differ from arid Arctic lake–stream systems where streams draining lakes are prone to intermittent flow (Spence 2006; Woo and Mielko 2007; Baki et al. 2012).

Lakes and streams differ in a number of ways: lakes store more water, typically have longer residence times, and have a greater surface area than streams. In contrast, lakes have a smaller perimeter than streams and therefore, may interact less with the terrestrial landscape (Baker et al. 2016). Partly because of these differences, lake water will typically have a different water quality composition than stream water. Therefore, the degree of downstream persistence of lake water may have important implications for stream water quality. For our study site, lake water contributions to downstream discharge were variable in time and distance downstream. This variability appears to be partly due the hydrologic conditions of the catchment. In a previous study, we conducted detailed hydrograph separations at the C6 catchment outlet using stable water isotopes collected from the lake outlet, C6, and groundwater sources (Leach et al. 2017). These hydrograph separations were conducted during (1) baseflow conditions prior to a rain event, (2) the C6 peak flow response to the rain event, and (3) during the C6 hydrograph recession limb when lake outlet discharge was at a maximum. Estimated lake water contributions to the C6 outlet were 21% during baseflow, 1% during the C6 peak flow, and 75% during the recession limb. These values cover the range of lake contribution estimated from the long-term samples used in this study (Fig. 5). The detailed hydrograph separations highlight how the shifting contributions of lake and hillslope water before, during, and after a rain event can contribute to the wide range of variability observed in this study.

The individual mixing model estimates of lake water contribution can exhibit large variability and this is partly due to uncertainty in characterizing the hillslope end member in the mixing model (Klaus and McDonnell 2013). Despite this uncertainty, there are three key conclusions that are supported by the analysis: (1) the lake contributions estimated using the isotope mixing model are clearly less than the hydrometric estimates, which helps constrain the estimated

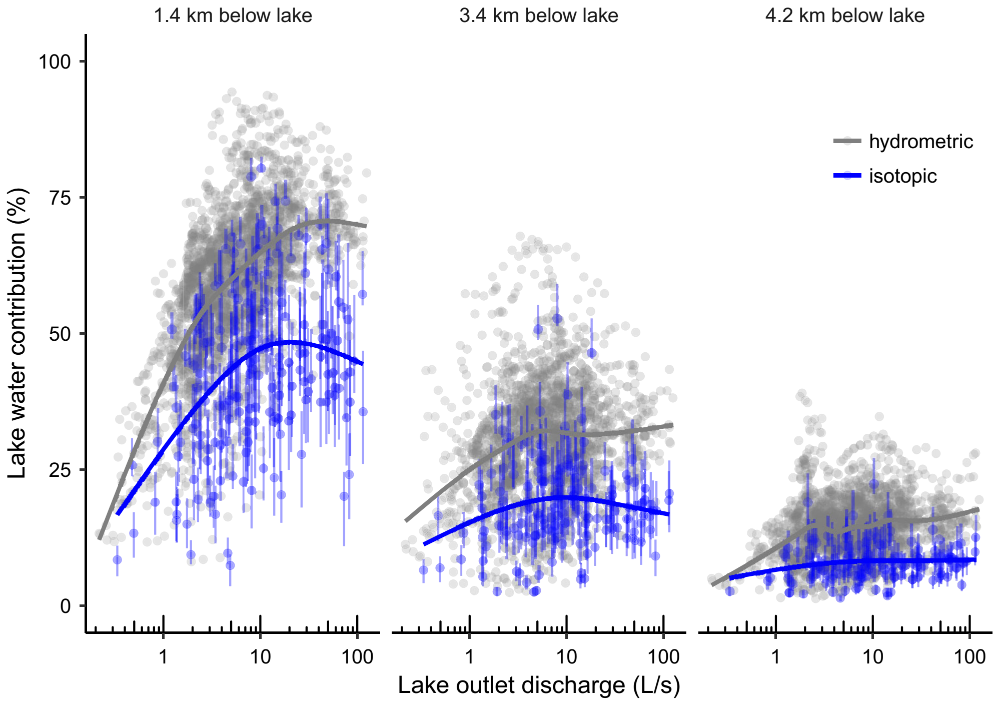

Fig. 5. Lake water contributions to streamflow at 1.4 km below lake (C6), 3.4 km below lake (C9), and 4.2 km below lake (C13) using hydrometric and isotopic approaches plotted against lake outlet (C5) discharge. Smoothed lines of best fit using local regression are provided for visual reference.

contributions and also suggest a strong hyporheic influence in this system (Payn et al. 2009), (2) the lake contribution estimates decrease with distance downstream, and (3) for the 1.4 and 3.4 km downstream sites, the lake contributions appear to peak at moderate lake outlet discharge. The validity of the last point is the most questionable given the uncertainty in the lake water contribution estimates; however, this finding is consistent with the detailed hydrograph separation analysis mentioned above that was conducted at the 1.4 km downstream location (Leach et al. 2017).

Implications for water quality and watershed response to environmental change

Lake water contributions to downstream discharge were highly variable over time, even for the furthest downstream catchment outlet. This variability may have important implications for water quality monitoring downstream of small lakes. For example, a water sample collected in our study catchment at 1.4 km downstream of the lake could be comprised of anywhere between 1% and 75% lake water, depending on the hydrologic conditions of the catchment. This variability in water source (lake vs. hillslope) has the potential to influence representation of a water quality sample. Without knowing the hydrologic conditions and the proportion of lake water in the sample, interpretation of the water quality observations may be in error.

This study focused on the influence of the lake on stream hydrology, specifically streamflow regime and downstream persistence of water molecules sourced from the lake. In terms of stream water quality, the latter sets the maximum downstream persistence of the lake influence since water serves as the transport mechanism. However, other water quality parameters may not act conservatively during transit from the lake outlet to downstream. For example, a study conducted on the same C5–C6 stream reach that focused on dissolved carbon demonstrated contrasting downstream persistence depending on carbon species (Lupon et al. 2019). Elevated dissolved methane and carbon dioxide concentrations in the lake water only persisted a few hundred meters downstream before evading to the atmosphere. Hence, although lake water persisted much further downstream, the influence of the lake on inorganic carbon species was restricted to a few hundred meters from the outlet. In contrast, dissolved organic carbon patterns downstream of the lake were influenced by hydrologic conditions and the lake influence appeared to be more persistent for dissolved organic carbon than for methane or carbon dioxide. Although more work is needed to understand how lake influence and downstream persistence changes through time for different water quality parameters, our study provides a framework for thinking about how lake- and hillslope-sourced waters interact in time and space to shape downstream water quality.

Only a few studies have directly addressed how lakes modify catchment-scale responses to environmental change; however, existing research suggests that lakes may exert a strong influence (Klaus et al. 2018). For example, headwater lakes can moderate the influence of forest harvesting on downstream thermal regimes, suggesting that catchments with lakes may be more resilient to forest cover disturbance than those without (Mellina et al. 2002). In contrast, lake thermal regimes may be more responsive to climate warming than streams (Roberts et al. 2017), which suggests that thermal regimes of catchments with lakes may be more sensitive to climate change than those without. In addition, the structure of the lake–stream network, the number of lakes present, and the characteristics of those lakes may all have a critical influence on how a catchment responds to environmental change (Epstein et al. 2013; Spence et al. 2018*a*). Important questions remain about the role of small lakes when predicting catchment response to environmental change: Are catchments with lakes more or less resilient to change than catchments without lakes? How do multiple lake–stream chains influence downstream discharge and water quality and does the spatial arrangement matter?

This study focused on results from a single lake–stream network. Based on this work, we demonstrate that lake influences will diminish as one moves further downstream, as hillslope or tributary contributions overwhelm lake contributions. However, the transition point between lake and hillslope dominated flow conditions will likely change in time and space as a function of the lake and its contributing catchment properties (lake size and residence time, catchment slope, and land cover), magnitude and distribution of hillslope contributing area, location and size of tributaries, precipitation event characteristics (magnitude, intensity, and duration), and catchment antecedent conditions. More research on lake–stream networks is needed to test and evaluate these hypotheses to develop a generalized understanding of these systems.

Conclusions

Using detailed and multiyear measurements from a lake–stream network, we show that small headwater lakes can maintain higher baseflows compared to catchments without lakes. In addition, the lake had a moderating influence on peakflow magnitude and timing immediately downstream of the lake, but this influence was lost by 1.4 km downstream. Lake water contributions to downstream flow were highly variable, ranging between 1% and 75% at 1.4 km below the lake, 0% and 50% 3.4 km downstream, and 0–25% 4.2 km downstream. Given the downstream persistence of water sourced from these small lakes, and their abundance in northern landscapes, it is critical to consider their potential influence when interpreting water quality observations made downstream of these waterbodies.

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Acknowledgments

We thank Peder Blomkvist, Pernilla Löfvenius, Ida Taberman, and the Krycklan field team for data collection and processing. We also thank Pat Soranno, the associate editor, and two anonymous reviewers for their time and feedback which greatly improved the paper. Funding for this project was provided by a NSERC Discovery Grant to JAL. The research in Krycklan has been funded by Swedish Science Foundation (VR) through SITES and other projects, FORMAS, Future Forests, Kempe Foundation, KAW (Branch-Points), and SKB.

Submitted 04 February 2019
Revised 08 April 2019
Accepted 20 April 2019