AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2017GL073834

Glacierized headwater streams as aquifer recharge corridors, subarctic Alaska

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Key Points:
- Glacier meltwater discharge represents >15% of total annual streamflow in a subarctic headwater with 3% glacier coverage
- Headwater streams lose 38 to 56% of annual streamflow to recharge of lowland aquifers
- Glacier-derived aquifer recharge via headwater streambeds may explain long-term increases in lowland river base flow

Supporting Information:
- Supporting Information S1

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Citation:
Liljedahl, A. K., A. Gädeke, S. O'Neel, T. A. Gatesman, and T. A. Douglas (2017), Glacierized headwater streams as aquifer recharge corridors, subarctic Alaska, *Geophys. Res. Lett.*, *44*, doi:10.1002/2017GL073834.

Received 10 MAY 2017
Accepted 1 JUL 2017
Accepted article online 6 JUL 2017

Abstract Arctic river discharge has increased in recent decades although sources and mechanisms remain debated. Abundant literature documents permafrost thaw and mountain glacier shrinkage over the past decades. Here we link glacier runoff to aquifer recharge via a losing headwater stream in subarctic Interior Alaska. Field measurements in Jarvis Creek (634 km^2), a subbasin of the Tanana and Yukon Rivers, show glacier meltwater runoff as a large component (15–28%) of total annual streamflow despite low glacier cover (3%). About half of annual headwater streamflow is lost to the aquifer (38 to 56%). The estimated long-term change in glacier-derived aquifer recharge exceeds the observed increase in Tanana River base flow. Our findings suggest a linkage between glacier wastage, aquifer recharge along the headwater stream corridor, and lowland winter discharge. Accordingly, glacierized headwater streambeds may serve as major aquifer recharge zones in semiarid climates and therefore contributing to year-round base flow of lowland rivers.

Plain Language Summary Observations of increased river discharge in summer and winter span the scientific community and Arctic residents. Changes in streamflow present implications for river travel throughout the year and impact sea ice growth and nutrient exports to Arctic Ocean coastal waters. Processes responsible for increasing river discharge are debated because no single process can explain increases in runoff of several rivers. Here we show that the ubiquitous mass loss from subarctic mountain glaciers feeds rivers not only in summer but also in the winter. We measured summer discharge at two places in the same glacier-fed headwater stream in Interior Alaska and found that the discharge is lower downstream that upstream. The difference represents water that is lost to infiltration into ground and subsequent aquifer recharge. The aquifer in turn feeds the larger lowland river, like the Tanana River, during winter. As such, glaciers across the semiarid regions can be important sources of water to streams and aquifers and an overlooked source of increasing river discharge reported across the Arctic.

1. Introduction

Mean annual discharge from large Eurasian [*Peterson et al.*, 2002] and North American rivers [*St. Jacques and Sauchyn*, 2009] to the Arctic Ocean has increased during recent decades along with air temperatures [*Serreze et al.*, 2000]. A corresponding increase of winter discharge suggests a growing groundwater influence in the high-latitude hydrologic cycle [*Brabets and Walvoord*, 2009; *Georgiyevsky et al.*, 1996; *Lammers et al.*, 2001; *Smith et al.*, 2007; *St. Jacques and Sauchyn*, 2009; *Walvoord and Striegl*, 2007]. The increase of freshwater fluxes to the Arctic Ocean [*Hill et al.*, 2015; *Neal et al.*, 2010] impacts biogeophysical processes such as sea ice growth [*Morison et al.*, 2012; *Nghiem et al.*, 2014], ocean circulation [*Rahmstorf*, 2002], river-ice thinning [*Herman-Mercer et al.*, 2011], development and incubation time for chum salmon eggs and embryos [*Burril et al.*, 2010], and biogeochemical freshwater exports [*Hood et al.*, 2015; *Neal et al.*, 2010; *Toohey et al.*, 2016; *Walvoord and Striegl*, 2007]. Accordingly, the potential for strong, unresolved feedbacks to regional terrestrial and maritime ecosystems and the global climate system is large.

The pan-Arctic response of increasing streamflow is clear, but less so are the mechanisms driving increases in winter discharge [*Bring et al.*, 2016; *Smith et al.*, 2007]. Increased winter discharge must be explained by an increased input of water to aquifers and/or an increased aquifer storage capacity. Other source waters to streamflow are generally frozen in winter. Analyses based on Gravity Recovery and Climate Experiment data show an increase in global groundwater storage in recent years, partially offsetting glacier melt induced sea level rise [*Reager et al.*, 2016]. Proposed mechanisms for increased winter discharge include permafrost thaw (meltwater release from ground ice and storage increase) [*St. Jacques and Sauchyn*, 2009; *Toohey et al.*, 2016;

Walvoord et al., 2012; *Yang et al.*, 2002], delayed soil freeze-up (storage increase) [*Yang et al.*, 2002], and altered precipitation with complicated regional patterns [*McClelland et al.*, 2004; *Zhang et al.*, 2013]. Conversely, increased groundwater flow can amplify permafrost degradation as advection dominates conduction in thermal erosion [*McKenzie and Voss*, 2013]. This, in turn, increases the aquifer storage capacity. However, precipitation is not systematically increasing across basins, which suggests a potentially overlooked source of groundwater input. Here we consider long-term mass loss of glacier ice as a major groundwater source constituent.

Mountain glacier mass loss is ubiquitous in recent decades [*Gardner et al.*, 2013], with some of the most rapid rates of change in Alaska [*Jacob et al.*, 2012; *Larsen et al.*, 2015; *Radić and Hock*, 2011] and in the Arctic [*Dyurgerov et al.*, 2010; *Geck et al.*, 2013; *Nuth et al.*, 2013; *Shahgedanova et al.*, 2012]. Glaciers in continental regions are generally losing volume at an accelerating rate [*Dyurgerov and Meier*, 2000; *McGrath et al.*, 2017] and small mountain glaciers (~1 km^2) are some of the most sensitive to climate and significant contributors to total glacier coverage loss [*Bolch et al.*, 2010; *McGrath et al.*, 2017; *Paul et al.*, 2004]. High-latitude mountain glaciers, which represent about 50% of the world's mountain glacier area [*Björnsson et al.*, 1996], have been identified via glacier mass balance studies to be a major source of the increased freshwater inflow to the Arctic Ocean [*Bring and Destouni*, 2011; *Dyurgerov et al.*, 2010; *Dyurgerov and Carter*, 2004; *Neal et al.*, 2010; *Weingartner et al.*, 2005].

Literature has to date focused on quantifying the mountain glacier contribution to summer streamflow [*Huss*, 2011; *Kaser et al.*, 2010; *Nolin et al.*, 2010; *O'Neel et al.*, 2014; *Pellicciotti et al.*, 2010; *Riedel et al.*, 2015; *Schaner et al.*, 2012] and subsequent sea level rise [*Dyurgerov and Meier*, 1997; *Gardner et al.*, 2011; *Radić and Hock*, 2011]. Glaciers modify the quantity and timing of summer streamflow [*Neal et al.*, 2010; *O'Neel et al.*, 2014; *Stahl and Moore*, 2006] even in basins with low glacier cover (<1%) [*Huss*, 2011; *Riedel et al.*, 2015] and especially in arid climates [*Kaser et al.*, 2010]. Glacier-derived aquifer recharge studies have been constrained to areas beneath the glacier ice [*Haldorsen et al.*, 2010; *Levy et al.*, 2015; *Robinson et al.*, 2009], although streamflow recession analyses suggest storage changes in glacier- and permafrost-affected watersheds [*Nowak and Hodson*, 2013]. Opportunities to explore implications of glacier runoff on watershed hydrology are particularly limited in the Arctic where discharge and glacier mass balance measurements are sparse and rarely colocated [*Björnsson et al.*, 1996; *Dyurgerov and Carter*, 2004].

Here we combine field measurements of glacier mass balance, differential streamflow (i.e., more than one measurement location at the same stream), and lowland groundwater levels with remote sensing of long-term glacier cover change to assess the role of glaciers on subarctic watershed-scale hydrology. Our objectives are to quantify glacier runoff contribution to (a) headwater streamflow and (b) streambed aquifer recharge and to (c) compare quantities of long-term glacier mass loss, glacier-derived streambed aquifer recharge, and lowland river base flow.

2. Study Area

The study area is the Tanana River watershed (53,075 km^2, 7% glacier cover), a major tributary to the Yukon River (Figure 1). The Tanana River drains the central and eastern part of the Alaska Range that has glaciated ridges of 2000 to 3000 m in altitude with individual peaks reaching 4000 m above sea level (asl). Two glacierized headwater streams, Jarvis Creek (634 km^2, 3% glacier cover) and Phelan Creek (31 km^2, 60% glacier cover), drain into the Delta River before entering the Tanana River and offer access to field measurements of both glacier mass balance and streamflow. The Tanana River lowlands are underlain by thin accumulation (tens of meters) of silt that overlays thick Cenozoic unconsolidated sediments primarily of alluvium (sometimes reaching hundreds of meters in depth) [*Brabets et al.*, 2000]. Lobes of glacial deposits extend from the mountains onto the lowlands [*Brabets et al.*, 2000].

The continental climate and discontinuous permafrost distribution that characterize the Tanana River watershed are representative of other large semiarid subarctic river systems, with a lowland mean annual air temperature of −1.9°C and mean annual precipitation of 305 mm [*Shulski and Wendler*, 2007]. Permafrost can reach nearly 100 m in thickness, and its temperature is typically warmer than −0.5°C [*Osterkamp and Romanovsky*, 1999]. Throughout the lowlands, measurements show permafrost warming and thawing from the top and bottom [*Osterkamp*, 2005; *Osterkamp and Romanovsky*, 1999] and increasing permafrost degradation in recent decades [*Jorgenson et al.*, 2001].

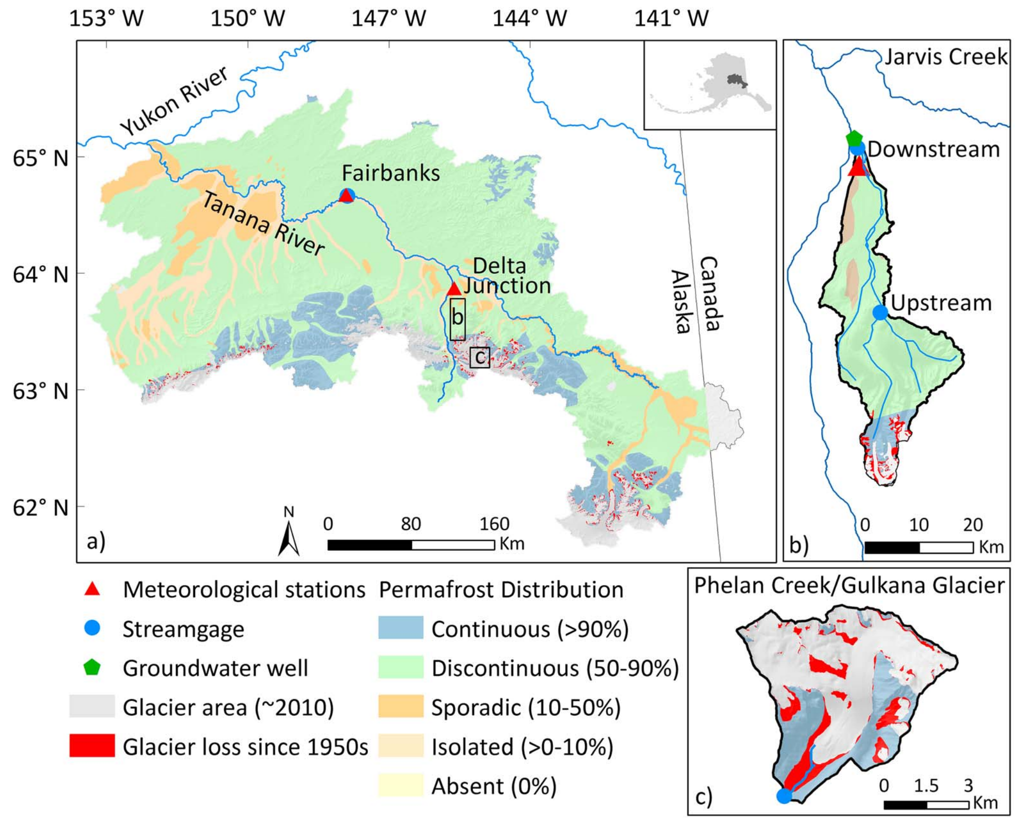

Figure 1. The three study watersheds. (a) Tanana River, (b) Jarvis Creek, and (c) Phelan Creek watersheds with respective meteorology and discharge monitoring sites. Also shown are permafrost distribution [*Jorgenson et al*., 2008] and recent and past glacier coverage.

Tanana River peak discharge typically occurs in July, due to a combination of high glacier runoff and rain storms [*Bennett et al*., 2015]. The Tanana River is the largest single contributor of streamflow (20%) and groundwater (27%) to the Yukon River [*Walvoord and Striegl*, 2007] and has exhibited increased annual and winter discharge in recent decades with no commensurate increase in Interior Alaska precipitation [*Brabets and Walvoord*, 2009; *Walvoord and Striegl*, 2007]. In nonglacierized watersheds, aquifer recharge is primarily constrained to the spring snowmelt event [*Kane*, 1981; *Kane and Stein*, 1983] as rainfall is typically lost as evapotranspiration (~250 mm each) [*Iwata et al*., 2012]. Modeling efforts suggest that 25 to 60% of the Tanana River's annual discharge is derived from glacier runoff [*Wada et al*., 2011]. Gulkana Glacier, located within the Tanana River watershed and one of two long-term glacier mass balance sites in Alaska, has experienced nearly continuously negative annual glacier mass balances that have led to a 25 m water equivalent (we) glacier-wide average loss, approximately 2 km of terminus retreat, and a 17% deglaciation of the watershed area since 1966 [*O'Neel et al*., 2014]. The current terminus of Gulkana Glacier is about 2 km away from the Phelan Creek gauging station, which is part of the U.S. Geological Survey (USGS) stream monitoring network in Alaska [*March and O'Neel*, 2011; *Wahl et al*., 1995]. The Jarvis stream length from glaciers to the lowermost discharge monitoring station is approximately 70 km with about half flowing through the lowlands.

3. Methods

3.1. Meteorology

Long-term meteorological records (year 1947 to 2016) were obtained from National Oceanic and Atmospheric Administration sites in Delta Junction (63.99 N, −145.72 W, 389 m asl, GHCND: USW00026415) and Fairbanks (64.80 N, −147.77 W, 132 m asl, GHCND: USW00026411) and 2012–2016 data from the Jarvis and Gulkana Glaciers (Figure 1 and Text S1 in the supporting information). Meteorological analyses include mean annual air temperature, summer warmth index (SWI, defined as the sum of all mean monthly air temperatures that exceed 0°C), winter precipitation (defined as the sum of precipitation observed during months with a mean monthly air temperature <0°C), and summer precipitation for a hydrologic year (1 October to 30 September).

3.2. Discharge and Groundwater

Quantities analyzed include annual and winter discharge for Tanana River, Phelan Creek, and Jarvis Creek and lowland groundwater levels. Mean daily discharge records were obtained from the U.S. Geological Survey at Phelan Creek (63.24 N, −145.47 W, 1124 m asl, ID15478040) and the Tanana River near Fairbanks (64.79 N, −147.84 W, 135 m asl, ID 15485500). Winter discharge, defined as the average streamflow from 1 January to 31 March, was analyzed for the Tanana River. Differential discharge of Jarvis Creek was measured in 2015 and 2016 near its confluence with the Delta River ("downstream site," 634 km^2, 64.02 N, −145.73 W, 360 m asl) and 55 km upstream ("upstream site," 351 km^2, 63.75 N, −145.65, 695 m asl) (Figure 1b and Text S2), which is immediately downstream of the nonglacier-fed McCumber Creek's inflow to Jarvis Creek. The percent loss of streamflow was quantified by the difference in the total annual or seasonal discharge (m^3) between the upstream and downstream gauging sites divided by the total discharge of the upstream site. Specific streamflow loss (mm) represented the total difference in annual discharge between the two sites (m^3) normalized to the watershed area of the downstream site. Ober Creek (55 km^2), a nonglacier-fed ephemeral stream, enters Jarvis Creek between the two gauging sites.

Groundwater levels (not flow) were measured ~800 m east of the Delta River and ~1.6 km downstream of the Jarvis Creek-Delta River confluence (64.04 N, −145.74 W, 354 m asl) (Figure 1b). Groundwater levels and temperature were measured inside an unused ~40 m deep household well with a 15 cm diameter steel pipe and casing. Groundwater data were logged every hour on a nonvented pressure transducer, which was hung on a wire (Text S2). Groundwater flow nor streambed hyporheic flows were measured.

3.3. Definition of Glacier Runoff

The definition of the glacier contribution to total runoff is ambiguous in the literature [*Radić and Hock*, 2014]. We quantified and defined glacier contribution to total runoff via two approaches: excess discharge and glacier meltwater runoff. Excess discharge is the glacier-derived runoff that is due to net mass loss (negative volume change) [*Lambrecht and Mayer*, 2009; *Radić and Hock*, 2014]. Excess discharge was calculated for the Tanana River watershed from the 1950s and ~2010 imagery and established volume-area scaling approaches [*Bahr et al.*, 1997, 2015] (Text S3). However, not all excess discharge may infiltrate the groundwater system. The portion of excess discharge supporting aquifer recharge was obtained from the percentage of streamflow loss as measured between the Jarvis Creek upstream and downstream gauging sites. The glacier-derived groundwater recharge was then compared to the measured winter discharge change (January through March). Different measurement intervals (1950–2010 glacier volume versus 1973–2016, winter discharge) necessitated us to assume the measured increase in winter discharge applies over the entire excess discharge interval. The base flow increase was assumed constant throughout the year.

Glacier meltwater runoff is the component that comes from any melt over the glacier area (ice, firn, and snow), irrespective of annual (net) mass balance [*Cogley*, 2012; *Radić and Hock*, 2014]. We estimate glacier meltwater runoff for the 2011–2016 period via the summer mass balance [*O'Neel et al.*, 2014] at both Jarvis and Gulkana glaciers. Glacier meltwater contribution to streamflow, i.e., the ratio of summer mass balance to total streamflow, was calculated based on annual runoff for the water year (1 October to 30 September) at Jarvis Creek upstream site and Phelan Creek.

4. Results

4.1. Meteorology and Discharge

Long-term meteorological measurements (1947–2016), limited to the Tanana River lowlands, show a warming in summer and increased mean annual air temperatures (Figure S1 and Table S1). The summer warmth index (SWI) averages 59°C (Delta Junction) and has increased on average 0.1°C yr^{-1} ($p \leq 0.01$). The mean annual temperature (−2.0°C) has warmed +0.03°C yr^{-1} ($p \leq 0.05$). Annual precipitation (318 mm) has decreased, albeit not statistically significantly (−0.6 mm yr^{-1}, p 0.13) (Table S1). Tanana River winter runoff increased since 1973 (23 mm, +0.1 mm yr^{-1}, Mann-Kendall $p \leq 0.01$) as did annual runoff at the glacierized

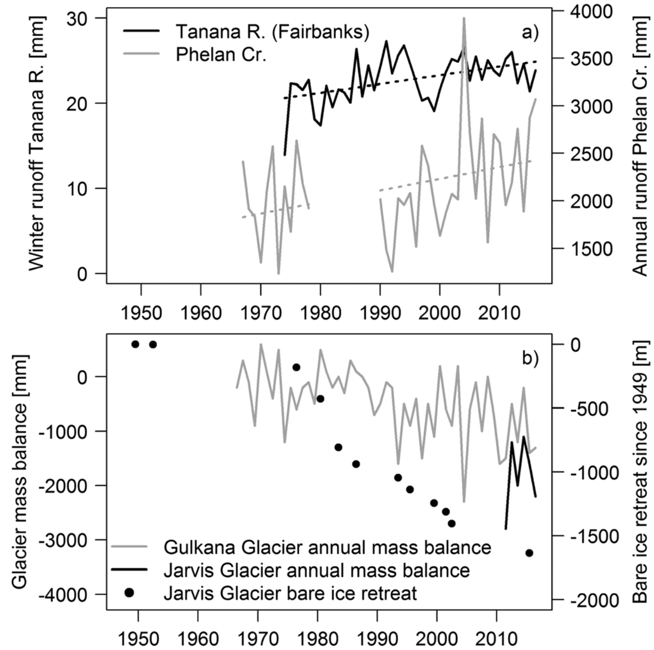

Figure 2. Field measurements of (a) runoff and (b) annual glacier mass balance. Tanana River winter (black line) and Phelan Creek annual runoff (gray line) show statistically significant increase. Annual glacier mass balance is negative and includes a sustained long-term shrinkage of the Gulkana Glacier and bare ice retreat of the Jarvis Glacier.

headwater Phelan Creek (2141 mm, +12.2 mm yr^{-1}, $p \leq 0.05$) (Figure 2). Annual runoff of Tanana River also increased (343 mm, +0.7 mm yr^{-1} $p \leq 0.1$). Winter discharge is negligible in Phelan Creek (March 2015–2016 average is 0.1 m^3 s^{-1}) and absent at the Jarvis Cr. downstream site. At the Jarvis Cr. upstream site, late winter discharge was 3.4 (12 April 2014), 3.0 (1 April 2015), and 3.3 m^3 s^{-1} (22 March 2016), which includes year-round flow from McCumber Creek.

Mean annual air temperature (−1.0°C) and SWI (62°C) in 2011–2016 were above the long-term average. Total annual precipitation in the lowland was lower (288 mm) during the recent 6 year period compared to long-term values. This difference was primarily attributed to reduced summer precipitation (193 mm during 2011–2016 compared to 224 mm during 1947–2016). All 6 years had SWI above the long-term average, while precipitation and mean annual air temperatures were both above and below the 1947–2016 average. Only mean annual air temperature presented a long-term record (high) during the 2011–2016 period where 2016 had unusual warmth (1.8°C). Mean annual air temperature at the Jarvis (1650 m asl) and Gulkana (1425 m asl) glaciers were −5.1 (2012–2015) and −3.2°C (2012–2015), respectively.

4.2. Glacier Coverage and Mass Balance

Tanana River watershed glacier coverage decreased by 12% during the 60 year time period (1950–2010) (Figure 1 and Table 1). At Jarvis Glacier, this long-term reduction is associated with an ~1600 m retreat of the bare-ice front from 1949 to 2015 (Figure 2). The recent negative annual mass balances (average −1.6 mwe, 2011–2016) at Jarvis Glacier included high seasonal losses where the summer mass balances averaged −3.0 mwe. (Table S2). For Gulkana Glacier 2011–2016, the annual and summer mass balance were also both negative albeit to a lesser extent (−1.0 and −2.0 mwe, respectively).

4.3. Glacier Runoff Contribution

Glacier meltwater runoff contributed on average 47% (871 to 1452 mm, 2011–2016) of annual runoff (average 2315 mm, from 1760 to 2932 mm, 2011–2016) at the headwater with the most glacier coverage (Phelan Creek) (Table S3). In the Jarvis Creek watershed with the least glacier coverage, glacier meltwater runoff represented 15% (114 mm in 2015) to 28% (209 mm in 2016) of the annual runoff (762 and 738 mm, respectively). Average glacier meltwater runoff (179 mm 2011–2016) to the Jarvis Creek upstream site represented 56% of average long-term annual lowland precipitation (319 mm, 1947–2016). At the Tanana River watershed scale, the 12% (516 km^2) glacier area reduction resulted in an estimated 16% glacier volume loss (484 km^3) from 1950 to 2010 (Table 1). The glacier area reduction corresponds to an average total excess discharge of 399 km^3 (363 to 435 km^3), when converted using the two different assumptions of glacier density.

4.4. Losing Headwater Streams

Our continuous differential discharge measurements in summer 2015 and 2016 show Jarvis Creek as a losing stream with discharge decreasing downstream (Figure 3 and Table S3). Annually, the loss of streamflow to the underlying aquifer averaged 46% and ranged from 44% in 2016 (stage-discharge RMSE produced a range

Table 1. Estimated Long-Term Mass Changes Within Tanana River Watershed[a]

	1950	2010	Change ρ = 0.75	Change ρ = 0.9
Glacier area (km^2)	4398	3881	−516	
Glacier ice volume (km^3)	3066	2582	−484	
Excess discharge (km^3)	na	na	+363	+435
Aquifer recharge from excess discharge (km^3)	na	na	+167	+200
Total change in base flow (km^3)	+85			

[a]Glacier coverage, and total glacier volume loss, glacier-derived "excess discharge" and total change in river base flow 1950–2010. The excess discharge presents a range of glacier density (ρ) obtained from literature (750 to 900 kg m^{-3}). The aquifer recharge is estimated from the average 2015 and 2016 observed streamflow loss in Jarvis Creek (46%). na, not applicable.

from 38 to 49%) to 48% in 2015 (41 to 56%). If constraining to the warm season only, the stream lost 16% (2 May to 24 September 2016) to 23% (June 15 to 8 September 2015). The aquifer recharge normalized to watershed area (downstream gauging site) ranged from 180 (2016) to 202 mm (2015), which is approximately twice the long-term average lowland winter precipitation (92 mm). At the Tanana River watershed scale, the glacier-derived excess discharge that recharged the aquifer, which ratio was obtained from the measurements in Jarvis Creek (46% loss), was estimated from 167 to 200 km^3 (Table 1). Over the same time interval, the total estimated change in Tanana River base flow was 85 km^3.

4.5. Lowland Groundwater Levels

Groundwater levels in the lowlands show large seasonal variations (Figure 3). Near the confluence of Jarvis Creek and the Delta River, groundwater levels varied up to 13.1 m (2015) and 13.8 m (2016) annually. The seasonal minimum of 24 m (11 May 2015) and 23 m (22 May 2016) below ground surface increased to a seasonal high of 10.9 m (2 August 2015) and 9.2 m (29 August 2016). Water levels increased most rapidly in early summer (+0.23 m d^{-1}, 11 May to 30 June 2015, and +0.32 m d^{-1}, 22 May to 30 June 2016). A slower increase followed in late summer (+0.05 m d^{-1}, 30 June to 2 August 2015, and +0.02 m d^{-1} 30 June to 29 August

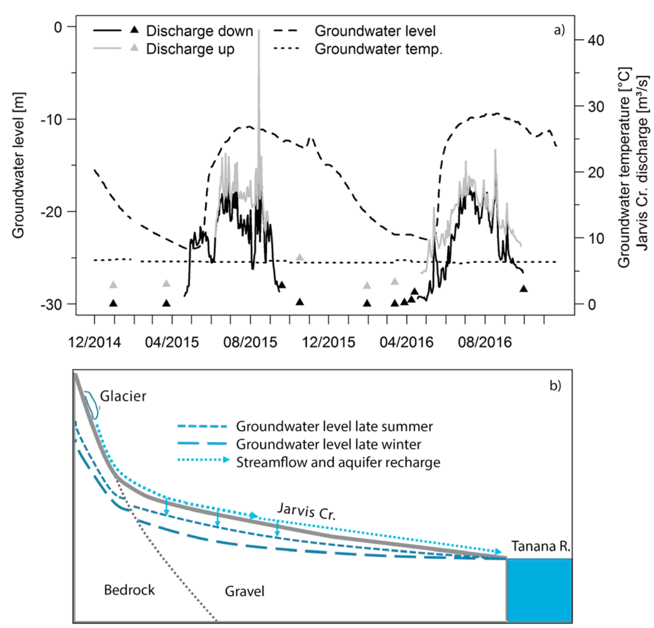

Figure 3. (a) Measured and (b) conceptualized groundwater levels and discharge in Jarvis Creek. Discharge measurements represent the downstream and upstream sites in 2015 and 2016. The solid lines are the continuous hydrograph as derived from stage-discharge relationships, while the triangles represent point discharge measurements during ice-affected conditions. Measured groundwater levels and temperatures (~30 m depth) are relative to the local ground surface. The glacierized headwater Jarvis Creek and its seasonal groundwater levels conceptualized in 2-D with the gradient decreasing in winter as the aquifer feeds the lowland Tanana River and Jarvis Creek streamflow recharging the aquifer in summer.

2016). Groundwater levels decreased steadily during fall and winter, fastest between December and February (-0.08 m d^{-1} in both years). Water temperatures remained steady throughout the years, averaging 6.4°C (5.6–6.8°C) at about ~30 m depth below the ground surface.

5. Discussion

Our study highlights the importance of glacier runoff on subarctic summer headwater discharge, groundwater recharge, and cold and warm season lowland base flow (Figure 3b). Glacier runoff plays a large role (>15%) in annual streamflow of headwaters with both low (3%) and high (60%) glacier cover. The percent glacier coverage was 20 times larger at the Phelan compared to the Jarvis Creek watershed, while the glacier meltwater contribution to annual streamflow approximately doubled (22 versus 47%). The nonlinearity can be explained by the increase in precipitation and decrease in evapotranspiration as one moves from lowlands to mountains [*Huss*, 2011; *Kaser et al.*, 2010], which cause large differences in specific runoff (750 and 2315 mm, respectively). Glacier contribution to streamflow has been shown to scale nonlinearly with the percentage of ice cover in the Alps [*Huss*, 2011], and we show that the phenomenon also holds for the subarctic.

Glacier runoff affects watershed hydrology beyond adding to summer streamflow. Differential streamflow measurements in the headwater stream Jarvis Creek show a large portion of the streamflow (at least 44% annually) infiltrating and recharging the aquifer as the creek enters the lowlands. When normalized to the watershed area, the total stream corridor aquifer recharge (180 to 202 mm) exceeds the potential aquifer recharge during snowmelt in the lowland (~100 mm). The annual aquifer recharge along the Jarvis Creek corridor is likely a conservative estimate as any additional input such as diffuse surface flow and/or ephemeral streams between the two discharge monitoring sites was ignored. Other stream losses, such a stream evaporation, are negligible in comparison to the groundwater recharge (Text S4). Accordingly, influent glacierized headwater streams can serve as a major recharge corridor to the underlying aquifer in semiarid climates.

The role of glaciers as groundwater recharge sources is established also at the regional scale. Long-term glacier-derived aquifer recharge estimates within the Tanana River watershed (167 to 200 km^3) are more than twice the observed base flow anomalies (85 km^3). The difference is likely due to an underestimated change in total annual base flow as our estimate applied the January through March discharge increase throughout the year. In winter, this aquifer is the sole contributor to lowland river discharge as all other sources are frozen. Accordingly, glacier mass loss, and associated excess discharge, from the Alaska Range has likely served as the dominant supply to Tanana River's long-term increase in winter discharge.

Aquifer recharge from stream corridors is limited by the supply of water and the bed surface area. In turn, aquifer recharge controls aquifer storage, which is also constrained by aquifer capacity. Thawing at the permafrost bottom [*Osterkamp*, 2005; *Osterkamp and Romanovsky*, 1999] has likely increased aquifer capacity and therefore also (glacier-derived) aquifer storage. Further, increased glacier-derived aquifer recharge could be an important mechanism by which bottom permafrost boundaries are eroding, especially at the observed groundwater temperatures (6°C). Accordingly, the excess discharge sourced from mountain glaciers has not only increased headwater streamflow, aquifer recharge, and storage but may also have increased aquifer capacity—all with the final effect of increasing winter discharge.

6. Conclusions

High-latitude mountain glaciers represent an overlooked source to subarctic river discharge and aquifer recharge. Our results suggest a linkage between glacier melt, headwater discharge, aquifer recharge, and lowland winter streamflow that may be hydrologically important also in other semiarid glacierized regions within and outside the subarctic. Our measurements show that an Interior Alaska headwater stream lost significant amounts of its annual water (46%) to the underlying aquifer, while glacier runoff represents a significant share (>15%) of annual discharge under both low (3%) and high (60%) glacier coverage. Glacier runoff, via its contribution to streamflow, is therefore amplifying subarctic aquifer recharge under a warming climate. Since the 1950s, long-term glacier coverage reduction in Tanana River basin produced excess discharge and subsequent aquifer recharge that exceeded the observed increase in lowland river base flow. The glacier mass loss has likely served as the dominant supply to the Tanana River's long-term increase in annual and winter discharge considering no commensurate increase in Interior Alaska precipitation. We conclude that the role of mountain glaciers on subarctic watershed hydrology and permafrost deserves increased attention, especially considering the well-documented decline in ice cover and increased winter river discharges.

Acknowledgments
The research was funded by the Arctic System Science Program (National Science Foundation, 2013–2016, award 1304905), Alaska Center for Climate Assessment and Policy (2015), Alaska University Transportation Center (2012–2013), Alaska Department of Transportation and Public Facilities (2012–2013), the Department of Defense's Strategic Environmental Research and Development Program (RC-2110, 2011–2015), the Engineer Research and Development Center's Center Directed Research and Army Basic Research (6.1) programs, the Pacific Northwest Transportation Consortium (2012–2013), USGS Climate Research and Development Program, and the National Institutes for Water Resources (2012). We thank R. Hock for providing input to Jarvis glacier stake mass balance design. Logistical and field support was provided by the Salcha-Delta Soil and Water Conservation District. We thank A. Orr, N. Jacobs, A. Chamberlain, T. Weiss, and J. Bailey for field and data processing support. There are no real or perceived financial conflicts of interest for any author. The data supporting the conclusions are available at the National Science Foundation data center (https://arcticdata.io/).

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