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No Groundwater, No Fish: The Critical Role of Groundwater in Supporting Non-Glacial, Salmon-Bearing Rivers in South-Central Alaska

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ABSTRACT

Groundwater discharge plays an important role in the hydrologic and ecologic functioning of rivers including sustaining streamflow and related habitat year-round. Simultaneously, groundwater supports the increasing demands of people as the global population continues to grow. Balancing the needs of users becomes increasingly important as climate change introduces greater uncertainty in water resources and fisheries, especially for economically important anadromous species that depend on freshwater resources. We investigated the seasonal and regional variability of groundwater contributions to six non-glacial mainstem salmon-bearing rivers in south-central Alaska. We hypothesized that groundwater contributes more than half of the annual streamflow, and nearly all of the streamflow during late summer and mid-winter periods. Our results show that groundwater discharge is the dominant source of streamflow, with an annual relative contribution of 70%. Groundwater contribution to streamflow varies seasonally, ranging from approximately 50%–70% during peak flow to 70%–80% during low flow. Groundwater contribution to streamflow also varies spatially, with maximum differences in groundwater contribution between watersheds ranging ±20 percentage points. However, all rivers in the study area followed similar trends, with higher groundwater contributions in summer and winter and lower contributions in spring and fall.

1 | Introduction

Groundwater, traditionally defined as water stored and transmitted within the saturated zone but commonly including the continuum of water stored and transmitted in both the unsaturated and saturated zones (Freeze and Cherry 1979), contributes 14%–90% of annual streamflow in the conterminous United States, though this contribution varies greatly across both regions and seasons (Winter et al. 1998). This groundwater-surface water connectivity is fundamental to maintenance of the natural flow regime, as it sustains year-round streamflow, especially during seasonal low flows and droughts (Kløve et al. 2014; Poff et al. 1997; Tague et al. 2008). Moreover, groundwater contributions affect stream temperature, chemistry, and dissolved oxygen conditions that support freshwater fish and other native biota (Brunke and Gonser 1997; Caissie 2006; Kurylyk et al. 2015), and provide critical ecosystem services (Boyd et al. 2015; Daily 1997).

However, groundwater levels are declining worldwide due to both anthropogenic and climatic forcings. Increasing agricultural, domestic, and industrial demands drive greater

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withdrawals, leading to widespread depletion (Jasechko et al. 2024; Konikow and Kendy 2005; UN-Water 2022). Additionally, the indirect effects of changing land use and land cover affect the recharge rates and thus the quantity and quality of groundwater resources (Gleeson et al. 2020; Green et al. 2011; Scanlon et al. 2005). These pressures are compounded by changes in regional precipitation and evapotranspiration patterns, as extreme weather events become more common (Xiong and Yang 2024). In particular, shifts in precipitation type and timing (e.g., shifts from snow to rain which causes surface runoff over frozen ground rather than storage in snow pack or infiltration in unfrozen ground), along with increases in the length of the growing season and overall evapotranspiration demand, threaten groundwater recharge, especially in polar and boreal regions (Amanambu et al. 2020; Fassnacht et al. 2016; Intergovernmental Panel on Climate Change (IPCC) 2023). In areas where groundwater withdrawals exceed sustainable recharge rates, streamflow is expected to diminish below minimum flow thresholds in 50% of watersheds globally by 2050 (de Graaf et al. 2019), threatening freshwater biodiversity including many species of fish, which are particularly vulnerable to altered flow regimes (Larsen and Woelfle-Erskine 2018; Perkin et al. 2017; Poff and Zimmerman 2010).

This delicate balance of groundwater resources between fish and people is exemplified in south-central Alaska. In this region, groundwater discharge commonly occurs proximal to rivers (Gerlach et al. 2022), contributing to freshwater inputs from headwater streams to estuaries (Bergstrom et al. 2021; Callahan et al. 2015; Haag et al. 2023; Kikuchi et al. 2012; Leaf et al. 2024; Nelson and Johnson 1981). In streams, groundwater augments streamflow (Callahan et al. 2015), delivers land-derived nutrient subsidies to streams (Callahan et al. 2017), and modulates stream temperatures (Callahan et al. 2015), keeping water warmer in winter and cooler in summer, the latter increasingly important for warming salmonid-streams under a changing climate (Mauger et al. 2017). At the same time, local communities and private landowners require groundwater as their primary source of water supply (Glass 1996; Munk et al. 2011). As the regional population grows, groundwater resources face increasing pressure from extraction and expanding land use, as well as the broader drying climatic trend (Klein et al. 2005; Berg et al. 2009).

In the state of Alaska, groundwater withdrawal remains largely unregulated, though some protections exist to maintain natural streamflow, including reservations of water (i.e., legal protections for minimum flows and levels in streams) and the Alaska Anadromous Waters Catalog (i.e., streams with legally documented anadromous fish use). Together, they apply to only a small portion of the state's streams, with approximately 3200 miles of streams having reservations of water and 79,768 miles of streams in the Alaska Anadromous Waters Catalog, the latter a conservative estimate as new streams are added to the catalog annually (Alaska Department of Natural Resources 2022; Giefer and Graziano 2024a, 2024b, 2024c, 2024d, 2024e, 2024f). In total, these protections cover only about 5% of all stream miles mapped in the National Hydrography Dataset for Alaska (U.S. Geological Survey 2023). However, in south-central Alaska, there is growing interest in expanding protection efforts beyond streams to include groundwater source areas through land acquisition and conservation (Walker et al. 2021; Brigino et al. 2023).

Such efforts are most effective when informed by an understanding of the spatially and temporally varying contributions of groundwater to streamflow. Groundwater contributions to streamflow are often quantified using tracer studies, which identify and characterize the chemical or isotopic composition of distinct source waters or end-members (e.g., precipitation and groundwater) (Pinder and Jones 1969; Sklash and Farvolden 1979; Somers and McKenzie 2020). Tracer studies have been applied in south-central Alaska to determine groundwater contribution to headwater streams during spring snowmelt and summer (Callahan et al. 2015), groundwater contribution from peatlands to streamflow during a dry period (Gracz et al. 2015), and groundwater contribution to non-glacial and glacial outlet streams during spring through early fall (Bergstrom et al. 2021), with estimates ranging from 30% to 60%.

However, annual groundwater contributions to mainstem rivers and potential seasonal fluctuations remain largely unquantified, highlighting the need for targeted studies in south-central Alaska. These rivers not only act as corridors from the headwaters to the ocean, but also provide critical migration routes and spawning grounds for salmonids (Huntsman and Falke 2019). In addition, mainstem rivers are highly valued by local communities for subsistence, cultural practices, and fish-based livelihoods (Flaherty et al. 2019; Guerrón-Orejuela 2024).

In this study, we quantify the relative contributions of groundwater to mainstem freshwater rivers in five south-central Alaskan watersheds for two and a half consecutive years. We hypothesized that (a) groundwater contributes more than half of annual streamflow and (b) nearly all of streamflow during late summer and mid-winter periods, when flows are low. To test these hypotheses, we use the following roadmap: (1) identify geochemical tracers to distinguish source waters within streamflow, (2) quantify source water contribution to instantaneous streamflow, and (3) characterize the annual, seasonal, and spatial patterns of groundwater contribution to streamflow.

2 | Site Description

This study was conducted in the Kenai Peninsula Lowlands, the unglaciated portion of the Kenai Peninsula in south-central Alaska (Figure 1). The Kenai Peninsula Lowlands (~1655 km^2) are located north of Kachemak Bay, west of the Kenai Mountain Range, and east of Cook Inlet and include five watersheds south to north: Anchor River (~586 km^2), Stariski Creek (~131 km^2), Happy Creek (~34 km^2), Deep Creek (~576 km^2), and the Ninilchik River (~329 km^2). The Anchor River has two prominent forks: the South Fork Anchor River (~399 km^2) and the North Fork Anchor River (~181 km^2). These watersheds drain into Cook Inlet, and all but one support salmon; the exception is Happy Creek, which has a waterfall at the mouth that acts as a natural fish barrier. Nevertheless, all five watersheds are included in this study.

The climate of the Kenai Peninsula Lowlands is characterized by short summers and long, cold winters, but transitions from a

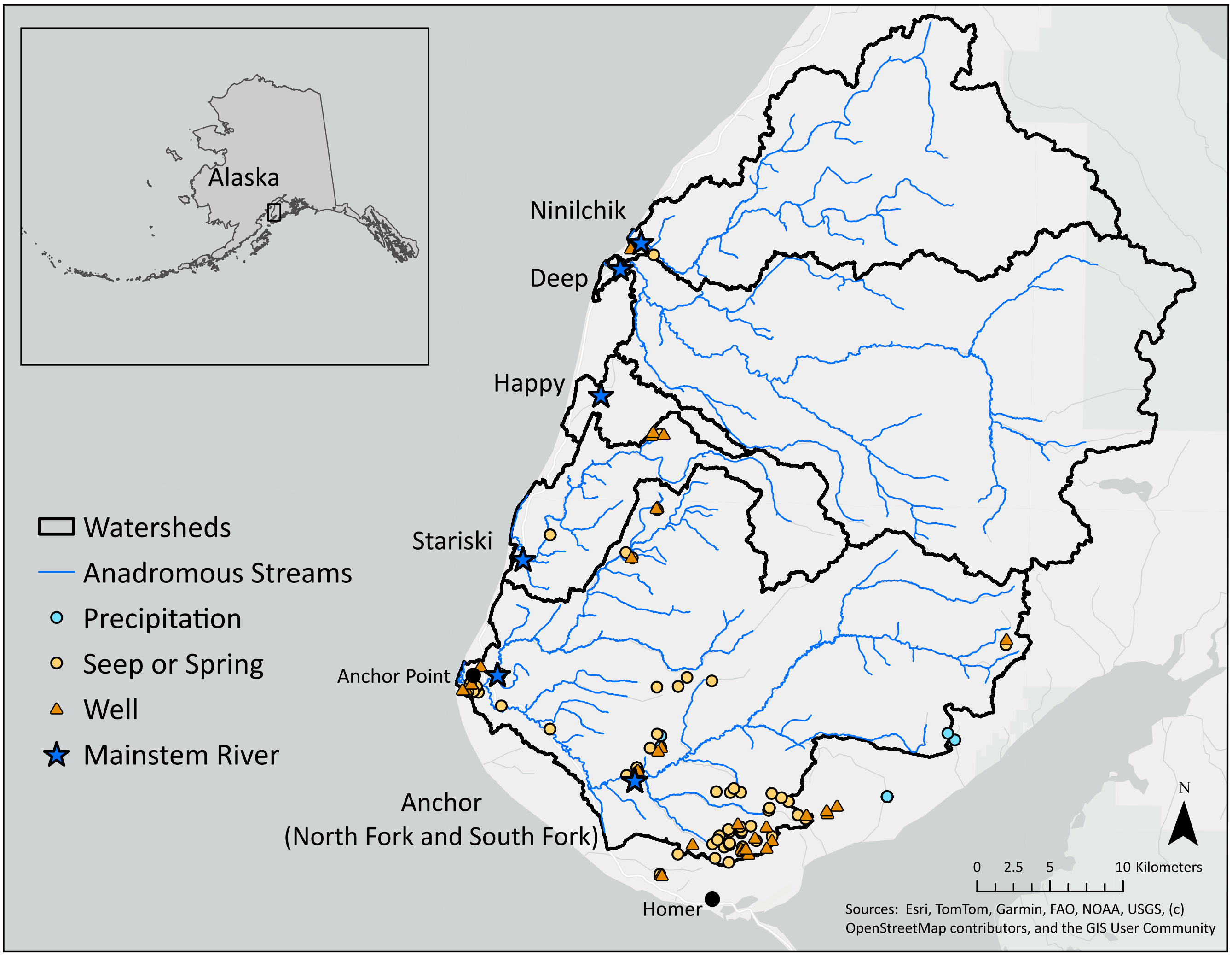

FIGURE 1 | Location of study area, major watersheds, and sample points.

temperate, ocean-influenced maritime climate to a more variable continental climate from south to north. The mean annual temperature and precipitation are 2.9°C and 755 mm, respectively (HOMER 8 NW, ALASKA [503672], 1991–2020). Precipitation and river discharge are seasonal, as exemplified by data from the water year 2018–2019, which was the last official complete year of river discharge data collection by the US Geological Survey in the study area (Figure 2). Of particular note is that baseflows occur both in late summer when air temperatures are high and precipitation is low, and in mid-winter when air temperatures are well below zero and precipitation is typically stored in snowpack. These seasonal patterns, however, may be shifting as the region is experiencing a drying trend, which may result from a lengthening of the growing season, higher temperatures, and increased evapotranspiration demand (Klein et al. 2005; Berg et al. 2009).

The geology of the Kenai Peninsula Lowlands is largely the result of its setting in a forearc sedimentary basin (Wilson and Hults 2012), and the topography reflects five major Pleistocene glaciations and numerous minor post-Pleistocene glacial advances (Karlstrom 1964; Reger et al. 2007). The tertiary and quaternary sedimentary geologic units present at the surface are consistent among the five watersheds (Wilson and Hults 2012), with dominant formations including the Beluga (Miocene) and Sterling (Pliocene–Miocene) Formations, both interbedded sandstone, siltstone, and claystone, along with minor interbedded carbonaceous shale, lignitic coal, and volcanic ash. These are variously draped with Pleistocene moraine, glaciolacustrine, outwash, and valley train deposits, and Holocene alluvium and terrace deposits. The overall topographic relief of the study watersheds ranges from 0 to 884 m above mean sea level (AMSL) but varies for each watershed: Anchor River (0–616 m AMSL), Stariski Creek (0–591 m AMSL), Happy Creek (0–268 m AMSL), Deep Creek (0–884 m AMSL), and Ninilchik River (0–622 m AMSL).

In the Kenai Peninsula Lowlands, groundwater recharge potential is typically highest in areas with low slopes, surficial deposits with high permeability, relatively high precipitation, and undeveloped land cover (Guerrón-Orejuela et al. 2023). This groundwater then discharges proximal to rivers by two mechanisms: hillslope groundwater and aquifer-outcrop groundwater (Gerlach et al. 2022). Hillslope groundwater mixes with annual precipitation and antecedent soil moisture, flowing through the shallow subsurface and discharging from seeps (Gerlach et al. 2022). Seeps are commonly expressed as diffuse groundwater discharge at topographic discontinuities.

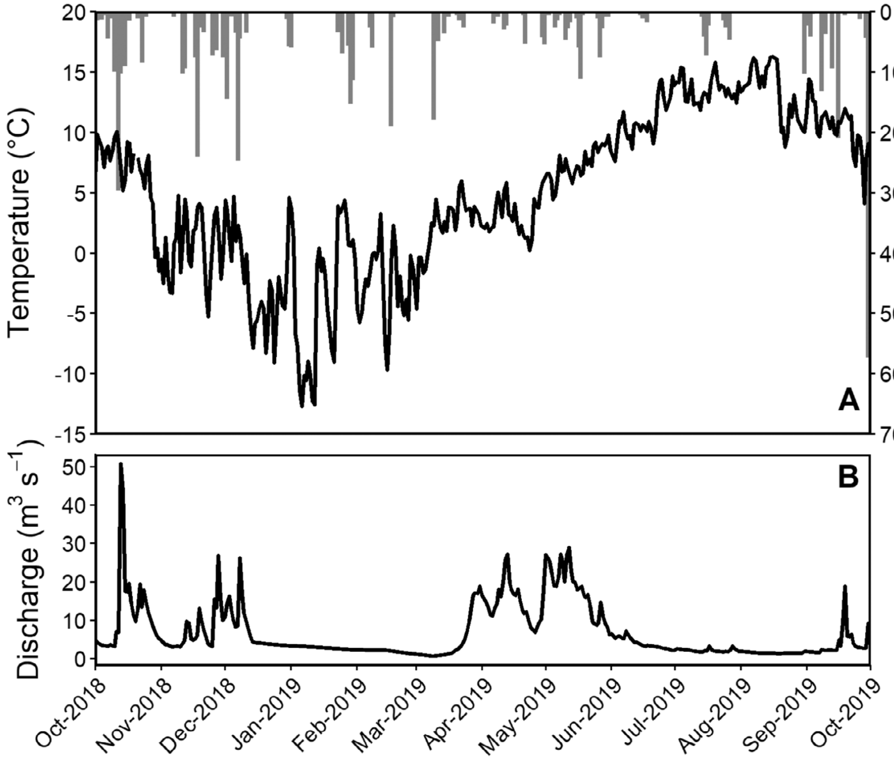

FIGURE 2 | Representative climate and discharge patterns in the Kenai Peninsula Lowlands, Alaska. (A) Mean daily precipitation (gray) and mean daily atmospheric temperature (black) in Anchor Point, Alaska (NOAA National Estuarine Research Reserve System [NERRS] 2025). (B) Mean daily discharge for the Anchor River, Alaska (U.S. Geological Survey 15239900 ANCHOR R NR ANCHOR POINT AK). The US Geological Survey ceased monitoring discharge in this region in 2020.

Aquifer-outcrop groundwater has recharged into the deeper subsurface and flows through thin, discontinuous aquifers, commonly discharging as springs (Gerlach et al. 2022). In this study area, springs are focused groundwater discharge from aquifer outcrops that have been exposed by the downcutting of modern-day rivers.

In these five watersheds, groundwater discharge supports stream hydrology and ecology by transporting nutrients, providing baseflow, and modulating stream temperature. Before discharging, this groundwater can pass through nitrogen-fixing alder patches, mobilizing nitrogen and delivering it to streamside wetlands where it increases the biomass of riparian plant species (Callahan et al. 2017; Whigham et al. 2017). That above-ground biomass drops into streams, serving as a primary food source for instream macroinvertebrates and thereafter juvenile salmonids (Shaftel et al. 2011; Dekar et al. 2011; Hiatt et al. 2017). The groundwater that passes directly to the headwater streams supports headwater streamflow, contributing approximately 40% of flow during spring snowmelt and 60% of flow in mid-summer, and modulates temperatures, keeping headwater streams habitable by preventing them from reaching lethal high temperatures during the summer and from freezing to solid ice during the winter (Callahan et al. 2015). This landscape connectivity to headwater streams supports numerous anadromous salmonid species, including coho (*Oncorhynchus kisutch*), pink (*O. gorbusha*), Chinook (*O. tshawytscha*), in addition to steelhead trout (*O. mykiss*) and Dolly Varden char (*Salvelinus malma*) (Walker et al. 2012; King et al. 2012).

3 | Methods

3.1 | Data Collection

We collected 287 water samples within the study area over 6 years (2018–2023) for chemical analysis (Figure 1). We collected 12 samples of precipitation (i.e., both rain and snow) and ephemeral overland flow (i.e., snowmelt and rainfall runoff) from two sites. We additionally acquired stable isotope data for 11 samples of precipitation collected from three sites from a previous study within our study area (Gracz et al. 2015; Gracz 2017). We collected 124 samples of groundwater (i.e., seeps, springs, and wells) from 96 sites. Seeps or springs included both shallow soil water and groundwater discharging at topographic discontinuities on hillslopes (i.e., hillslope groundwater, viz. Gerlach et al. 2022) and groundwater discharging from springs at aquifer outcrops (i.e., aquifer-outcrop groundwater, viz. Gerlach et al. 2022). Wells included shallow piezometers installed 1–3 m below the ground surface and residential and public water-supply wells at depths ranging from 3 to 92 m below the ground surface. We collected 150 samples of mainstem river water from the South Fork and North Fork Anchor Rivers, Stariski Creek, Happy Creek, Deep Creek, and the Ninilichik River, south to north, respectively.

The timing of sampling was specific to water type and season (Table 1). We collected precipitation and ephemeral overland flow samples opportunistically and groundwater samples periodically in late summer and early fall. We collected river water samples from the South Fork Anchor River weekly in spring-fall

TABLE 1 | Sampling frequency for source waters and river sites from June 2018 to October 2023. Groundwater includes seeps, springs, and wells. The “X” indicates sampling occurred.

Date	Precipitation[a]	Seep or Spring	Well	South Fork Anchor River	North Fork Anchor River	Stariski Creek	Happy Creek	Deep Creek	Ninilchik River
Jun 2018		X	X						
Jul 2018		X	X						
Aug 2018–May 2019				Gap in sampling record					
Jun 2019		X	X						
Jul 2019		X	X						
Aug 2019–Mar 2021				Gap in sampling record					
Apr 2021	X			X					
May 2021	X			X					
Jun 2021				X					
Jul 2021				X					
Aug 2021				X					
Sep 2021		X	X	X		X	X	X	X
Oct 2021				X					
Nov 2021				X					
Dec 2021				X					
Jan 2022				X					
Feb 2022				X					
Mar 2022				X					
Apr 2022				X					
May 2022				X					
Jun 2022		X	X	X	X	X	X	X	X
Jul 2022	X	X	X	X	X	X	X	X	X
Aug 2022				X					
Sep 2022		X	X	X	X	X	X	X	X
Oct 2022				Gap in sampling record					
Nov 2022				X					
Dec 2022				X					
Jan 2023	X			X	X	X	X	X	X
Feb 2023				X					
Mar 2023				X					
Apr 2023	X			X	X	X	X	X	X
May 2023				X					
Jun 2023				X					
Jul 2023		X	X	X	X	X	X	X	X

(Continues)

TABLE 1 | (Continued)

Date	Precipitation[a]	Seep or Spring	Well	South Fork Anchor River	North Fork Anchor River	Stariski Creek	Happy Creek	Deep Creek	Ninilchik River
Aug 2023				X					
Sep 2023		X	X	X	X	X	X	X	X
Oct 2023				X					

[a]Precipitation samples collected in April and May represent snow.

and monthly in winter and from the North Fork Anchor River, Stariski Creek, Happy Creek, Deep Creek, and the Ninilichik River quarterly. There was a gap in all sampling from August 2018 to May 2019 because we lacked winter field support, and again from August 2019 to March 2021 because we lacked winter field support and were unable to travel during the Covid-19 pandemic.

We measured temperature, pH, and specific conductance in the field using handheld meters (e.g., YSI Pro 1030 or the equivalent). For dissolved ion analyses, we filtered samples with a 0.45 μm nylon filter in the field if the weather permitted or immediately upon returning to the Kachemak Bay National Estuarine Research Reserve (KBNERR) lab if weather conditions precluded on-site filtration. Filtrate was stored in 50 mL polypropylene bottles for subsequent analysis. For stable isotope analyses, we placed unfiltered samples in 20 mL HDPE bottles wrapped in parafilm and tightly capped to prevent contact with ambient air and continued fractionation during transport and storage. All samples were stored in a cooler with ice packs in the field and then immediately frozen (dissolved ion samples) or refrigerated (stable isotope samples) upon returning to the KBNERR lab for subsequent transfer to Tampa, FL.

3.2 | Water Chemistry

Samples collected in 2018–2023 were analyzed for cations on a Perkin Elmer Avio 200 ICP-OES at the University of South Florida (USF) Center for Geochemical Analysis in Tampa, FL. Anion concentrations were measured on an ion chromatograph using EPA method 325.2 at Advanced Environmental Laboratories Inc. in Tampa, FL (2018) or on a Thermo-Dionex Integrion Modular HP-IC (2019–2023) at the USF Center for Geochemical Analysis. Detection limits were 10 μg/L for cations and 0.20 mg/L (2018) or 0.5 mg/L (2019–2023) for anions. There were 118 samples for which the concentrations of Si, Sr, Cl, SO_4, and NO_3 were below the detection limits. To calculate mean concentrations, all concentrations below the detection limit were assigned values corresponding to half of the detection limit. Carbonate alkalinity was estimated by assuming all other cations and anions were measured, and that bicarbonate and carbonate accounted for the missing charge in charge balance error analyses (e.g., Parkhurst 1997; Rains 2011).

Stable isotopes (i.e., δ^2H and δ^{18}O) were analyzed at the USF Stable Isotope Laboratory with a Picarro cavity ring-down spectrometer. Deuterium (^{2}H) and oxygen-18 (^{18}O) are reported in standard delta (δ) notation:

$$\delta = \left[\left(\frac{R_{sample}}{R_{standard}}\right) - 1\right] \times 100 \quad (1)$$

where R is the ratio of the heavy isotope to the light isotope. The δ^2H and δ^{18}O values are reported in per mil deviation relative to Vienna Standard Mean Ocean Water (VSMOW). Quality assurance for cation, anion, and isotope analyses was provided through the analysis of field and lab duplicate samples for approximately 10% of the total water samples. Quality control was provided through the analysis of external and internal reference standards that accounted for approximately 20% of analytical runs.

3.3 | Mixing Model

Our approach to determine the contributions of source waters to streamflow is based on both traditional two-end-member mass-balance hydrograph separation (Pinder and Jones 1969; Sklash and Farvolden 1979) and multivariate statistical end-member mixing analysis (EMMA) (Christophersen and Hooper 1992). Both approaches can lead to the identification of the same end-members and similar estimates of end-member contributions to streamflow (Ramón et al. 2021). The first step in both techniques is the identification of dissolved ions that do not undergo in-stream chemical transformations (i.e., conservative tracers). We identified conservative tracers by examining bivariate scatter plots of all possible combinations of solutes in stream samples for collinear behavior (Hooper 2003), selecting those that show good linear fit ($R^2 > 0.5$ and $p < 0.01$) (Barthold et al. 2011; Ramón et al. 2021).

In EMMA, the concentrations of the conservative tracers in samples are standardized (i.e., subtract the mean and divide by the standard deviation) and subsequently analyzed using principal component analysis (PCA). The number of principal components retained from the PCA is estimated by the rule of one, where the last principal component retained must explain 1/nth of the variance, where n is the number of tracers (Jöreskog et al. 1976). The number of end-members required to explain river water is the number of principal components plus one. Oftentimes, two principal components are retained, suggesting that three end-members are required to explain river water (Christophersen and Hooper 1992; Barthold et al. 2011). All potential end-members are projected into the U-space defined by streamflow samples, and the set of source waters whose orthogonal projections best bind river samples are chosen as end-members (Christophersen and Hooper 1992).

In our study area, there was no physical or geochemical evidence to justify selecting three end-members. Rather, all evidence suggested that streamflow is predominantly comprised of two sources: (a) precipitation and ephemeral overland flow, including snowmelt and rainfall runoff, and (b) groundwater, the latter combining all plausible groundwater sources (i.e., seeps, springs, and wells). Hereafter, we refer to these as “precipitation” and “groundwater”, respectively. Therefore, as a first-order approach to source water contribution, we used PCA and a two-tracer, two-end-member mass-balance mixing model with these two end-members.

We used the tracers with the highest PCA weights (i.e., first principal component axis) to create a bivariate scatter plot of the streamflow samples and the means of the precipitation and groundwater end-members. We used a mass-balance mixing model to calculate end-member contributions to streamflow samples, with the assumption that evapoconcentration is insignificant and river water is the instantaneous linear mixture of the chosen end-members. We calculated the relative contribution of end-members to streamflow using the following equation:

$$f_{gw} = \frac{C_{sf} - C_{pr}}{C_{gw} - C_{pr}} \quad (2)$$

where f_{gw} is the fraction of streamflow attributable to groundwater, C_{sf} is the concentration of the tracer in streamflow, C_{pr} is the average concentration of the tracer in precipitation, C_{gw} is the average concentration of the tracer in groundwater.

4 | Results

4.1 | Water Chemistry

All sampled waters were circumneutral and fresh (Table 2). Excluding precipitation because these samples were not measured, the range in pH average values was 6.43 (wells) to 7.52 (Ninilchik River), and the range in specific conductance average values was 68.74 μS/cm (Happy Creek) to 169.65 μS/cm (wells).

4.1.1 | Stable Isotopes

Isotope values were fairly consistent across all samples (Table 2). All samples generally fell along the Global Meteoric Water Line (GMWL) (Rozanski et al. 1993), suggesting limited evaporation in these waters or long water-rock interaction time (Figure 3). Groundwater sources (i.e., seeps, springs, and wells) and river samples generally fell within the range of our local precipitation points, suggesting that these are all modern waters and do not include substantive Pleistocene groundwater (Figure 3).

4.1.2 | Dissolved Ions

Dissolved ion water chemistry among source waters varied by water type. The concentrations of dissolved ions were generally low or below detection limits in precipitation, high in groundwater, and intermediate in river water (Table 2).

The concentrations of dissolved ions were variable across groundwater sources (i.e., seeps, springs, and wells), with the highest mean concentrations generally observed in the wells. Each groundwater source has examples of relatively low, intermediate, and high concentrations of dissolved ions, and seep, spring, and well samples overlap one another, with no clear chemical fingerprint to separate them in two-dimensional space (Table 2, Figure 4A). Although groundwater sources varied, groundwater generally plotted as magnesium-bicarbonate to sodium-bicarbonate types, while precipitation was plotted as sodium-chloride type (Figure 4A).

The concentrations of dissolved ions were generally intermediate in river water (Table 2). River water from all watersheds overlapped on Piper diagrams and were generally of the magnesium-bicarbonate type (Figure 4B). Specific conductance and concentrations of all dissolved ions followed dilution or flushing patterns following snowmelt and rainfall events in weekly South Fork Anchor River samples (Figure 5A,B). Specific conductance and the concentrations of conservative ions (e.g., Mg) are generally inversely correlated with increasing freshwater inputs to the river (i.e., snowmelt or rainfall) and reached minimum concentrations during snowmelt in May 2023 (Figure 5C,D).

4.2 | Mixing-Model Analysis

4.2.1 | End-Members

We reduced the 13 measured analytes to six conservative tracers: Mg, Ca, Si, Sr, $\delta^{18}O$, and $\delta^{2}H$, based on criteria for good collinear fits ($R^2 > 0.5$ and $p < 0.01$) in river water (Figure S1; Barthold et al. 2011; Ramón et al. 2021). Using these conservative tracers, we performed a PCA, and the first two principal components together explained approximately 88.2% of the total variance (Figure S2). The conservative tracers with the highest loadings on the first principal component were Ca and Sr, with loadings of 0.518 and 0.515, respectively (Table S1). We used these as conservative tracers in our two-end-member mass-balance mixing model (Figure 6A).

The values of Ca and Sr concentrations are similar for seeps, springs, and wells. In this first-order approach to estimating groundwater contribution to streamflow, we combined all groundwater sources (i.e., seeps, springs, and wells) into a single end-member (Figure 6B). The values of Ca and Sr concentrations in streamflow are generally intermediate between the two end-members, indicating that streamflow is a mixture of the end-member source waters (Figure 6B).

4.2.2 | Mass-Balance Mixing Model

We calculated the relative proportion of groundwater in river water using Ca and Sr as tracers (Equation 2) for the river sampling period (2021–2023). The results are presented as average monthly values for the South Fork Anchor River (Figure 7). For the five northern rivers, we calculated the relative contribution of groundwater as described for the South Fork Anchor River and used the average of these values as “regional” groundwater contributions (Figure 7).

TABLE 2 | The concentrations of solutes and stable isotopes as measured in precipitation, seeps or springs, wells, and rivers. Values are means and standard deviations. 'NA' indicates a variable was not measured. Concentrations are reported as mg/L or stable isotopes, as ‰ VSMOW.

	Precipitation	Seep or Spring	Well	SF anchor river	NF anchor river	Stariski Creek	Happy Creek	Deep Creek	Ninilchik River
n (Samples)	23[a]	83	41	101	9	10	10	10	10
n (Sites)	5	58	38	1	1	1	1	1	1
T (°C)	NA	6.40 ± 3.12	9.96 ± 3.86	5.68 ± 4.32	11.97 ± 3.55	10.78 ± 4.24	9.01 ± 3.19	10.40 ± 4.69	10.49 ± 5.34
pH	NA	6.46 ± 0.52	6.43 ± 0.68	7.45 ± 0.51	7.15 ± 0.66	7.19 ± 0.80	7.05 ± 0.62	7.42 ± 1.07	7.52 ± 0.61
SPC (μS/cm)	NA	106.17 ± 57.77	169.65 ± 96.01	76.80 ± 20.65	85.39 ± 18.95	85.20 ± 15.99	68.74 ± 15.87	77.21 ± 11.19	84.76 ± 33.75
Na	1.75 ± 4.25	5.84 ± 5.11	7.93 ± 9.46	3.94 ± 2.64	6.31 ± 3.30	4.87 ± 1.19	3.75 ± 1.01	4.20 ± 3.01	6.22 ± 1.67
K	0.53 ± 0.16	1.46 ± 0.95	3.05 ± 3.12	1.43 ± 0.37	1.29 ± 0.57	1.50 ± 0.28	1.02 ± 0.32	1.17 ± 0.43	1.71 ± 0.25
Mg	0.18 ± 0.30	2.43 ± 1.86	5.14 ± 4.72	3.31 ± 0.97	2.78 ± 0.78	3.20 ± 0.54	2.20 ± 0.41	3.37 ± 0.68	3.51 ± 0.58
Ca	0.45 ± 0.77	6.30 ± 4.33	8.54 ± 5.11	5.44 ± 1.22	6.07 ± 1.25	6.32 ± 0.87	5.59 ± 0.72	6.06 ± 0.61	7.56 ± 0.86
Si[b]	0.45 ± 1.22	6.89 ± 4.73	6.74 ± 6.64	11.18 ± 3.26	9.58 ± 1.89	9.55 ± 2.16	7.19 ± 2.67	10.34 ± 1.90	10.56 ± 2.57
Sr[b]	0.01 ± 0.00	0.05 ± 0.03	0.05 ± 0.03	0.03 ± 0.01	0.04 ± 0.01	0.04 ± 0.01	0.04 ± 0.01	0.04 ± 0.01	0.05 ± 0.01
Cl[b]	1.12 ± 1.19	9.48 ± 15.21	8.27 ± 8.74	2.55 ± 0.71	3.68 ± 0.76	2.74 ± 0.57	2.86 ± 1.01	1.67 ± 0.35	2.01 ± 0.56
SO_4[b]	0.50 ± 0.47	1.58 ± 1.17	1.85 ± 1.61	0.89 ± 0.35	1.05 ± 0.36	0.64 ± 0.37	0.59 ± 0.31	0.95 ± 0.35	0.83 ± 0.36
NO_3[b]	0.90 ± 0.55	2.26 ± 4.40[c]	2.99 ± 4.59[c]	1.10 ± 0.62	1.10 ± 0.65	1.18 ± 0.87	1.11 ± 1.48	0.54 ± 0.34	1.19 ± 1.22
Alkalinity	9.23 ± 17.98	90.27 ± 51.09	117.32 ± 94.57	136.46 ± 38.21	125.80 ± 24.60	126.96 ± 22.30	95.43 ± 26.89	133.64 ± 21.36	145.99 ± 20.72
δ^2H[d]	−116.80 ± 20.83	−114.72 ± 6.12	−117.25 ± 6.26	−119.98 ± 5.56	−116.60 ± 5.02	−119.15 ± 6.18	−117.29 ± 6.25	−125.51 ± 7.75	−122.87 ± 10.07
$\delta^{18}O$[d]	−14.82 ± 2.61	−15.17 ± 0.81	−15.48 ± 0.78	−15.84 ± 0.60	−15.39 ± 0.54	−15.59 ± 0.65	−15.31 ± 0.77	−16.54 ± 0.70	−16.08 ± 1.03

[a]Precipitation sample count includes 11 additional samples from a previous study that had stable isotope data only; ion chemistry values reflect only samples collected in this study.
[b]Concentrations below the detection limit were replaced with one-half the detection limit. The number of affected samples is: precipitation (4: Si; 9: Sr; 1: Cl; 10: SO_4; 5: NO_3), seep or spring (10: SO_4; 14: NO_3), well (10: SO_4; 11: NO_3), and river samples (23: SO_4; 25: NO_3).
[c]NO_3 was not measured in the 2018 and 2019 samples. Measured NO_3 $n = 61$ (seep or spring) and $n = 33$ (well).
[d]Stable isotopes were not analyzed for every sample. The number of analyzed samples is: 15 precipitation, 66 seep or spring, 28 well, 65 South Fork Anchor River, 5 North Fork Anchor River, 6 Stariski Creek, 6 Happy Creek, 6 Deep Creek, and 6 Ninilchik River.

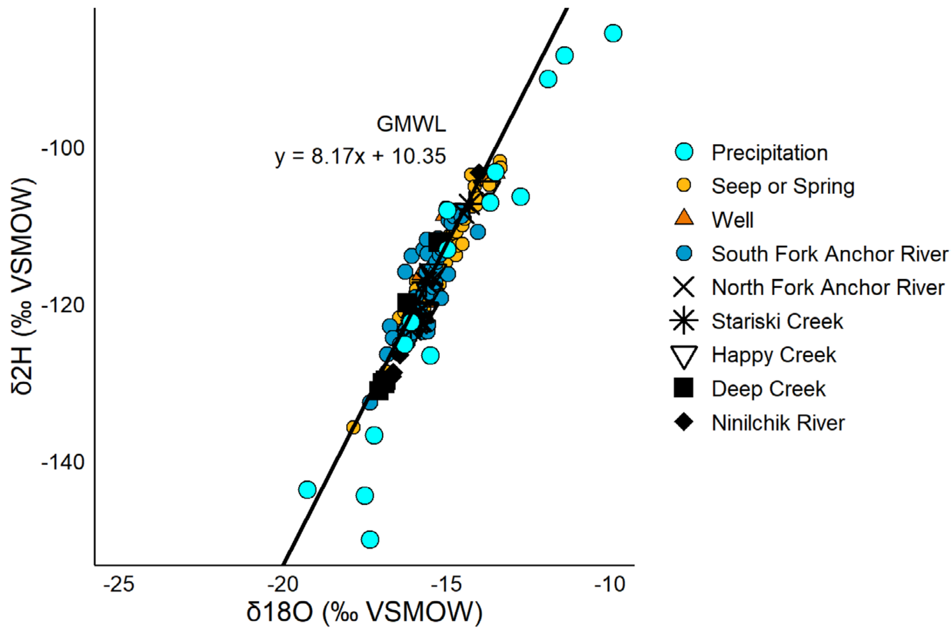

FIGURE 3 | Stable water isotope values for source waters and river samples as compared to the Global Meteoric Water Line (GMWL). Precipitation points include samples collected from a previous study (Gracz et al. 2015; Gracz 2017).

The contribution of groundwater to streamflow varies seasonally. The monthly groundwater contribution to the South Fork Anchor River was highest during low flows in winter and summer, with the maximum monthly groundwater contribution reaching approximately 90% in winter (Figure 7). The groundwater contribution to the South Fork Anchor River was lowest during peak flows in spring and fall, with the minimum monthly groundwater contribution reaching approximately 40% in spring. On average, the annual relative contribution of groundwater to the South Fork Anchor River was approximately 70%. While the groundwater contribution to instantaneous streamflow ranged from 40% to 90%, the maximum difference in monthly groundwater contribution values between the South Fork Anchor River and the average values for the northern rivers was 20 percentage points (Figure 7 and Figure S3). Across all watersheds, the groundwater contribution to streamflow was higher in winter and summer and lower in spring and fall.

5 | Discussion

5.1 | Contributions of Groundwater to Streamflow

Groundwater is essential for streamflow generation on the South Fork Anchor River in the Kenai Peninsula Lowlands, Alaska. We hypothesized that (a) groundwater contributes more than half of annual streamflow and (b) nearly all of streamflow during late summer and mid-winter periods when flows are low. Here, we found that groundwater comprises approximately 70% of annual streamflow but that the groundwater contribution to instantaneous streamflow varied through time, from approximately 40%–90% across individual sampling events (Figure 7). There are notable peak flows associated with the annual snowmelt in spring and early fall precipitation, including rain-on-snow events (Figure 2). During these periods, precipitation influences river chemistry, as indicated by decreased concentrations of conservative tracers due to dilution (Figure 5). Even then, groundwater still comprises a seasonal average of approximately 50%–70% of instantaneous streamflow (Figure 7). There are also notable low flows associated with a lack of precipitation in mid-summer and a lack of runoff when air temperatures are well below freezing in mid-winter (Figure 2). At these times, groundwater comprises on average approximately 70%–80% of instantaneous streamflow (Figure 7). These findings are consistent with previous research in headwater streams throughout the Kenai Peninsula Lowlands, where Callahan et al. (2015) found that groundwater comprised 40% of instantaneous headwater streamflow during spring snowmelt and 60% of headwater streamflow during mid-summer dry periods. Our results greatly expand on this understanding, extending results both to the mainstem of the South Fork Anchor River and throughout all months for 2.5 years, critically including mid-winter when groundwater comprises approximately 80% of the instantaneous streamflow (Figure 7).

Similarly, groundwater is essential for streamflow generation in all other watersheds in the study area, i.e., the Kenai Peninsula Lowlands, Alaska. Extending the patterns observed in the South Fork Anchor River, groundwater comprises similar percentages of annual and instantaneous streamflow across the northern watersheds, with maximum differences of approximately ±20 percentage points between instantaneous measurements made on the same days in the South Fork Anchor River and the average values for the northern rivers (Figure 7 and Figure S3). There is some physiographic variability among these watersheds. For example, there is a maritime to continental climatic trend from south to north, and the watershed size ranges from 34 km^2 (Happy Creek) to 586 km^2 (combined South Fork and North Fork Anchor Rivers), and total watershed relief ranges from 0 to 268 m AMSL for the Happy Creek watershed to 0–884 m AMSL for the Deep Creek watershed. Still, these watersheds are broadly comparable in terms of climate, geology, topography, and land use-land cover, and are therefore comprised of the same hydrologic landscape units (sensu

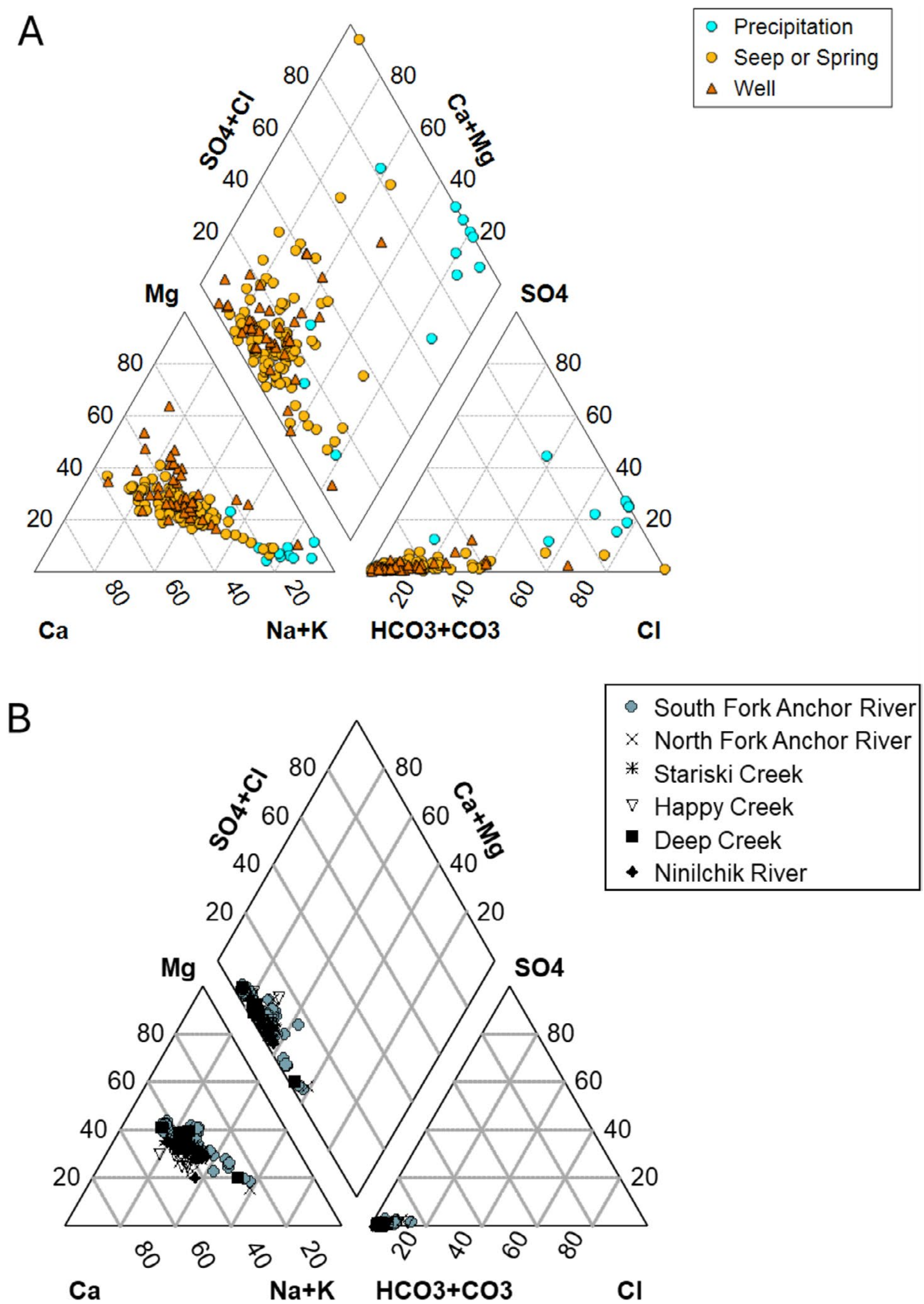

FIGURE 4 | Piper diagrams with selected solutes for (A) precipitation, seep or spring, and well samples, and (B) river samples.

Winter 2001) and classified in the same hydrologic landscape regions (Wolock et al. 2004). Though groundwater likely comprises a substantial fraction of streamflow in the watersheds with similar sedimentary rock units and aquifers to the north and south of the Kenai Peninsula Lowlands, our results cannot be directly extended to these other watersheds. Watersheds to the north and south of the study area differ geologically, especially in the headwaters where a variety of tectonic melanges of mixed metaclastic and metavolcanic deposits predominate (Wilson and Hults 2012), are commonly far larger (e.g., the Kenai River Watershed, > 5000 km^2, Weiner 1998), commonly have much greater topographic relief (e.g., watersheds south of Kachemak Bay which rise upwards towards more than 1500 m AMSL, Jenckes et al. 2023), and are partially supplied by glacial melt water (Bergstrom et al. 2021). As glacial waters are depleted in the temperate glacial watersheds to the north and south of the Kenai Peninsula Lowlands due to shifts in climate norms, groundwater will likely play a larger role in the hydrologic function of these systems, as it does in the Kenai Peninsula Lowlands (Vincent et al. 2019; Somers et al. 2016).

We identified Ca and Sr as the conservative, natural tracers to differentiate source waters within streamflow (Figure 6). The patterns revealed by these tracers supported our adoption of the broadest yet most parsimonious definition of groundwater: water that is stored and transmitted below the ground surface. Sensu Freeze and Cherry (1979), we acknowledge the traditional definition of groundwater as water stored and transmitted

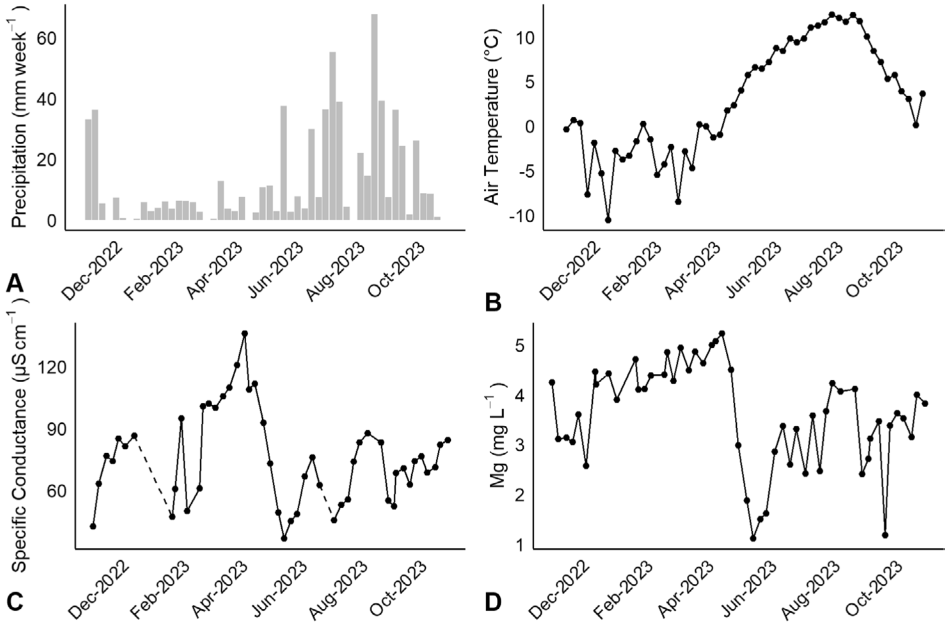

FIGURE 5 | Time series of (A, B) meteorological and (C, D) river chemistry illustrating seasonal dilution or flushing during the period samples were collected weekly from the South Fork Anchor River (October 2022–October 2023). Meteorological data is sourced from Anchor Point, Alaska (NOAA National Estuarine Research Reserve System [NERRS] 2025). Dashed lines represent trends over time periods where specific conductance was not measured in the field.

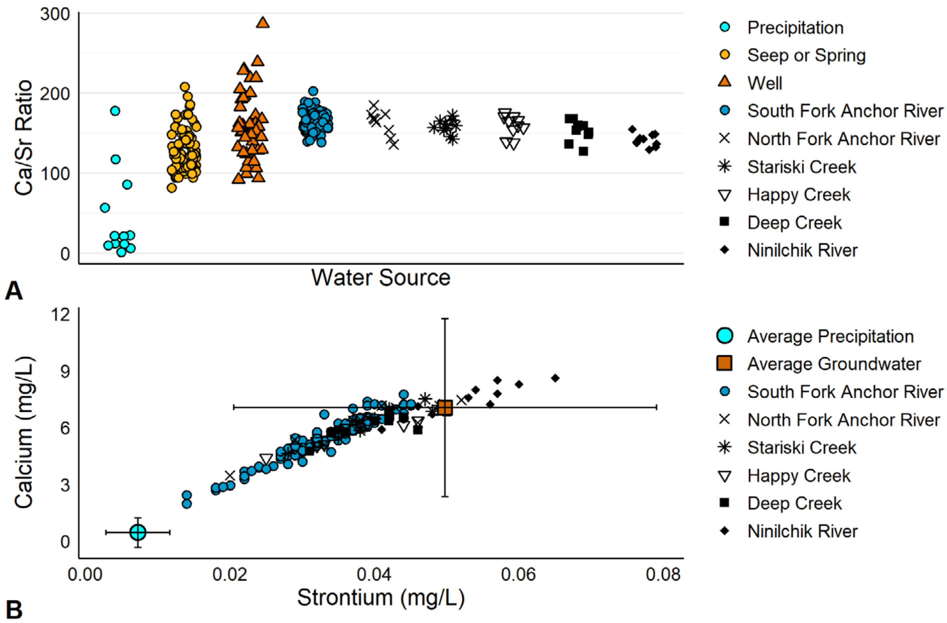

FIGURE 6 | End-member mixing-model plots of conservative tracer (Ca and Sr) concentrations in (A) precipitation, seep or spring, well, and river samples and (B) river samples and end-members (i.e., precipitation and groundwater) reported as average values. Cross-hairs represent standard deviations.

within the saturated zone, but simultaneously acknowledge the continuum of water stored and transmitted from the near-surface, unsaturated zone (i.e., the vadose zone) through the deeper, saturated zone (i.e., the phreatic zone). Others have separated the vadose and phreatic zones into two separate end-members (e.g., Burns et al. 2001; Orlova and Branfireun 2014). We chose not to do so due to our understanding of fluid flows in this landscape, which in turn is informed both by our observations and our data. Groundwater in this landscape is stored, transmitted, and discharged back to the surface along a continuum of complex, intermixed pathways (Figure 8, Gerlach et al. 2022). Our chemistry data supports this conceptual model. Isotopic analysis indicates these groundwaters are modern and are derived from recent precipitation rather than from long-term Pleistocene storage (Figure 3). Similarly, dissolved ion analyses (Table 2) indicate there has been little evolution of chemical composition that would result from long-term water-rock interaction (Figure 4) and that while concentration of analytes may

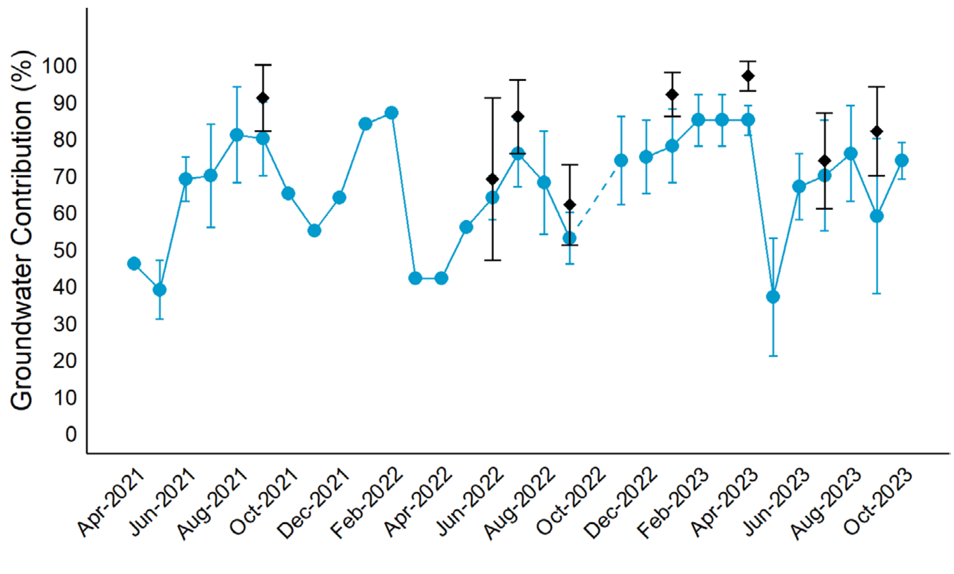

FIGURE 7 | Relative mean groundwater contribution to streamflow in the South Fork Anchor River and the northern watersheds (North Fork Anchor River, Stariski Creek, Happy Creek, Deep Creek, and Ninilchik River), shown with standard deviation bars. The South Fork Anchor River points without standard deviation bars represent months where only one river sample was taken. Dashed lines represent trends over time periods where the South Fork Anchor River was not sampled.

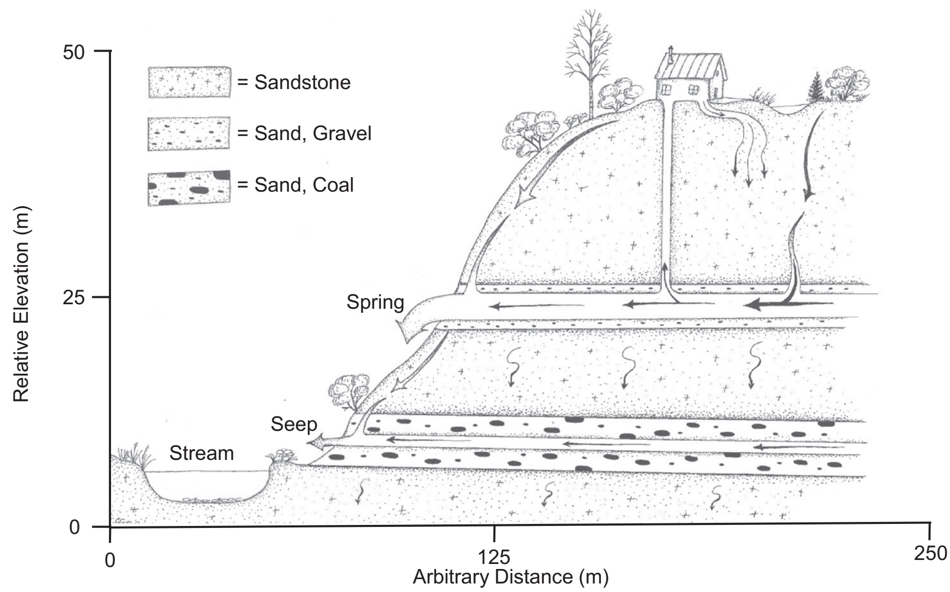

FIGURE 8 | Schematic geologic cross-section of two types of groundwater that occur in the Kenai Peninsula Lowlands, Alaska. Hillslope groundwater moves along the shallow subsurface while aquifer-outcrop groundwater recharges the deeper subsurface aquifers. These sources often mix before discharging to the rivers. Illustration drawn by Conrad Field from field observations by the authors of this article.

differ among water sources and streamflow, the ratio of Ca/Sr is relatively constant across seeps, springs, and wells and rivers (Figure 6). This indicates that Ca and Sr dissolve and mix proportionally along flow paths, reinforcing the concept of a single hydrologic continuum rather than discrete end-members. Furthermore, these groundwaters can occur simultaneously along the same flow paths, often mixing prior to discharging to the rivers (Figure 8). In other words, these are not different end-members; rather, this is a single hydrologic system characterized by mixed groundwaters with differing underground residence times, ranging from hours to years (cf., Callahan et al. 2015). There is evidence that some hillslope groundwater (e.g., seeps) and aquifer-outcrop groundwater (e.g., springs) are intermittent while others are perennial (Brigino, unpublished data). However, there is insufficient justification to create separate end-members, especially since the mainstem rivers express the convolution of these source waters over long periods of time (Rains et al. 2016).

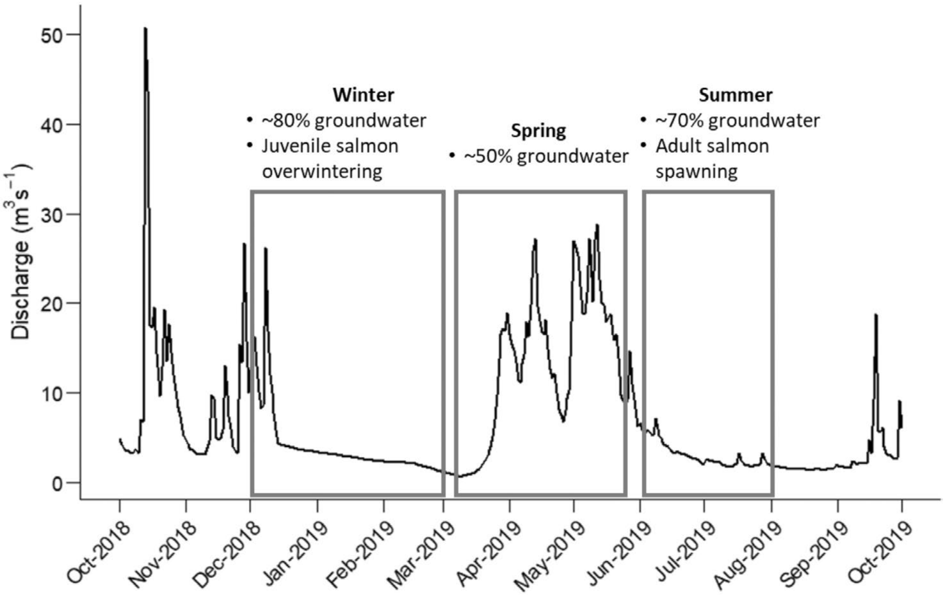

FIGURE 9 | Mean daily discharge for the Anchor River, Alaska (US Geological Survey 15239900 ANCHOR R NR ANCHOR POINT AK), relative groundwater contributions to streamflow (this study), and general salmon behaviors in the Kenai Peninsula Lowlands, Alaska (Alaska Department of Fish and Game 2020).

This understanding informed our selection of a traditional hydrograph separation approach using a two-end-member, mass-balance mixing model (Figure 6). We implemented the initial steps of the EMMA approach to select end-member tracers (Figure S1 and Figure S2, Table S1). EMMA is often intended for use when there are three or more independent end-members, such as peatland water, soil water, and deep groundwater (Christophersen and Hooper 1992). This is useful for getting a detailed understanding of catchment hydrology at the reach scale, where the contributions of different geographic source areas can be resolved in streamflow generation. As stated, we were not confident that there are three or more independent end-members. Furthermore, uncertainties can arise in EMMA from utilizing differing amounts of major and minor tracers, not identifying all end-members, or incorrectly characterizing time-varying end-members (Barthold et al. 2011; Carrera et al. 2004; Delsman et al. 2013; Hooper et al. 1990). If uncertainties are neglected, elevated importance can be erroneously attributed to end-members. With these variabilities and uncertainties in mind, we are confident in our first-order approach and the conclusion that shows that groundwater is critical to streamflow generation in this region.

5.2 | Importance of Groundwater to Fish and People

5.2.1 | Fish

Groundwater discharge is essential to year-round streamflow generation in the Kenai Peninsula Lowlands, Alaska (Figure 7). In addition, it is vital for modulating stream temperatures (Callahan et al. 2015) and stream nutrient concentrations (Callahan et al. 2017). The beneficiaries of this are the fish, specifically salmonids, and most notably coho salmon, which are documented in the Alaska Anadromous Waters Catalog in five of the six mainstem rivers of our study area, the exception being Happy Creek, which has a natural fish barrier (Figure 1). Groundwater provides cold-water refugia in summer and warm-water refugia in the winter. Temperatures outside of salmonid tolerances have implications for reproductive potential, behavior, and distribution, growth, and can lead to mortality (Crozier et al. 2008; Jones et al. 2020; Leppi et al. 2014). Cold-water refugia in summer are becoming increasingly important in Alaskan rivers, including south-central Alaska where rivers have been documented to exceed spawning and incubation temperature limits (Mauger et al. 2017). Salmonids overwinter in these streams, relying on groundwater to maintain ice-free pools and channels (Callahan 2014). Coho salmon spend at least one winter and sometimes two winters in the streams before out-migrating in spring (Groot and Margolis 1991), thereby passing through at least one and sometimes more than one critical time period when streamflow is almost entirely sourced from groundwater (Figure 9). Furthermore, groundwater first interacts with different landscape elements, one of which may be nitrogen-fixing alder patches on adjacent hillslopes. Additional nitrogen is mobilized by groundwater and thereafter delivered to riparian wetlands and streams, where it boosts streamside above-ground primary productivity (Callahan et al. 2017; Whigham et al. 2017). This above-ground primary productivity then drops into streams, where juvenile salmonids preferentially feed on the allochthonous sources (Dekar et al. 2011).

5.2.2 | Demands on a Limited Resource

Groundwater is the primary source of water for agricultural, domestic, and industrial uses in the Kenai Peninsula Lowlands (Glass 1996). Most wells are for individual domestic use and target the shallowest aquifer capable of producing sufficient yield, often as little as 15–20 L/min. Many residences are located on hillslopes rather than valley bottoms, and many of these wells tap the same aquifers that outcrop as seeps and springs along nearby hillslope proximal to the rivers (Figure 8). Chemical analyses of water from seeps, springs, and wells show similar signatures (Figures 4 and 6 and Figure S2), supporting the interpretation that they draw from the same aquifers. This is further corroborated by Gerlach et al. (2022), who used well-drilling logs to model aquifers and aquifer outcrops and then field-verified that the modeled aquifer-outcrops were both present and the source of springs. Furthermore, many springs are also enclosed in spring boxes for direct human use, illustrating that these aquifers supply both natural discharge and domestic water. Unsurprisingly, even surface water drinking resources, such as the Bridge Creek Reservoir that supplies numerous residents of the City of Homer, are comprised of over 50% groundwater (Brigino et al. 2023).

5.2.3 | Delicate Balance

Both fish and people use the same groundwater resources in the Kenai Peninsula Lowlands (Figure 8). Aquifers in this region are thin and discontinuous (Gerlach et al. 2022), so these groundwater resources are limited. These limited groundwater resources then both sustain streamflow and simultaneously provide most of the water supply, which is a particularly delicate balance in summer when salmon migrate and spawn, approximately 70% of river discharge is sourced from groundwater (Figure 9), and the seasonal population surges and water use doubles compared to winter (Cook 2023–2024). Though not used for water supply, hillslope groundwater is also vulnerable to interruptions to flow paths through land use–land cover change, including public and private roads. Meanwhile, groundwater recharge is threatened by the regional climatic drying trend (Berg et al. 2009; Klein et al. 2005).

Managing this shared groundwater resource is therefore complex and requires the involvement of diverse stakeholders, including private landowners who both rely on and can potentially influence water quantity (Walker et al. 2021). Because many groundwater uses in Alaska require a water right (Alaska Department of Natural Resources 2025b), understanding where and when groundwater sustains streamflow is directly relevant for evaluating availability and managing competing demands for private and public benefit. Furthermore, these results provide data that can guide the hydrologic studies required by reservations of water (Alaska Department of Natural Resources 2025a), informing methodology and monitoring for such applications. We shared our findings with resource managers and well-owners, fostering local awareness and stewardship to help identify priority areas for source water protection, including land acquisition initiatives aimed at safeguarding both drinking water and groundwater-dependent salmon rivers (Brigino et al. 2023).

5.3 | No Groundwater, No Fish

In the Kenai Peninsula Lowlands, groundwater sustains both river water quantity and quality. As hillslope groundwater and aquifer-outcrop groundwater sources vary in space and time, the individual importance of each specific groundwater source to streamflow also varies in space and time. However, hillslope groundwater may be a substantial proportion of streamflow generation seasonally, while aquifer-outcrop groundwater is likely a dominant proportion of streamflow generation year-round (Brigino, unpublished data). While both are essential for the maintenance of streamflow, they likely play different roles in water quality, including thermal modulation, delivering nutrient subsidies, and maintaining channel connectivity necessary for salmon spawning and rearing. It is the continued interaction between surface and subsurface flow paths that allows non-glacial, salmon-bearing rivers to persist. In short, if there is no groundwater, there are no fish.

6 | Conclusion

Groundwater contributions to streamflow are critical in the Kenai Peninsula Lowlands, Alaska. Our results show that while groundwater contributions to rivers vary spatially and temporally, groundwater is the main source of streamflow throughout the year, but most especially during times of baseflow in summer and winter. Future research should focus on the differing roles of hillslope groundwater and aquifer-outcrop groundwater support to salmon-bearing rivers.

Author Contributions

Tyelyn Brigino: conceptualization, investigation, methodology, formal analysis, visualization, writing – original draft, writing – review and editing. **Kai Rains:** conceptualization, methodology, supervision, writing – original draft, writing – review and editing. **Edgar Guerrón-Orejuela:** investigation, writing – review and editing. **Jacob Argueta:** investigation, writing – review and editing. **Syverine Bentz:** investigation, writing – review and editing. **Coowe Walker:** conceptualization, resources, funding acquisition. **Mark Rains:** conceptualization, methodology, supervision, writing – original draft, writing – review and editing, funding acquisition.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available and can be found here: https://figshare.com/s/1a92937f28fe99416121.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Bivariate solute plots of stream water chemistry from the South Fork Anchor River in the Kenai Peninsula Lowlands, Alaska. **Figure S2:** Principal component scores for sampled waters. The first two principal components (PC 1–2) explained 88.2% of the total variance. **Figure S3:** Relative mean groundwater contribution to streamflow in the five northern rivers. Points with standard deviation bars represent the month of July where two river samples were collected. **Table S1:** Loadings of conservative tracers on the first two principal components (PC1 and PC2) from the principal component analysis.