Regional groundwater flow in an area mapped as continuous permafrost, NE Alaska (USA)

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Abstract Fundamental knowledge of groundwater systems in areas of permafrost is often lacking. The likelihood of finding good quality groundwater resources of acceptable quantities generally decreases as the areal coverage of permafrost increases. In areas of continuous permafrost, the probability of finding areas of groundwater recharge and discharge are minimal. Still, in northeastern Alaska (USA), the presence of numerous springs and associated downstream aufeis formations clearly indicates that there has to be a groundwater system with the required complementary areas of groundwater recharge and transmission. Recharge zones and transmission pathways in this area of extensive permafrost, however, are essentially unknown. This study shows that the recharge occurs on the south side of the Brooks Range in northeastern Alaska, where extensive limestone outcrops are found. The transmission zone is beneath the permafrost, with discharge occurring through the springs via taliks through the permafrost (where faults are present) and also likely at the northern edge of the permafrost along the Beaufort Sea coast.

Keywords Hydrochemistry · Groundwater flow · Permafrost · Springs · Alaska (USA)

Received: 31 May 2012 / Accepted: 13 November 2012

Published in the theme issue "Hydrogeology of Cold Regions"

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Introduction

Permafrost is extensive in the northern hemisphere. Williams (1970) described frozen ground as an impermeable layer which (1) restricts recharge, discharge and the transmission of groundwater, (2) acts as a confining layer and (3) limits the volume of aquifers where liquid water can be stored. Generally, the hydraulic conductivity of ice-rich frozen soils is so low in areas of continuous permafrost (Burt and Williams 1976; Horiguchi and Miller 1980; Kane and Stein 1983a, b) that near-surface water is hydraulically disconnected from deeper subpermafrost groundwater systems.

Despite the low hydraulic conductivity of permafrost, it is evident from the presence of springs and icings in northeastern Alaska (Fig. 1), that groundwater flow is active in this area mapped as continuous permafrost. The origin and pathways of groundwater to these springs are unknown. Springs can arise from local recharge sources traveling through short, suprapermafrost pathways, or non-local recharge areas traveling through complex subpermafrost pathways. Unfortunately, few groundwater observations exist in this and other continuous permafrost regions.

The goal of this study is to understand the source of spring water in northeastern Alaska as a first step towards gaining more comprehensive knowledge of groundwater flow systems in continuous permafrost systems. In this initial reconnaissance, data are used that were collected as part of other investigations. Information is drawn from surface observations (springs) and measurements (flow rate, spring water age, water quality, temperature, etc.), geochemical and isotopic data, and the results of the few groundwater studies that have been carried out in continuous permafrost environments. Based on these sources of information, it is argued that subpermafrost groundwater originates from the other side (south side) of the Brooks Range (Fig. 1), as illustrated in Fig. 2, and that transmission of groundwater crosses the topographic divide. The likelihood of permafrost is much greater on the north side of the Brooks Range than the south side (Brown et al. 1998); plus, limestone outcrops are more extensive on the south side (State of Alaska 2008). Following a summary of the present knowledge on groundwater in permafrost regions, observations and interpretations that support this premise are presented.

Hydrogeology Journal (2013) 21: 41–52 DOI 10.1007/s10040-012-0937-0

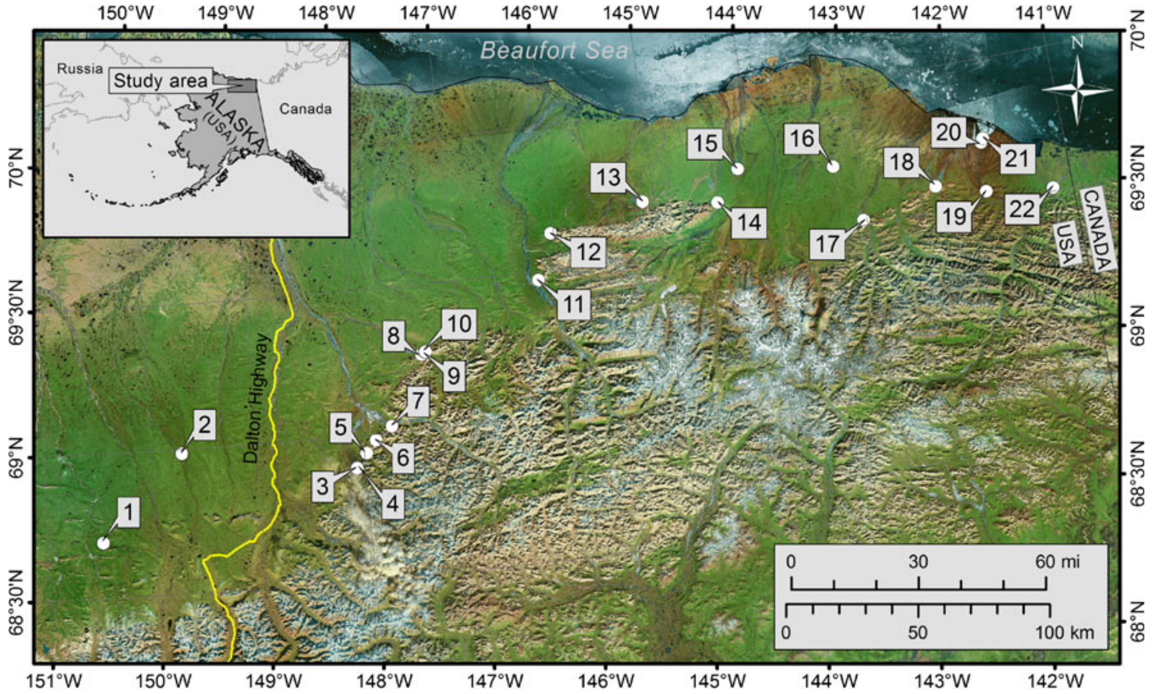

Fig. 1 Map showing the location of springs on the North Slope in eastern Alaska that were used extensively in this article. Springs numbered from west to east

Previous knowledge

An understanding of groundwater dynamics in northern Alaska and other continuous permafrost regions has been slow to develop. Part of the lack of progress is due to limited information on permafrost distribution, and a lack of demand for water-resource information in this sparsely populated region. In the small villages with minimal water needs, surface water (streams and lakes) generally is the source of choice. Interest in groundwater development is generally associated with resource development where larger quantities of water are needed. Williams and van Everdingen (1973) produced a review paper on groundwater investigations in permafrost regions of North America for the Second International Conference on Permafrost. They presented material on the following topics; permafrost and movement of groundwater, availability of groundwater, icings, pingos and artesian pressures, influence of permafrost on water quality, methodology, studies of basin hydrology, investigations for pipeline projects, hydrologic model studies and research needs. Since their review, the number of

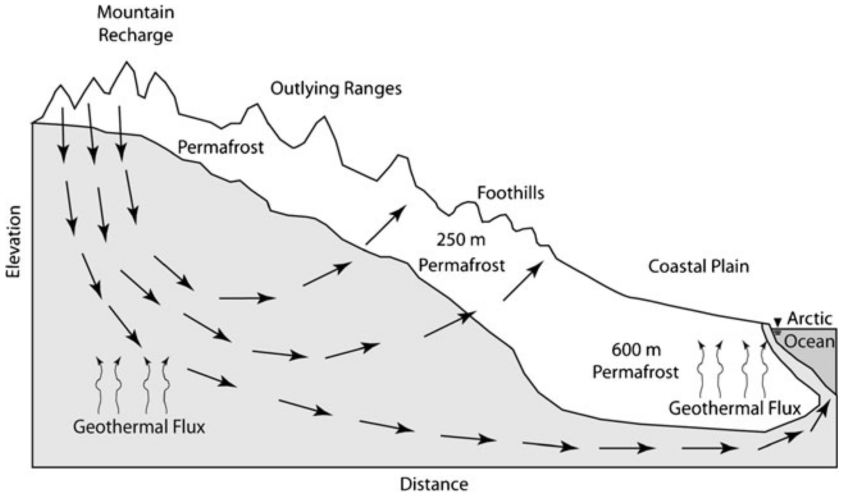

Fig. 2 Simple conceptual representation of the groundwater flow system in an area mapped as continuous permafrost in NE Alaska, assuming that groundwater recharges through permafrost free areas of limestone on the south side of the Brooks Range and discharges through taliks (probably coinciding with faults), extending through the permafrost north of the Brooks Range. Some discharge is apt to discharge along the northern boundary of the permafrost and the coast

hydrologic studies in regions with continuous and discontinuous permafrost has expanded, mostly because of concern about climate change and its impact on permafrost. While the primary interest of this study is in recharge, transmission and discharge of subpermafrost groundwater in continuous permafrost regions, first there is a review of groundwater in discontinuous regions where more information is available. The role of suprapermafrost groundwater is not addressed here as it does not constitute a large enough subsurface storage reservoir for groundwater development.

Subpermafrost groundwater associated with discontinuous permafrost

In areas of discontinuous permafrost, south-facing slopes are typically permafrost free, while north facing slopes and valley bottoms are generally underlain by permafrost (US Department of Agriculture, Soil Conservation Service 1963). East- and west-facing slopes represent a transition from no permafrost to permafrost with variable amounts of permafrost. Whether permafrost exists or not is more complex as drainage, soils and vegetation may influence specific site conditions. Where permafrost is near the thawing temperature, generally near the southern limit of permafrost, it is less likely to be present on east- and west-facing slopes, while it is more likely as one progresses northward and the mean annual air temperature decreases. More on the distribution of permafrost can be found in Brown et al. (1998) for the circumpolar Arctic and Ferrians (1998) specifically for Alaska.

Groundwater systems typically consist of recharge on permanently unfrozen south-facing slopes (and those areas on east- and west-facing slopes without permafrost) with transmission from the point of recharge to the valley bottom. This water discharges at the surface where either taliks (unfrozen zones) exist through the permafrost in the vicinity of lakes and streams or permafrost is simply absent. Also, discharge springs can often be found at the base of slopes where groundwater first encounters permafrost in the valley bottom.

Areas of permafrost are unlikely candidates for subpermafrost groundwater recharge due to ice in the soil pores significantly reducing the hydraulic conductivity. The hydraulic conductivity of frozen soils can be several orders of magnitude lower than comparable unfrozen soils; the amount of reduction in the hydraulic conductivity of frozen soils depends upon the amount of ice in the pores or the thickness of the unfrozen film on the surface of the soil particles with generally high ice contents (thin unfrozen films), resulting in low hydraulic conductivities (Burt and Williams 1976; Horiguchi and Miller 1980; Kane and Stein 1983a, b). Anderson and Morgenstern (1973) showed that the amount of unfrozen water in a frozen soil was related to the soil-particle surface area—the greater the surface area the greater the unfrozen water content (assuming of course that the moisture content equals or exceeds the predicted unfrozen water content).

Recharge in unfrozen zones can flow under permafrost to discharge zones that penetrate up through the permafrost. Along such flowpaths, permafrost impacts the direction of flow and can also act as a confining layer leading to artesian conditions (Linell 1973). Although ice significantly reduces soil hydraulic conductivity of seasonally frozen soils, snowmelt can infiltrate partially frozen soils at rates sufficient to generate groundwater recharge (Kane and Stein 1983a, b). This is particularly true for well-drained soils. Deep lakes and other water bodies can create taliks that serve as discharge zones for subpermafrost groundwater. For example, Kane and Slaughter (1973) demonstrated that permafrost was absent beneath a small lake, 4.5 m maximum depth, located in a valley bottom with permafrost extending down 40–70 m depth adjacent to the lake. They documented the discharge of subpermafrost groundwater by measuring the hydraulic head at various depths beneath the lake bottom with piezometers. The hydraulic head was above the lake water-surface elevation for all piezometers. Some nearby shallower lakes were found to have no hydraulic connection to the deeper subpermafrost groundwater.

Subpermafrost groundwater associated with continuous permafrost

Continuous permafrost is generally found north of the continental divide in the Brooks Range of northern Alaska; an area referred to as the North Slope. Prior to the early 1970s (when oil was discovered in Prudhoe Bay), very little was known about water resources on the North Slope, either surface or subsurface. The USGS initiated a stream-gauging program in the vicinity of Prudhoe Bay area shortly after oil was discovered. Childers et al. (1977) also initiated a hydrological reconnaissance program in the eastern North Slope in 1975 in response to potential construction of oil and gas pipelines. Two of the hydrologic characteristics (although there were others) that they targeted were icings (aufeis) and springs. In their survey, they sampled 18 springs with discharges ranging from 0.03 to 2.5 m^3/s (30 to 2,500 l/sec) and water temperatures from 0 to 33 °C. Complementary to springs were aufeis formations found downstream from these springs during the winter and spring seasons (with some formations persisting over the summer to the next winter some years).

These springs are indicative of subpermafrost groundwater discharge. If these springs were emanating from fractures in the bedrock, where was this water being recharged and what was the pathway from the area of recharge to the area of discharge? The entire North Slope is mapped as continuous permafrost (Brown et al. 1998; Ferrians 1998), but for the origin of the water for these springs to be subpermafrost groundwater there has to be taliks penetrating through the entire depth of permafrost. Also, there must be areas free of permafrost for recharge to occur.

An earlier study in the central Alaskan Arctic (area west of Dalton Highway to the western boundary of the Chandler River basin), a region not noticeably rich in observable springs like those found in the eastern Alaskan Arctic, was published on regional groundwater flow based on the measured thermal regime in exploratory oil and gas wells (Deming et al. 1992). It should be noted that, in areas of recharge, advective heat transport by the groundwater is counter to the geothermal gradient, while downstream they are acting in concert, as illustrated in Fig. 2. They describe a thermal pattern coherent with forced convection due to a topographically driven groundwater flow system at the regional scale. Further, they found that both heat flow and subsurface temperatures varied consistently from relatively low values in the foothills to much higher values on the coastal plain. Because there are few readily discernible signs of subpermafrost groundwater discharge from the continental divide to the Arctic Ocean, it is hypothesized for their study area that recharge occurs in the Brooks Range and discharge occurs into the Arctic Ocean with flow occurring as subpermafrost groundwater flow underneath the permafrost. This is essentially the same model for regional groundwater flow that is used here for the northeastern part of the state (Fig. 1); however, the conclusions presented here are not based on heat flow, but on the visible evidence of numerous springs indicating subpermafrost discharge and the water quality of these springs. During recent field excursions, late winter evidence of relatively small aufeis formations and associated springs in the central Alaskan Arctic, especially in the valleys at the transition from the mountains to the foothills, has been seen. It should be noted that the mountains in the central part of the Alaskan Arctic are much farther from the Arctic Ocean than in the northeastern part of the North Slope (Fig. 1).

In permafrost, heat conduction is the main heat-flow mechanism. Where permafrost is lacking or taliks may exist through the permafrost and groundwater flow is present, advective heat transport may occur in concert with conduction (Kane et al. 2001; Rowland et al. 2011). Clearly the thaw bulb beneath a lake in an area of continuous permafrost could be a subpermafrost groundwater discharge pathway. However, Brewer (1958) found that the thaw bulb beneath an Alaskan Arctic lake on the coastal plain did not come close to penetrating the permafrost; the permafrost was too thick and the temperature of the permafrost too low (< 10 °C). Arcone et al. (1998) found that the thaw bulb beneath Arctic streams appears to be a thin layer extending across the channel; this conclusion has been supported by many other observations (Bradford et al. 2005; Brosten et al. 2009a, b). Therefore, it is not likely that surface-water bodies and associated thaw bulbs in the Alaskan Arctic represent pathways for subpermafrost groundwater discharge; however, for larger, deeper lakes (like Teshekpuk Lake in the northwestern sector of the North Slope, maximum depth 6 m and surface area of 430 km^2), it is a possibility. It is clear from the presence of numerous springs that an Arctic groundwater system is present in this part of Alaska. Hall and Roswell (1981) and others suggest that faults may represent the most likely pathway for groundwater discharge in this permafrost environment.

Aufeis

Aufeis, also referred to as *naleds* (Russian) and icings, is a hydrologic winter process of high latitude streams and rivers whereby water, from in and/or beneath the stream, under pressures greater than hydrostatic pressure (Kane 1981), flows out on top of the ice where it subsequently freezes and adds to the thickness of the ice in the channel/floodplain. This process is repeated several times during the winter and, at the end of the cold season, the channel and adjacent floodplain can be completely filled with ice. The thickness of the aufeis is much greater than the depth of the water in the channel prior to freeze-up. For substantial aufeis formations to develop, there needs to be a source of subpermafrost groundwater or water from near surface taliks; the greater the source volume, the greater the volume of the downstream aufeis formation.

Setting

The North Slope of Alaska (Fig. 1) is an area of 230,000 km^2 consisting of three physiographic units from south to north: mountains, foothills and coastal plain. The drainages are predominantly north-draining, flowing out of the mountains, through the foothills and over the coastal plain before discharging into the Beaufort Sea. The Brooks Range (an extension of the Rocky Mountains) has basically an east–west-trending continental divide with an approximate maximum elevation of 2,500 m above sea level; the mountains are closer to the Arctic Ocean coastline in the northeastern part of the state than in the northwestern part (Fig. 1). The elevation range for the foothills is approximately 150–1,200 m with the coastal plain being less than 150 m and the mountains greater than 1,200 m.

Permafrost is assumed to be continuous in this area with taliks extending through it in the vicinity of subpermafrost springs. The permafrost thickness is poorly documented inland away from the coast (because of few exploratory wells) but is estimated to be approximately 250 m thick. Along the coast where there have been extensive drilling programs, permafrost depths as great as 600 m have been observed. Lachenbruch and Marshall (1986) reported that the long-term mean annual temperature at the top of the permafrost ranges from −4 °C in the Brooks Range to −12 °C along the coast. The depth of the active layer on the North Slope averages about 50 cm, but generally decreases from south to north and is greater in well-drained sites. Surficial active layer soils generally are composed of an organic layer (approximately 25 cm thick, although quite variable) over a mineral layer which is generally near saturation. Thaw lakes are much more prevalent on the coastal plain than elsewhere; there are lakes of glacial origin, especially in the foothills closer to the Brooks Range.

Vegetation is almost continuous over the coastal plain and foothills with tussock tundra over the foothills and sedge tundra on the coastal plain. Shrubs (1–2 m in height) are common in the foothills and southern extent of the coastal plain and expanding (Tape et al. 2006). A few patches of trees can be found, especially in riparian areas in the foothills. Alpine communities are found in the mountains along with bare rock outcrops.

Numerous studies have shown that climate warming is ongoing on the North Slope of Alaska (Stafford et al. 2000; Chapman and Walsh 1993; Serreze et al. 2000) as well as other high latitude environments. It is also established that most of this warming is seasonal, occurring in winter. There is some statistically weak evidence (Stafford et al. 2000) that precipitation is decreasing, particularly in summer. Even though the hydrologic cycle is likely intensifying (Rawlins et al. 2010) through positive trends in hydrologic fluxes, the impact of climate change on the processes studied here are probably not measureable, as it took thousands of years for the permafrost to form.

One of the obvious indicators of groundwater discharge in areas of permafrost is the formation of aufeis in a channel and adjacent floodplain, usually somewhere downstream of a spring (Kane 1981; Hall and Roswell 1981; Yoshikawa et al. 2007; Carey 1973; Harden et al. 1977). There is a lot of speculation concerning why aufeis forms where it does and why the volume of the formation varies from year-to-year although the spring flow is relatively steady; unfortunately there have been very few detailed studies on various aufeis processes. It is clear from the study of Kane (1981) that aufeis growth occurs during episodic warm periods during the winter and not cold spells. During these warm periods, pressures build up under the ice, deforming the ice and inducing cracks that let water flow out onto the surface and freeze. As the ice thickens during the winter, the pressure needed to produce another overflow must be greater than the last overflow event.

Figure 1 shows the location of many of the springs on the northeastern North Slope of Alaska. Many of these springs have been visited in the past, first in detail by Childers et al. (1977). Visibly, a majority of the springs are located at the base (Fig. 1) of many of the outer mountain ranges (like the Shublik and Sadlerochit mountains). Childers et al. (1977) examined the flow rates, temperature, and chemistry of the more predominant springs. There are many springs in this region and not all are presented here. Some are very close to others, often the exact location of springs is confused with neighboring springs (particularly for studies carried out before the advent of GPS).

Geology

Although the presence of permafrost in this environment has a significant impact on the groundwater flow system, the regional geology also is quite important. The scrutiny of the geology of this region has been driven, not by water resources, but oil and gas development. The Brooks Range constitutes the southern boundary of the study area, to the north are lesser mountains and foothills whose rock exposures give insight to the geology farther north under the coastal plain. Around 400 Ma ago (ma), the pre-Mississippian sequence formed a wide range of rock types including argillites (compact rock of siltstone, claystone or shale), graywackes (coarse grained sandstone), quartzite (metamorphic rock of mainly quartz), carbonate (mainly limestone and dolomite) and some local deposits. Repeated uplift and faulting due to compressional stresses around 145 ma produced the Brooks Range; continued compression pushed older rocks over younger rocks producing unconformities. The thin, structurally less sound beds were aggressively deformed and overturned. Thicker, more competent beds are stacked up like leaning books (Bureau of Land Management and Alaska National History Association 1993). For the area of study, this resulted in a series of four parallel east–west-trending mountain systems from the continental divide northward. It is in the valleys of these progressively lower, downstream drainages that many of the springs reported here are found (Fig. 1); it is assumed that the springs originate along faults in these up-thrusted unconformities.

Williams (1970) confirms the existence of various types of faults in limestone (Mississippian and Pennsylvanian age) associated with the springs in northeastern Alaska. Also, Beikman and Lathram (1976) and others have mapped the distribution of faults across northern Alaska. They show that there are many more faults in northeastern Alaska than in the northwestern sector; this also matches the distribution of major icing formations. Finally, Hall and Roswell (1981) have produced a map that shows the colocation of springs and faults in northeastern Alaska.

Observations

Presented below are physical and chemical data collected at various springs, both by others and by University of Alaska Fairbanks, Water and Environmental Research Center (UAF/WERC) personnel on numerous visits to the area. Most of the visits to the springs were made in late winter when the springs are more easily spotted because the relatively warm discharge melts the surrounding snow. Many of the springs emanate off the side hillslopes or from the base of hillslopes and then travel a short distance to a river or stream. In some cases, all of the flow is collected in a single channel; however, in some cases the flow is quite dispersed making it difficult to get accurate measurements of discharge rates. It is likely that there are springs discharging from the bed of streams or rivers that are undetected and are rapidly diluted by base flow from upstream. Flood Creek (spring No. 6, Table 1) would appear to fall into this category; the channel remains ice-free for a long distance during winter with only the one obvious spring adjacent to the stream. The distribution of springs is shown in Fig. 1. Except for a few springs on the coastal plain, most of the springs are located on the northern fringe of the Brooks Range, including the outer ranges of the Shublik and Sadlerochit mountains.

Table 1 Physical properties of springs on the eastern North Slope of Alaska where meaningful measurements have been made either by UAF/WERC or the USGS (Childers et al. 1977). Springs ordered from west to east

Spring No. and name		Lat (deg/min)	Long (deg/min)	Elev (m asl)	Discharge *Q* (l/s)	Specific Conductivity (μS/cm)	pH	Temp (°C)
1	May Creek	68 41.570	−150 29.018	423		263	6.5	0.4
2	Kuparuk River	68 59.150	−149 42.400	408		251	6.4	0.1
3	Lupine	68 53.512	−148 4.920	497	42.5	298	8.1	1.0
4	Saviukviayak West	68 53.389	−148 4.832	507	2,520	259	8.0	4.8
5	Saviukviayak Trib	68 56.333	−147 58.750	678	1,529	239	7.9	3.5
6	Flood Creek	68 58.813	−147 52.862	425	2,350	237	8.2	7.7
7	Ivishak Hillside	69 1.4120	−147 43.284	406	5,494	238	8.2	7.4
8	Echooka River West	69 15.583	−147 22.833	391	623	257	7.9	7.0
9	Echooka Hillside	69 16.041	−147 20.706	404		250	8.1	4.7
10	Echooka Valley	69 16.051	−147 20.454	403		249	8.1	4.7
11	Shublik	68 28.333	−146 11.833	414	680	275	8.0	5.5
12	Red Hill	69 37.617	−146 1.633	357	24	1,000	7.0	33.0
13	Katakturuk Trib	69 41.700	−145 6.550	422	122	245	8.2	1.0
14	Sadlerochit	69 39.383	−144 23.617	308	991	410	7.9	13.0
15	Hulahula River Icing	69 45.650	−144 9.250	166	207	240	8.0	1.0
16	Okerokovik River	69 43.100	−143 14.417	160	736	300	7.3	1.0
17	Aichilik River	69 31.100	−143 2.000	318	42.4	338	8.0	3.6
18	Ekaluakat River	69 35.450	−142 18.000	203	144	350	7.9	6.4
19	Kongakut River	69 32.600	−141 49.633	141	368	276	7.9	1.0
20	Kongakut River Above Delta	69 42.833	−141 47.500	30	2,503	210	6.7	
21	Kongakut River Delta	69 43.600	−141 46.117	17	1,048	215	7.9	1.0
22	Clarence River	69 30.733	−141 11.617	151	133	250	6.8	0.0

Eastward, the springs and mountains are located closer to the coast. This results in a general decreasing trend in the general elevation of springs.

Discharge from springs

The measured temperature of springs (Table 1, Fig. 3) ranges from 0 to 33 °C. There are a large number of springs that have temperatures at or just above the freezing point of water. Most of these springs are located either on the west or east ends of the study area. When sampling in the winter with snow on the ground, it is possible that the measurements are not made at the point where the spring first emerges from the ground, but some distance downstream. In late spring during snowmelt or in the summer, it is possible that spring flow is also mixed with summer precipitation/runoff both diluting and altering the quality and temperature of the spring water. During ablation, mixing will reduce the temperature if it is not already at 0 °C; during the summer, precipitation could alter the spring water temperature either up or down. While Fig. 3 shows the ranges of temperature and discharge of springs, there is no relationship between the two variables.

The flow rate (Table 1) from springs varies from high (5,494 l/s, Ivishak Hillside spring No. 7) to low (24 l/s, Red Hill spring No. 12). What is not known is how much heat is required to keep the taliks open for the springs to exist; the amount of advected heat will depend upon the groundwater water temperature and the flow rate. A quick rumination of this yields the conclusion that the amount of advected energy needs to offset the heat conducted from the talik by the colder permafrost and this will depend upon the geometry of the talik which is presently not known. For example, Red Hill spring with a discharge of 24.1 l/s (Childers et al. 1977) has been measured at temperatures ranging from 29 to 33 °C and Okpilak spring (69°17.227′–144°1.063′) with even lower flow has been measured at 38 °C. However, Fig. 3 shows that there are several springs near 0 °C with rather low flows that appear to be able to maintain the required taliks. A plot of discharge versus elevation (Fig. 4) shows no discernible pattern, but there is a tendency for spring elevation to decrease from west to east.

Collectively for all the springs citied in this study, the discharge is 20,000 l/s, which would require a groundwater recharge area of 3,150 km^2. This calculation is based on annual precipitation in the Brooks Range of around 400 mm (Kane et al. 2012) and a runoff coefficient of 0.5 for the north side of the Brooks Range (Kane et al. 2000), which would

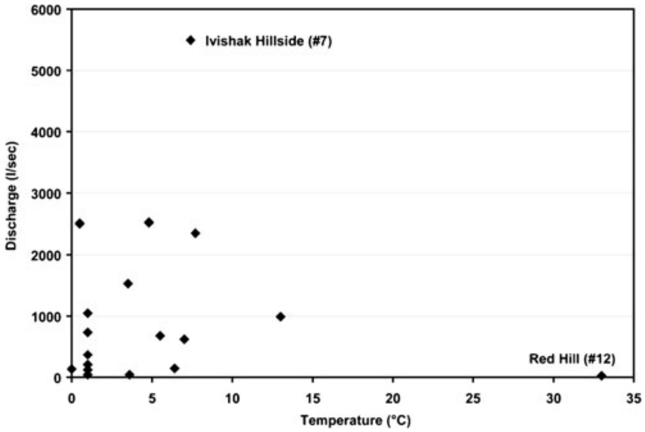

Fig. 3 A plot of water temperature versus spring discharge; *Ivishak Hillside* has the highest flow rate at 5,500 l/s (T=7.4 °C) and *Red Hill* has the highest temperature at 33 °C (Q=24 l/s)

DOI 10.1007/s10040-012-0937-0

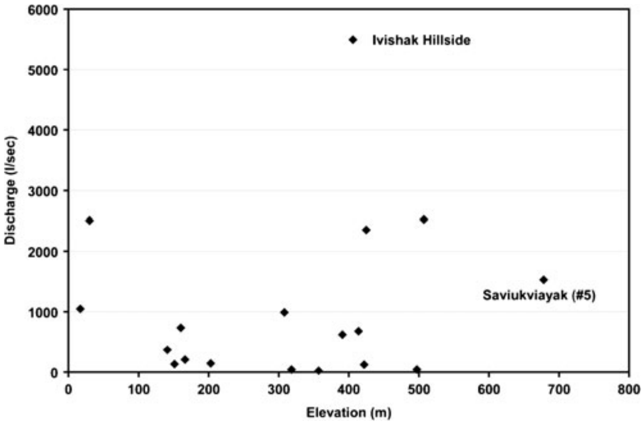

Fig. 4 Plot of elevation versus discharge for springs in northeastern Alaska where detailed data have been collected

leave a maximum of 200 mm of potential recharge. This 200-mm estimate of annual recharge is obviously conservative as it does not include evapotranspiration.

The State of Alaska (2008) geological map shows that the areal coverage of surficial limestone is much greater (at least one-half of the eastern one-third of the Brooks Range) than the recharge area derived in the preceding paragraph. Although potential recharge areas are widespread through the whole of the Brooks Range, the distribution of surficial limestone is greater, both on the south side of the Brooks Range and east of the Dalton Highway.

Specific conductivity

Specific conductivity was measured at all of the springs (Table 1; Fig. 5) visited by personnel either from the University of Alaska Fairbanks in the last decade or the USGS in the early 1970s. There was little difference between similar measurements taken by the two organizations at the same springs. The values ranged from a low of 210 µS/cm to a high of 1,000 µS/cm. Most of the measured values were in the high 200s. The high value of specific conductivity was at a hot spring (Red Hill, spring No. 12, Table 1) with a measured temperature of 33 °C. The ionic constituents that increase specific conductivity of water are calcium, magnesium, sodium, potassium, bicarbonate, sulfate and chloride; calcium and bicarbonate are the two most significant contributors to specific conductivity of these springs, while magnesium and sulfate also influence the measured values (Tables 1 and 2).

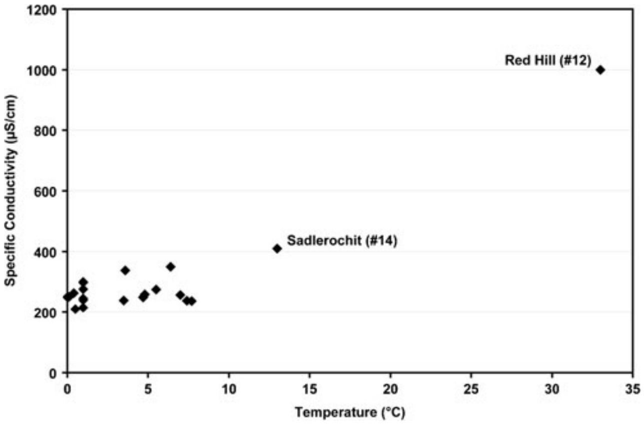

Fig. 5 Relationship between specific conductivity and spring temperature showing an increase in specific conductivity with temperature

Spring-water chemistry

The data presented here is a mix of data collected by the USGS and the University of Alaska Fairbanks, Water and Environmental Research Center (UAF/WERC). It is assumed that the USGS followed their protocol for testing back in the 1970s. In the measurements UAF/WERC personnel made, the procedures outlined in APKA-AWWA-WEF (1998) were followed. Where both parties collected the same data for a common site, the magnitude of the measurements was quite similar. This indicated that the data could be collectively used together and the properties had not significantly changed over the 25-year period between sampling campaigns.

The pH of the spring water ranged from a low of 6.4 to a high of 8.2 (Table 1). The low values (6.4–6.8) were found at both the east and west ends of the study area. The pH in the middle of the study area was above 7.0, with 16 of 22 values in the narrow range of 7.9–8.2. The pH values found here are typical of groundwater in general.

Calcium levels (Table 2; Fig. 6) vary from 36 to 78 mg/l for the springs with one outlier at 7.4 mg/l (Kuparuk, spring No. 2). Calcium levels are generally low for groundwater in igneous and metamorphic bedrock and high for carbonate sedimentary formations. With the extensive limestone bedrock in the Brooks Range (State of Alaska 2008), especially in the eastern sector, high levels of calcium should be expected if that is the pathway of the groundwater. As mentioned previously, the Kuparuk River spring (No. 2) has the low outlier value of calcium; this spring has many features that separate it from the quality of most of the other springs. For example, it has a low pH, temperature near 0 °C, and low magnesium and potassium levels.

Magnesium levels (Table 2; Fig. 6) range from 0.7 to 21 mg/l. The springs in the middle of the study area have the highest values with Red Hill (No. 12) at 21 mg/l and Sadlerochit (No. 14) at 18 mg/l. About one-half of the springs are in the 7–9 mg/l range. Sodium levels are generally low (0.3–2.8 mg/l) except for the same two springs, Red Hill (120 mg/l) and Sadlerochit (7.8 mg/l). These two springs are also warmer than the other springs that were analyzed in detail; the higher sodium and temperature values are likely a result of deeper groundwater flow. Potassium, which is not very soluble, ranges from 0.1 to 5.8 mg/l, with Red Hill the highest. Sadlerochit spring has the highest chloride level at 4.0 mg/l, while most of the remaining springs are below 1.0 mg/l.

Groundwater with high bicarbonate levels are generally an indication of limestone or dolomite bedrock. Bicarbonate levels (Table 2; Figs. 6 and 7) of the springs ranged from 62 to 322 mg/l with an average of 146 mg/l. The hot

Table 2 Chemical constituents for springs sampled on the eastern North Slope of Alaska, data from UAF/WERC and USGS (Childers et al. 1977)

Spring No. and name		Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	Sulfate (mg/l)	Cl (mg/l)	Bicarbonate (mg/l)
1	May Creek	50.8	7.95	1.9	0.3	2.15	0.24	
2	Kuparuk River	7.4	1.12	0.83	0.1	23.1	0.19	
3	Lupine	51	7.7	0.4	0.1	20.8	0.22	177
4	Saviukviayak West	40	9.2	0.7	0.1	8.5	0.7	155
5	Saviukviayak Trib	39	7.3	0.8	0.5	12	0.5	137
6	Flood Creek	52	8.8	0.3	0.5	13.1	0.18	136
7	Ivishak Hillside	47	8.72	0.3	0.1	14	0.16	128
8	Echooka River West	36	9.8	1.3	0.2	24	1.3	131
9	Echooka Hillside	40.1	9.48	0.47	0.1	33.6	0.15	
10	Echooka Valley	39.8	9.17	0.47	0.1	31.6	0.13	
11	Shublik	38	11	1.5	0.3	37	1.3	127
12	Red Hill	55	21	120	5.8	150	1.1	322
13	Katakturuk Trib	52		0.5	0.5	1.8	0.8	130
14	Sadlerochit	78	18	7.8	1	71	4.0	156
15	Hulahula River Icing	51		0.7	0.2	27	1.3	116
16	Okerokovik River			1.1	0.3	22	1.3	163
17	Aichilik River	65		2.8	2.1	39	2.0	148
18	Ekaluakat River	69	4.5	0.6		25	3.6	165
19	Kongakut River	50	1	0.5		25	0.9	134
20	Kongakut River Above Delta			1.1		17	1.0	62
21	Kongakut River Delta	46	1.1	1.1		17	0.5	122
22	Clarence River	53	0.7	0.5		12	0.7	124

spring (Red Hill, No. 12) had the highest and the Kongakut River above the delta (No. 20) had the lowest.

The lowest value of calcium (Table 2) was at the Kuparuk River aufeis (spring No. 2) at 7.4 mg/l, which compares to the area average for all springs of around 50 mg/l. Sulfate was the major contributor to the specific conductivity at this site. Sadlerochit (spring No. 14) has the highest concentration of calcium at 78 mg/l (Table 2) and the second highest specific conductivity of 410 µS/cm. Except for the two hot springs, Red Hill and Okpilak, Sadlerochit is the warmest spring at 13 °C with a flow of approximately 1,000 l/s. Red Hill, with the highest specific conductivity (Table 2), has average Ca levels (55 mg/l) and high levels of magnesium (21 mg/l), sodium (120 mg/l), potassium (5.8 mg/l) and sulfate (150 mg/l) compared with the other springs. Alkalinity was measured at several springs; most alkalinity (capacity to neutralize acids) is due to carbonate and bicarbonate. Figure 8 shows the strong relationship between specific conductivity and alkalinity.

Radiocarbon dating

A few samples of spring water were collected for radiocarbon dating. There are many possible sources of error when performing ^{14}C dating of groundwater; the three major sources of error are: (1) the ^{14}C level of atmospheric CO_2 is not constant, (2) recharge entering the groundwater system may mix with other water of different ages, and (3) carbon from other sources (some much older

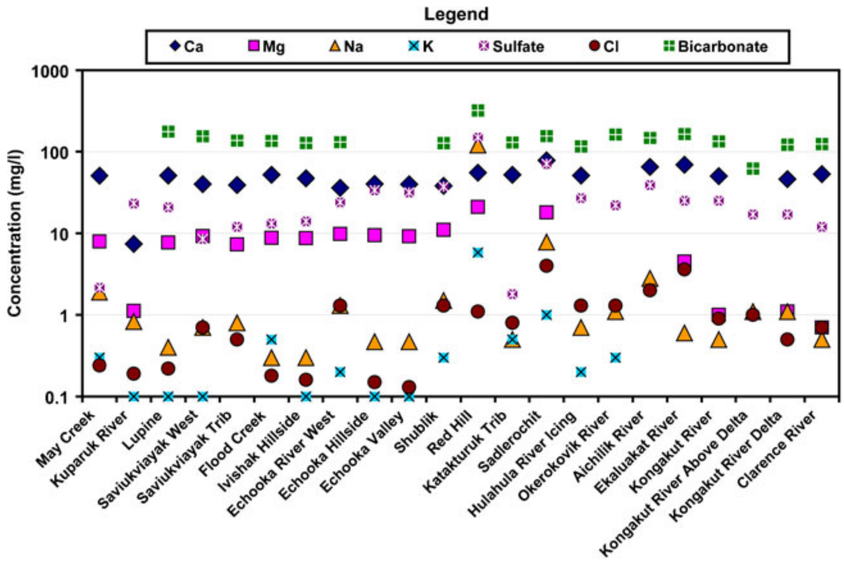

Fig. 6 A plot of spring-water chemistry for data collected by the USGS (Childers et al. 1977) and UAF/WERC. Some data is absent in cases where there were no measurements; also note the *log scale* on the y-axis

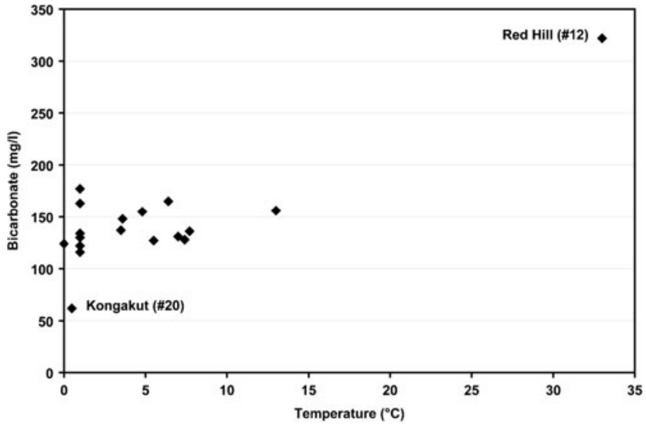

Fig. 7 Water temperature versus the bicarbonate level of springs. All of the bicarbonate levels are fairly high and are probably due to limestone rocks

such as limestone and other carbonate rocks) may dissolve into the groundwater. There are models (Pearson 1965; Pearson and Hanshaw 1970) that require additional data and assumptions to make adjustments to the groundwater age. The net result of all these errors is that the groundwater is younger than determined by a straightforward analysis of ^{14}C. In this case, it was only intended to get a rough idea of the age to determine if there was sufficient time for the groundwater to flow beneath the permafrost and then surface somewhere downstream through taliks. After completing this exercise for a few of the springs, it was found that the age of the discharging spring water was around 1,500–1,000 years BP (Fig. 9). Some of the springs—such as Kuparuk (No. 2) and Hulahula (No. 15)—that are distant from the mountains appear to be younger (Table 3); the two hot springs—Red Hill (No. 12) and Okpilak—seem to be the oldest measured (Table 3); this seems reasonable as they are the most distant from the identified recharge area. It is hypothesized that the Kuparuk spring functions differently than most of the other springs as the pH, Ca, Mg and K are much lower, while the percent modern carbon (pMC) values (Fig. 9) are much higher (Table 3). The higher the percent modern carbon, the younger the water. The age of discharging water at the two hot springs—Red Hill (No. 12) and Okpilak—appears to be in the 3,000–7,000 year range. From a physical standpoint, it would seem logical that the water for the two hot springs would travel longer, farther and deeper, thus warming due to geothermal heat.

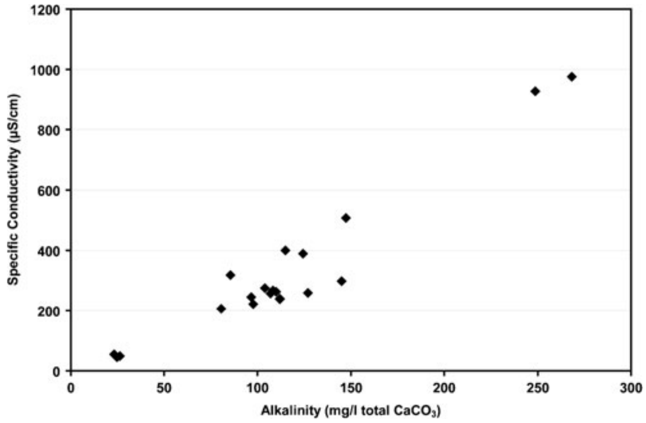

Fig. 8 Plot of alkalinity versus specific conductivity of springs in northeastern Alaska. The data plotted here are a mix of some of the springs in Table 1 and new springs (like Okpilak) that had not been sampled before

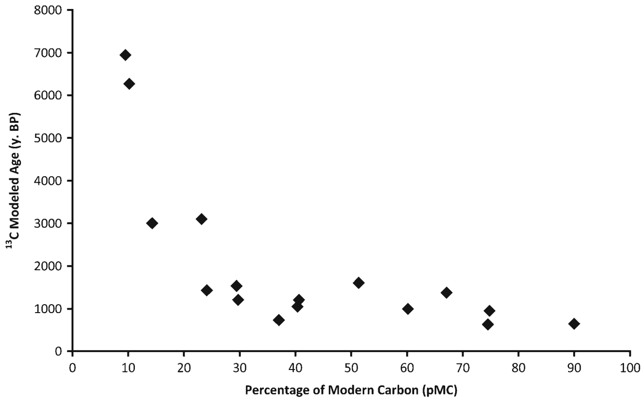

Fig. 9 Plot of the percent of modern carbon (pMC) versus δ^{13}C mixing modeled age in northeastern Alaska where detailed data have been collected (Table 3). Most of the spring water was less than 2,000 years old except two hot springs (Okpilak and Red Hill hot springs), which are the farthest from the hypothesized recharge area

Spring-water isotopic composition

The last contribution to this study was the measurement of isotope ratios (δ^2H (or δD) and δ^{18}O) of some of the springs on the North Slope and snowpack and some rainfall on a south–north transect along the Dalton Highway both north and south of the Brooks Range (Fig. 10). Although the isotope concentration of individual precipitation events is variable, the isotopic signatures of the precipitation on the near south side of the Brooks Range and the few springs observed north of the Brooks Range were similar. They indicated that the recharge for the springs most likely came from the south side of the Brooks Range. Generally, the isotopic signature of precipitation north of the Brooks Range is lighter than the heavier spring water (Fig. 10).

Discussion

Interest in potential groundwater flow on the North Slope of Alaska for this study resulted from various field observations during a number of related hydrologic research projects. UAF/WERC hydrologic investigations concentrated on active layer and surficial hydrological processes (Kane et al. 1989, 2000; McNamara et al. 1998). There are, however, two aufeis deposits in the Kuparuk watershed that were of interest; why were they there and what was the origin of the water that allowed them to form? There also existed several USGS open file reports about aufeis deposits in more remote areas (away from the road system) of the North Slope. It was not until the last decade that UAF/WERC personnel were able to

Table 3 Results of radiocarbon dating of springs on the eastern North Slope of Alaska

Name and spring No.[a]	δ^{13}C (‰)	Libby age[b] (years)	pMC (%)	δ^{13}C model age (years)
Kuparuk River (No. 2)	−19.0	850±30	89.96±0.35	700
Ivishak Hillside (No. 7)	−3.1	9,740±40	29.72±0.15	852
Flood Creek (No. 6)	−3.6	7,280±40	40.35±0.19	789
Echooka Valley (No. 10)	−6.1	4,080 ±30	60.17±0.27	867
Saviukviayak River (No. 5)	−3.9	9,820±40	29.43±0.16	1,187
Lupine (No. 3)	−7.5	5,350±40	51.36±0.23	1,449
Well at Pump station	−6.6	11,740±40	23.17±0.13	2,739
Hulahula River (No. 15)	−7.4	2,360±40	74.5±0.37	629
Sadlerochit River (No. 14)	−4.0	11,440±40	24.1±0.12	1,430
Kavik River	−10.8	2,330±40	74.8±0.37	951
Okpilak Hot Spring	−7.5	15,610±50	14.3±0.09	3,002
Red Hill Hot Spring 1	−9.2	18,350±80	10.2±0.10	6,270
Red Hill Hot Spring 2	−9.8	18,950±80	9.5±0.09	6,948
Shublik River (No. 11)	−5.0	7,230±40	40.6±0.20	1,205
Slope Mountain spring	−11.3	3,200±40	67.1±0.33	1,373

[a] Note that some of these springs are not numbered

[b] Method of carbon dating developed by Willard Libby, University of Chicago

get helicopter support for their research projects and could visit some of these more remote sites. Individually, the springs may not seem very significant hydrologically, with the largest spring discharging about 5,500 l/s (5.5 m^3/s). Collectively the 22 springs presented in Table 1 discharge over 20,000 l/s (20 m^3/s). The significance of these springs at the watershed scale can be better appreciated by the size of the aufeis formations that develops downstream at winter's end (Sloan et al. 1976; Yoshikawa et al. 2007). Aufeis is an important water-storage component in the winter months and influences the local geomorphology and ecology. Sloan et al. (1976) reported that the larger aufeis formations generally developed at the same locations each year, but the depth and areal coverage varied from year-to-year.

Clearly, some of these large springs discharge more water annually than seems possible from a water-balance viewpoint at the watershed scale. In the Saviukviayak River tributary spring (spring No. 5, Table 1), the discharge was measured at 1,529 l/s; assuming the discharge is constant over a period of 1 year (measurements show this to be generally true), this would be equivalent to a depth of 591 mm over the 83 km^2 drainage area above the spring. This 591 mm would be the equivalent groundwater recharge required above the spring in the watershed to produce the spring discharge. Best estimate of annual precipitation measured over a 4-year period for this area by this study is about 400 mm (Kane et al. 2012). In an adjacent creek (spring No. 6, Flood Creek, drainage area 207 km^2), the depth of hypothetical groundwater recharge over the basin above the spring would be 233 mm in comparison again with average annual precipitation around 400 mm. In addition to spring discharge, there is both surface runoff and evapotranspiration from the watershed above the spring. It should be recalled that these watersheds also have extensive permafrost that will further prevent recharge. These two cases demonstrate that a significant amount of the groundwater recharge for these two springs has to originate outside the watersheds from where the discharge occurs. The headwaters of these two watersheds border on the continental divide, so the likely source (some may come from adjacent watersheds) for groundwater recharge is on the south side of the continental divide in the Brooks Range.

One of the most extensive surficial rock formations in the Brooks Range, especially on the south side of the divide, is limestone, conglomerate, shale, and dolomite

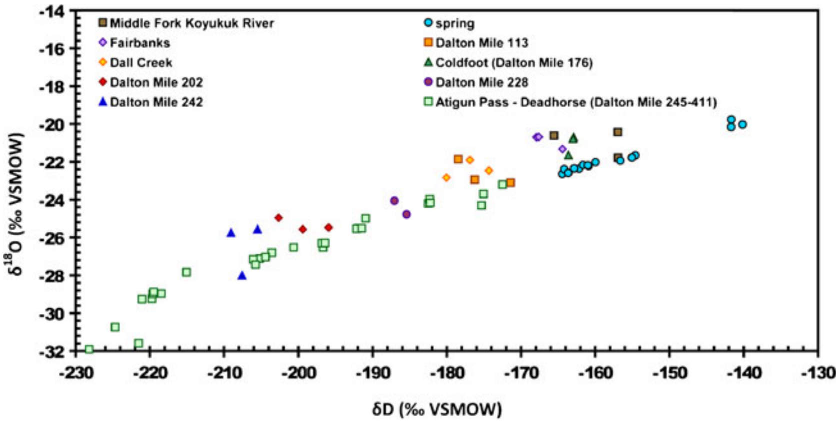

Fig. 10 Plot of deuterium (δD or hydrogen (δ^{2}H)) versus oxygen (δ^{18}O) isotopes of spring runoff in northern and central Alaska. Spring water samples (*blue circles*) are similar to values for the central or southern parts of the Brooks Range. Water samples north of the continental divide in the Brooks Range (*green squares*) are lighter than spring water in the same area

(State of Alaska 2008) of the Pennsylvanian and Mississippian periods. As one progresses west in the Brooks Range, this predominantly limestone bedrock starts to thin out around the Dalton Highway. West of the highway to the Alaska coastline (Chukchi Sea) there is limited limestone like bedrock outcrops; this is also an area of minimal environmental (meteorology, hydrology, etc.) study. Springs are known to exist in the area because of the aufeis formations that are observed at winter's end. However, these formations are not as extensive as those observed east of the Dalton Highway. This is the same area where Deming et al. (1992) carried out their evaluation of regional groundwater flow based on the thermal data garnered from oil/gas exploration holes. They concluded that there was subpermafrost groundwater flow, although they did not expound on areas of recharge or discharge. Instead, they assumed that the recharge was somewhere in the Brooks Range and the discharge was at the northern terminus of the permafrost along the coast.

The spring chemistry (specific conductance, bicarbonate and alkalinity) demonstrates that the pathway of groundwater flow is likely through bedrock dominated by limestone. The geologic map (State of Alaska 2008) shows that there is widespread limestone in the area, particularly on the south side of the continental divide. While the areas of groundwater discharge (springs) occur in taliks of limited surface area, groundwater recharge zones must be much more expansive and permafrost free. Obviously, there is a much greater chance of permafrost-free surficial rock formations on the warmer south side of the Brooks Range than on the north side.

The travel time of 1,000–1,500 years seems reasonable. If a typical distance (45–85 km) from the point of recharge to the point of discharge is divided by the travel time (1,000–1,500 years), a Darcy velocity range of 30–85 m/year is obtained. Also, if the hydraulic gradient is approximated (change in elevation divided by travel distance) for this mountainous region and divided into the Darcy velocity, a hydraulic conductivity can be estimated. In this case, the range is approximately 1×10^{-6}–1×10^{-9} m/s. These values are in the range of values reported for limestone and dolomite in the literature (Freeze and Cherry 1979). So, the estimated travel time of 1,000–1,500 years seems plausible for this setting

Conclusions

The springs in the eastern North Slope of Alaska are clear evidence that a groundwater flow system exists in an environment mapped as continuous permafrost. Attempts are made here to demonstrate that the recharge for the groundwater system feeding the springs occurs at the higher elevations on the south side of the Brooks Range in areas where limestone bedrock at the surface is extensive and the water flows northward under the permafrost to discharge through taliks in the permafrost or ultimately into the Arctic Ocean (Fig. 2). While groundwater discharge can occur at concentrated areas like springs, groundwater recharge is generally much more spatially distributed over larger areas.

Data on the water balance of two watersheds (close to the continental divide) with springs on the north side of the Brooks Range have been presented here. The conclusion is that there is not sufficient recharge area within the watersheds to sustain the flow of the springs. Recharge could come from watersheds on each side of the catchment accommodating the spring, but is more likely that water is coming from the other side of the continental divide. Also, the south-facing slopes of the Brooks Range are more prone to having areas free of permafrost than north-facing slopes because of the warmer climate; the continental divide in the Brooks Range represents the transition from discontinuous to continuous permafrost.

The water chemistry of the springs indicates that, with one or two exceptions, the groundwater has had extensive contact with limestone aquifers. Also, the chemical differences between springs show that different groundwater processes are ongoing. The small amount of ^{14}C age dating that was carried out indicates that there is sufficient travel time for groundwater to travel through limestone aquifers from higher elevations on the south side of the Brooks Range to the points of spring discharge on the north side. The two warmest springs are located the farthest away from the recharge area; this fits the concept of geothermal heating of deeper groundwater flow. Finally, stable isotope ratios (δ^2H and δ^{18}O) hint that there is a match between precipitation (mostly snow) on the south side and springs on the north side of the Brooks Range.

There is some doubt about the source of groundwater for springs located north and out from the Brooks Range, like the Kuparuk River spring. One common characteristic of these springs is that their temperature is just above 0 °C. Many of these springs also have other characteristics that differ such as pH (generally lower) and Ca, Mg, K and sulfate (generally lower). If the water for these springs is not subpermafrost groundwater, then the only likely source is water stored in taliks within glacial moraines along the drainages, a concept that has not been discussed in the literature yet.

Acknowledgements The results reported here were not the outcome of one specific funded project, but instead come from measurements collected from several projects carried out in the area and the USGS contribution of Childers et al. (1977) in the 1970s. This work was funded in part by National Science Foundation grants OPP-9814984, OPP-0335941, ARC-0229705. We also acknowledge the US Fish and Wildlife Service for permitting us to enter the wildlife refuge for sampling of springs.

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