Potential impacts of a changing Arctic on community water sources on the Seward Peninsula, Alaska

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This paper discusses the potential impacts of climate change on community drinking water sources on the Seward Peninsula. The vulnerability assessment was largely based on the likelihood that the water source would be impacted by a change in the permafrost regime. Factors that were considered were the likely change in the permafrost condition of a watershed, the watershed area, and the contribution of groundwater to streamflow. Results showed that the change in permafrost condition is likely to impact some communities much more than others, even though the communities are near to each other. Communities that will experience little change to the permafrost in their watersheds, have a significant contribution of base flow to their streams and rivers, or have water sources with large watersheds were not found to be vulnerable. On the other hand, communities with small watersheds, watersheds that were likely to see a significant change in the permafrost regime, or watersheds with little winter base flow were seen to be vulnerable to climate change. The results of this work could be valuable to community leadership when considering future vulnerability. The same approach could be used across the Arctic to assess the potential impact of climate change on community water sources and ultimate sustainability.


1. Introduction

The purpose of this project was to better understand the impact of climate change on water resources in the Arctic and the people who depend on them. The paper begins with a background on observed and projected climate and environmental change in the Arctic and Alaska in particular. Such changes may have potentially important consequences for future water availability, ergo community sustainability, through the redistribution of freshwater in time and space. Subsequent sections will discuss, in order, study objectives and location, methods employed for data collection and analysis, study results, a discussion of findings, and finally, conclusions.

1.1. Temperature and Precipitation

Surface air temperature is a widely measured climate variable and is commonly used as an indicator of climate change. Within the instrumental record in the Arctic, surface air temperature has increased [Hinzman et al., 2005], warming 0.6°C since the early 20th century, with the 20th century believed to be the warmest in the past 400 years [Overpeck et al., 1997]. The peak temperatures of the 20th century, however, were around 1945, before a period of cooler temperatures [Overpeck et al., 1997]. Since the 1970s, surface air temperatures have risen, though the change varies spatially and by season [Serreze et al., 2000]. On average, Alaska has shown warming on both an annual and seasonal basis, with the exception of fall [Serreze et al., 2000]. A change in temperature could affect the winter frost depth, period of snow cover, form of precipitation (rain versus snow), and permafrost condition, all of which have a significant impact on the water resources [White et al., 2007].

Precipitation is difficult to measure in the Arctic and complex to predict. Arctic precipitation is likely to have increased by 1% per decade over the last century [Arctic Climate Impact Assessment, 2005]. While precipitation has increased, the summer surface water balance (precipitation minus potential evapotranspiration, P-PET) has decreased for Alaska’s North Slope, coastal plain, and interior regions since 1960 [Oechel et al., 2000; Hinzman et al., 2005]. Winter precipitation has increased since the 1970s, and arctic winter precipitation is projected to increase with continuing climate change [Serreze et al., 2000].

1.2. Permafrost and Surface Water

Permafrost warming, degradation, and disappearance are of particular importance to water resources in cold regions. A number of studies have reported trends of increas-
ing permafrost temperatures in the arctic and subarctic [Osterkamp, 2003; Clow and Urban, 2002; Osterkamp and Romanovsky, 1999; Lachenbruch and Marshall, 1986]. In Alaska, the changes are attributed to both increased temperature as well as the insulating effect of greater winter snow depth [Osterkamp and Romanovsky, 1999]. Permafrost degradation ensuing from continued temperature increases may have important implications for the distribution of water over land [White et al., 2007]. In continuous permafrost, temperature increases generally appear to be associated with greater surface water as infiltration of newly thawed soil moisture is severely limited by the low permeability of the underlying permafrost. However, in discontinuous permafrost, degradation is associated with the loss of surface water as the periodic absence of underlying permafrost allows previously perched surface water to drain to deeper aquifers [Yoshikawa and Hinzman, 2003; Smith et al., 2005]. Such behavior has been observed in Siberia and on the Seward Peninsula of Alaska. In Siberia, lakes in continuous permafrost regions increased in size and number, while those in discontinuous permafrost regions shrank or disappeared since 1972 [Smith et al., 2005]. Likewise, tundra ponds on the Seward Peninsula, an area of discontinuous permafrost, decreased in area or disappeared over the last 50 years [Yoshikawa and Hinzman, 2003].

1.3. Groundwater and Water Supplies

[6] In most regions of the Arctic, small streams do not flow in winter unless they serve to discharge a groundwater aquifer. In general, large watersheds are much more likely than small watersheds to have a groundwater aquifer that sustains streamflow throughout the year. Streams in small watersheds, particularly those with continuous permafrost, flow only seasonally.

[7] Streams with a significant groundwater contribution will be impacted less by climate change, at least initially, than streams with a small groundwater component. This is because groundwater aquifers, particularly those with long residence times or storage capacities, respond slowly to change. In addition, streams with large watersheds will be impacted less by climate change than streams with small watersheds since large watersheds often have a diversity of permafrost and nonpermafrost regions offering some buffer to changes in permafrost distribution [Woo, 1986].

2. Study Objective and Location

[8] The objective of this study was to present a vulnerability assessment for drinking water resources on the Seward Peninsula. The method could be used across the Arctic to evaluate the potential impact of climate change on water resources and the follow-on impact to people.

[9] In order to address the study objective, we first used existing data sets, such as regional temperature and precipitation from weather stations and global climate model (GCM) projections to predict permafrost distribution 100 annums into the future. The potential change in permafrost distribution in a watershed, coupled with the watershed area and percent of streamflow attributable to groundwater was used to rate the relative vulnerability of the water resources in a changing climate.

[10] As a model case study for the Arctic, our work focused on the Seward Peninsula of Alaska. The Seward Peninsula currently lies at the boundary between continuous and discontinuous permafrost. As such, the region may be vulnerable to the potential impacts of climate change on permafrost hydrology in the near term. The Seward Peninsula is home to approximately 5600 inhabitants. The peninsula is bounded by the Chukchi Sea and Kotzebue Sound to the north, Bering Strait to the west, and Norton Sound to the south (Figure 1). Nome is the primary transportation and supply hub of the Seward Peninsula. Other communities with year-round inhabitants include Breivig Mission, Deering, Elim, Golovin, Shishmaref, Teller, Wales, and White Mountain. Additional town sites and fish camps are inhabited seasonally. Only Nome and Teller are connected by road. No roads connect the Seward Peninsula to the remainder of Alaska, and only small aircraft facilitate the transport of people and goods across the Seward Peninsula year-round.

[11] While all of the Seward Peninsula communities studied have a municipal water supply, many residents rely on rivers, lakes, rainfall and ice for drinking water. These “traditional” water sources are needed when the municipal supply fails, or when residents are at remote hunting or fishing camps.

3. Data and Methods

3.1. Groundwater Contribution to Streams

[12] The potential impact of climate change on small streams, such as those used by many rural communities in the Arctic, will largely be a function of the relative percentage of groundwater contributing to the stream. The method for estimating groundwater contributions to surface water was based on the assumption that winter stream flow, in the prolonged absence of surface runoff, was derived from groundwater contribution. On this basis, it was assumed that end of winter, under-ice stream water conductivity reflected the conductivity of the contributing groundwater. As such,
summer base flow contributions were estimated with a surface and groundwater conductivity mixing model according to the following equations:

\[
Q_b + Q_s = 1 \\
Q_s = (C - C_b) / (C_s - C_b),
\]

where \(Q_b\) is proportion base flow, \(Q_s\) is proportion stormflow, \(C_b\) is base flow conductivity (winter), \(C_s\) is stormflow conductivity, \(C\) is stream conductivity as used by MacLean et al. [1999] (citing mixing model of Pearce et al. [1986]). The conductivity of the precipitation and runoff input was assumed to be within the range of 0 to 50 \(\mu\)S/cm, which yielded estimates of summer groundwater contributions that bracket the true proportion.

[13] Conductivity was measured during summer 2005 and late winter 2006 in five community’s water sources, with additional measurements between July 2005 and October 2006 made by volunteers and project personnel in four communities. Summer 2005 measurement of specific conductance was made with a Hach Sension5 conductivity meter with automatic nonlinear NaCl correction for temperature. Late winter measurements of actual conductivity were made with a YSI 30 conductivity meter. Temperature correction for YSI readings were made with the equation \(SC = AC/(1 + 0.02(T - 25))\), where \(SC\) is specific conductance, \(AC\) is actual conductivity, and \(T\) is temperature in degrees Celsius [Hem, 1985]. An additional handheld Hanna 98129 pH/EC/TDS probe was left with a volunteer in Wales for monthly measurements of the local streams and Extech EC 400 ExStik conductivity probes were left with volunteers in White Mountain, Elim and Golovin.

3.2. Predicting Permafrost Distribution

[14] The presence of permafrost controls surface runoff and infiltration to groundwater and is perhaps the most important control on hydrology, particularly in a changing climate. In order to better understand the impacts of climate change on water resources on the Seward Peninsula, a permafrost prediction model was constructed. Permafrost was modeled using the TTOP [Smith and Risenborough, 1996] and MicroMet models [Liston and Elder, 2006]. TTOP estimates the temperature at the top of the permafrost on the basis of surface temperature calculated using MicroMet from meteorological data. The TTOP model is

\[ T_{TOP} = (I_{ST} * k_T / k_F - I_{SF}) / P, \]

where \(I_{ST}\) and \(I_{SF}\) are soil surface thawing and freezing indices, respectively, \(k_T\) and \(k_F\) are the average thawed and frozen bulk soil thermal conductivity for the active layer, and \(P\) is period (365 days).

[15] Permafrost extent and type (continuous, discontinuous) were modeled for past, present, and future conditions. Current conditions were modeled with data from 11 meteorological stations on the Seward Peninsula. These stations are owned by the National Weather Service, Natural Resources Conservation Service (SNOTEL sites), Bureau of Land Management, and the University of Alaska Fairbanks. Future simulations of permafrost were modeled on the basis of expected climate change as described by Canadian Centre for Climate Modeling and Analysis (CCCma) coupled global climate model (GCM). The model version used was 3.1 (3.75 degree lat/lon grid resolution) (http://www.cccma.bc.ec.gc.ca/models/cgcm3.shtml). The scenario used was SRES A1B, a middle-of-the-road emission scenario (CO2 levels gradually rise to 16 GtC (Giga tons Carbon) per year in 2050 and then decline to 13 GtC per year by 2100). The output of the model was average annual temperature at the bottom of the active layer (top of permafrost table). This output was partitioned on the basis of temperature thresholds, resulting in ground classification as continuous permafrost (colder than \(-5^\circ\)C), discontinuous \((-5^\circ\)C to \(-0.01^\circ\)C), or thawing permafrost (warmer than \(-0.01^\circ\)C). The permafrost distributions reflect an average temperature at the top of the permafrost for the years 2092–2095. Thus the classification indicates what permafrost type is sustainable at the modeled ground temperatures.

3.3. Watershed Area Analysis

[16] In the watershed analysis, watershed area was calculated using RiverTools 2.0, a software application for digital terrain and river network analysis. The digital elevation model used as input to the Rivertools software was based on 100-m grid resolution.

3.4. Vulnerability Index

[17] The potential impact of climate change on water resources was described using a vulnerability index. A vulnerability index was developed that incorporated current permafrost distribution and projected trends, groundwater contribution to stream flow, and watershed area. Each parameter from this list was assigned a vulnerability factor from 1 to 5, where 1 indicated the lowest vulnerability and 5 indicated the greatest vulnerability. Vulnerability factors are defined in Table 1 for a range of conductivity/groundwater contributions, permafrost trends, and watershed area. The greater the contribution of groundwater to a stream, the less likely it was assumed that near-term climate change would impact the water resource. Conductivity vulnerability factors were based on the percentage of groundwater contribution calculated as described in section 3.1. Areas tending toward permafrost degradation or loss were considered more vulnerable owing to the important role of permafrost in local hydrology. Finally, large watersheds were considered less vulnerable to climate induced changes than small watersheds. The future vulnerability index was calculated as the average of the vulnerability factors for percent summer groundwater contribution (based on the low end of the estimate range), permafrost loss (reduction in area underlain by continuous permafrost or increase in area classified as thawing permafrost, with changes reflecting differences between 2001–2004 and 2092–2095 model runs), and catchment area.

4. Results

4.1. Groundwater Contributions

[18] Field measurements of conductivity for water sources are presented in Table 2. Conductivity measurements from June 2005, July 2005, and late March through early April 2006 show a range of about 50 to 600 \(\mu\)S/cm for most water sources. Late winter conductivity ranged from 105 to
450 μS/cm. Late winter stream conductivities were used to estimate groundwater contributions, as previously discussed. Estimated groundwater contributions for water sources are also shown in Table 2. The range of groundwater contribution was based on an assumed range of rainfall conductivity used in the stream mixing model (0–50 μS/cm).

[19] The assumption that groundwater flow becomes an increasingly large contributor to streamflow throughout winter is supported by monthly measurements from Village Creek in Wales (Table 3). This data showed an increasing conductivity trend from September (181 μS/cm) through April (334 μS/cm), and a sudden drop during snowmelt.

### 4.2. Permafrost Changes

[20] Permafrost modeling results at the local watershed scale are presented in Table 4. Samples of images are shown in Figures 2–4 for watersheds used by White Mountain, Teller, and Golovin, respectively. As can be seen, some areas that are currently underlain by continuous permafrost are expected to shift to discontinuous permafrost or thawing ground, while some areas of discontinuous permafrost may continue thawing. All watersheds showed a loss of continuous permafrost, though the magnitude and fraction converted to a thawing or permafrost-free region varied. As shown in Table 4, on an area-weighted basis, continuous permafrost losses ranged from 7% of watershed areas used by residents of Elim to 16% for watershed areas used by residents of Golovin. Increases in thawing area ranged from 3% to 28%, again for watersheds at Elim and Golovin, respectively. The fact that these values were area weighted, masks some of the dramatic changes in small watersheds. For example, some small watersheds showed no net gain in thawing permafrost ground while others showed an increase by as much as 46%.

[21] The coincidence of the maximum area-weighted continuous permafrost loss and maximum thawing permafrost gain in Golovin indicated that more of the permafrost change at Golovin was conversion of permafrosted areas to thawed, or thawing ground, whereas for Elim, watersheds showed more conversion of continuous permafrost to discontinuous permafrost.

### 4.3. Water Source Vulnerability

[22] Table 5 shows the vulnerability factors for each community water source, with consideration given to watershed area, groundwater contribution to stream flow, and projected changes to permafrost distribution. Teller and Wales are dependent on particularly small watersheds, with three of the five combined basins less than 10 km² and only one basin larger than 50 km². Golovin has three watersheds with areas greater than 50 km². Elim has many potential water sources, of which three watersheds are greater than 50 km² and one greater than 1000 km². White Mountain has two basins with areas greater than 50 km², with the Fish River being quite large at greater than 5000 km².

### Table 2. Specific Conductance Measurements and Groundwater Calculations

<table>
<thead>
<tr>
<th>Community</th>
<th>Water Source</th>
<th>March/April 2006 Stream Conductivity, μS/cm</th>
<th>June 2005 Stream Conductivity, μS/cm</th>
<th>July 2005 Stream Conductivity, μS/cm</th>
<th>Maximum Recorded Stream Conductivity, μS/cm</th>
<th>Groundwater Contribution, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elim</td>
<td>Tubutulik</td>
<td>220</td>
<td>–</td>
<td>–</td>
<td>220</td>
<td>80–100</td>
</tr>
<tr>
<td></td>
<td>Kwiniuk River (Moses Point)</td>
<td>225</td>
<td>–</td>
<td>91</td>
<td>225</td>
<td>60–80</td>
</tr>
<tr>
<td></td>
<td>Iron Creek</td>
<td>449</td>
<td>588</td>
<td>346</td>
<td>588</td>
<td>40–60</td>
</tr>
<tr>
<td></td>
<td>Turner Creek</td>
<td>404</td>
<td>620</td>
<td>368</td>
<td>620</td>
<td>20–40</td>
</tr>
<tr>
<td></td>
<td>Infiltration Gallery at Town Creek (Shelby Well)</td>
<td>411</td>
<td>–</td>
<td>478</td>
<td>478</td>
<td>0–20; or no winter flow</td>
</tr>
<tr>
<td></td>
<td>Corel Creek</td>
<td>–</td>
<td>–</td>
<td>200</td>
<td>200</td>
<td>no winter flow</td>
</tr>
<tr>
<td></td>
<td>Elim Hot Springs</td>
<td>–</td>
<td>–</td>
<td>3100</td>
<td>3100</td>
<td>no winter flow</td>
</tr>
<tr>
<td>Golovin</td>
<td>Kachauik (Kitchalvik)</td>
<td>147</td>
<td>70</td>
<td>127</td>
<td>147</td>
<td>60–80</td>
</tr>
<tr>
<td></td>
<td>Cheenik Creek</td>
<td>157</td>
<td>72</td>
<td>–</td>
<td>157</td>
<td>40–60</td>
</tr>
<tr>
<td></td>
<td>Kilamuvik Creek</td>
<td>106</td>
<td>83</td>
<td>91</td>
<td>106</td>
<td>20–40</td>
</tr>
<tr>
<td></td>
<td>Big Lake Springs</td>
<td>–</td>
<td>–</td>
<td>80</td>
<td>80</td>
<td>no winter flow</td>
</tr>
<tr>
<td></td>
<td>McKinley Creek</td>
<td>–</td>
<td>–</td>
<td>1500</td>
<td>1500</td>
<td>no winter flow</td>
</tr>
<tr>
<td>Teller</td>
<td>Coyote Creek</td>
<td>–</td>
<td>–</td>
<td>588</td>
<td>588</td>
<td>no winter flow</td>
</tr>
<tr>
<td></td>
<td>Bluestone Creek</td>
<td>–</td>
<td>–</td>
<td>258</td>
<td>258</td>
<td>no winter flow</td>
</tr>
<tr>
<td></td>
<td>Wooley Rd. Creek</td>
<td>–</td>
<td>–</td>
<td>65</td>
<td>65</td>
<td>no winter flow</td>
</tr>
<tr>
<td>Wales</td>
<td>Village Creek</td>
<td>368</td>
<td>45</td>
<td>–</td>
<td>384</td>
<td>no winter flow</td>
</tr>
<tr>
<td></td>
<td>Gilbert Creek</td>
<td>–</td>
<td>38</td>
<td>–</td>
<td>38</td>
<td>no winter flow</td>
</tr>
<tr>
<td>White Mountain</td>
<td>Aggie Creek</td>
<td>365</td>
<td>–</td>
<td>299</td>
<td>365</td>
<td>no winter flow</td>
</tr>
<tr>
<td></td>
<td>Christmas Creek</td>
<td>252</td>
<td>–</td>
<td>300</td>
<td>300</td>
<td>no winter flow</td>
</tr>
<tr>
<td></td>
<td>Fish River</td>
<td>316</td>
<td>147</td>
<td>117</td>
<td>320</td>
<td>no winter flow</td>
</tr>
<tr>
<td></td>
<td>Niukluk</td>
<td>–</td>
<td>–</td>
<td>120</td>
<td>120</td>
<td>no winter flow</td>
</tr>
<tr>
<td></td>
<td>Creek above Puttu</td>
<td>–</td>
<td>–</td>
<td>304</td>
<td>304</td>
<td>no winter flow</td>
</tr>
</tbody>
</table>

*Municipal water source.*
As with watershed area, Teller and Wales show particular vulnerability with respect to groundwater contributions. Wales’ two water sources factor at 4 and 5 on the vulnerability scale, while the only source that could be evaluated in Teller, Coyote Creek, factored at 5. Golovin also indicated relatively high vulnerability, with three of five evaluated sources ranked at 4. However, the uncertainty in the groundwater contribution estimates for two of those sources was high, and they could potentially have lower vulnerability. Elim and White Mountain show a wide range of vulnerabilities across their water sources, with Elim factoring between 2 and 4 on the vulnerability scale and White Mountain between 1 and 4.

Table 3. Monthly Conductivity Measurements in Wales, Alaska

<table>
<thead>
<tr>
<th>Date, mm/dd/yyyy</th>
<th>Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>09/18/2005</td>
<td>181</td>
</tr>
<tr>
<td>10/15/2005</td>
<td>207</td>
</tr>
<tr>
<td>11/12/2005</td>
<td>211</td>
</tr>
<tr>
<td>12/10/2005</td>
<td>300</td>
</tr>
<tr>
<td>01/14/2006</td>
<td>275</td>
</tr>
<tr>
<td>02/11/2006</td>
<td>303</td>
</tr>
<tr>
<td>04/02/2006</td>
<td>368</td>
</tr>
<tr>
<td>05/07/2006</td>
<td>8*</td>
</tr>
<tr>
<td>05/20/2006</td>
<td>121</td>
</tr>
<tr>
<td>10/13/2006</td>
<td>154</td>
</tr>
<tr>
<td>10/14/2006</td>
<td>149</td>
</tr>
</tbody>
</table>

Snow melt influence.

Figure 2. These two images show the change in permafrost from (top) the 2001–2004 air temperature to (bottom) the modeled 2092–2095 air temperature for the Fish River. This watershed is used by the community of White Mountain. The dark blue indicates continuous permafrost, the light blue indicates discontinuous permafrost, and the white indicates thawing permafrost (or permafrost-free).

Figure 3. These two images show the change in permafrost from (top) the 2001–2004 air temperature to (bottom) the modeled 2092–2095 air temperature for Coyote Creek. This watershed is used by the community of Teller. The dark blue indicates continuous permafrost, the light blue indicates discontinuous permafrost, and the white indicates thawing permafrost (or permafrost-free).

[23] As with watershed area, Teller and Wales show particular vulnerability with respect to groundwater contributions. Wales’ two water sources factor at 4 and 5 on the vulnerability scale, while the only source that could be evaluated in Teller, Coyote Creek, factored at 5. Golovin also indicated relatively high vulnerability, with three of five evaluated sources ranked at 4. However, the uncertainty in the groundwater contribution estimates for two of those sources was high, and they could potentially have lower vulnerability. Elim and White Mountain show a wide range of vulnerabilities across their water sources, with Elim factoring between 2 and 4 on the vulnerability scale and White Mountain between 1 and 4.
With the exception of Golovin, most communities had low permafrost vulnerability, ranging between 1 and 3. Golovin, on the other hand, shows vulnerability to permafrost changes, with two sources factoring at 3 and the other two sources factoring at 4 and 5. The permafrost factor was compounded by the relatively small watersheds associated with Golovin’s water sources.

The overall vulnerability index incorporated the influence of the watershed area, groundwater contribution, and permafrost change factors. The resulting vulnerability index values, shown in Table 5, ranged between 2.0 and 4.3, with an overall mean of 3.0. Average community based vulnerabilities ranged from 2.2 in White Mountain to 3.8 and 4.0 in Golovin and Teller, respectively.

5. Discussion

Electrical conductivity of currently available surface water sources gave some insight into their likelihood to persist into the coming century. The range of base flow conductivities may be due to residence time (related to depth and flow patterns) and aquifer media. Assuming approximately similar aquifer media, streams like Kilamuvik at Golovin are believed to have shallow groundwater input with limited residence time. For such basins, changes in precipitation will be quickly reflected in base flow and are therefore considered more sensitive to climate change. The Fish River, Iron Creek, Turner Creek, and Village Creek, on the other hand, likely have groundwater with a relatively higher residence time and will be less susceptible to near-term climate change.

The permafrost modeling results indicated a consistent regional trend toward warming permafrost. This warming and subsequent change of underlying permafrost will have an effect on regional hydrology. In the absence of detailed hydrologic modeling of this region, an assessment of relative influence may still be considered.

On a community basis, White Mountain’s water sources appeared to be the least vulnerable, with an average vulnerability of 2.2. In addition, this community presently draws its municipal supply from wells. Permafrost trends in the surface water catchments indicate generally modest future changes from continuous to discontinuous permafrost. If these trends materialize, then this could lead to reduction in surface flow, while groundwater resources may actually increase as a larger fraction of precipitation could serve to recharge groundwater. Elim also exhibits low vulnerability, averaging 2.7. The municipal water supply is partially dependent on subsurface collection galleries and natural springs. Use of available groundwater will further improve the ability of these communities to cope with future changes to surface water.

The communities of Golovin and Teller appear to be the most vulnerable, with average vulnerabilities of 3.8 and 4.0, respectively. In both communities, the watersheds used for municipal water sources show high vulnerabilities and are expected to change from discontinuous permafrost to thawing permafrost conditions. This environmental change could potentially lead to reduced surface flow as a result of greater precipitation infiltration and drainage to groundwater aquifers.

The communities on the Seward Peninsula reflect a range of potential vulnerabilities. For example, White Mountain presently draws its municipal supply from groundwater, yet this community also has several large alternative surface sources that are likely to persist into the future. A second category of vulnerability reflects communities that may experience reduced productivity from current municipal sources, but have alternative sources that are likely to persist. Other communities, however, are considered especially vulnerable when current municipal supplies are at risk of dwindling and have limited alternative resources to which they can turn. Given the central role of adequate water resources to community sustainability, this form of assess-
### Table 4. Projected Changes to Occur Over Next 100 Years to Permafrost Distribution in Study Watersheds

<table>
<thead>
<tr>
<th>Community</th>
<th>Stream</th>
<th>Watershed Area, km²</th>
<th>Net Continuous Permafrost Change (% Watershed Area)</th>
<th>Net Discontinuous Permafrost Change (% Watershed Area)</th>
<th>Net Permafrost-free Change (% Watershed Area)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elim</td>
<td>Tubutulik River</td>
<td>1,063</td>
<td>-6%</td>
<td>4%</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>Kwniniuk River (Moses Point)</td>
<td>547</td>
<td>-8%</td>
<td>3%</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>Iron Creek</td>
<td>59</td>
<td>-6%</td>
<td>8%</td>
<td>-2%</td>
</tr>
<tr>
<td></td>
<td>Turner Creek</td>
<td>3</td>
<td>-18%</td>
<td>-4%</td>
<td>22%</td>
</tr>
<tr>
<td></td>
<td>Infiltration Gallery at Town Creek (Shelby Well)*</td>
<td>9</td>
<td>-18%</td>
<td>-7%</td>
<td>25%</td>
</tr>
<tr>
<td>Corel Creek</td>
<td></td>
<td></td>
<td>-5%</td>
<td>3%</td>
<td>2%</td>
</tr>
<tr>
<td>Elim Hot Springs</td>
<td></td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>Community Average</td>
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<td>273</td>
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<td>-14%</td>
<td>25%</td>
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</tr>
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<td>46%</td>
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<tr>
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<td>-50%</td>
<td>48%</td>
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</tr>
<tr>
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<td>ND</td>
<td>ND</td>
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<td>-23%</td>
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<tr>
<td>Gilbert Creek</td>
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<td>ND</td>
<td>ND</td>
<td>ND</td>
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</tr>
<tr>
<td>Community Average</td>
<td></td>
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<td>6%</td>
</tr>
<tr>
<td>White Mountain</td>
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<td>-2%</td>
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</tr>
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<td>Fish River</td>
<td>5850</td>
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<td>-2%</td>
<td>13%</td>
<td></td>
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<tr>
<td>Niukluk</td>
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<td>14%</td>
<td>0%</td>
<td></td>
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<tr>
<td>Creek above Puttu</td>
<td>38</td>
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<td>10%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>Community Average</td>
<td></td>
<td></td>
<td>-12%</td>
<td>-2%</td>
<td>13%</td>
</tr>
<tr>
<td>*ND, no data; watershed unresolved by DEM. *Municipal water source.</td>
<td></td>
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### Table 5. Water Source Vulnerability Factors and Vulnerability Index

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<th>Community</th>
<th>Water Source</th>
<th>Watershed Area Factor</th>
<th>Groundwater Factor</th>
<th>Permafrost Factor</th>
<th>Vulnerability Index</th>
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<td>2</td>
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<tr>
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<td>Kwniniuk River (Moses Point)</td>
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<td>1</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
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<td>Iron Creek</td>
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<td>1</td>
<td>2.0</td>
<td></td>
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<tr>
<td></td>
<td>Turner Creek</td>
<td>5</td>
<td>3</td>
<td>3.3</td>
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</tr>
<tr>
<td></td>
<td>Infiltration Gallery at Town Creek (Shelby Well)*</td>
<td>4</td>
<td>3</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
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<td>-</td>
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<tr>
<td>Elim Hot Springs</td>
<td></td>
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<td>-</td>
<td>-</td>
<td></td>
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<tr>
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<td>-</td>
<td>-</td>
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<td>3</td>
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<td>-</td>
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<td>-</td>
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</tr>
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<td>5</td>
<td>3</td>
<td>4.0</td>
<td></td>
</tr>
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<td>Bluestone Creek</td>
<td>3</td>
<td>-</td>
<td>2</td>
<td>-</td>
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</tr>
<tr>
<td>Wooley Rd. Creek</td>
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<td>-</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
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<td>4</td>
<td>4</td>
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<td>5</td>
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<td>-</td>
<td>-</td>
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<td>Teller</td>
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<td>4</td>
<td>5</td>
<td>4.0</td>
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<td>-</td>
<td>2</td>
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<tr>
<td>Wooley Rd. Creek</td>
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<td>-</td>
<td>1</td>
<td>-</td>
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<tr>
<td>White Mountain</td>
<td></td>
<td>4</td>
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<td>3.3</td>
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<td>4</td>
<td>1</td>
<td>2</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Niukluk</td>
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<td>-</td>
<td>2</td>
<td>-</td>
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<tr>
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<td>4</td>
<td>-</td>
<td>2</td>
<td>-</td>
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</tr>
<tr>
<td>*Municipal water source.</td>
<td></td>
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</table>
ment may be used to evaluate the adaptability of current communities across the Arctic in response to climate change.

[31] The results from this study could be broadly applied in the Arctic. The permafrost model could be applied wherever adequate information is known about the current climate and landscape. It was shown that permafrost in nearby watersheds, even in a small area like the Seward Peninsula, is expected to respond uniquely to climate change. This puts some communities at risk to significant change in their water resource, while others are likely to experience little change at all. This was certainly the case when comparing the secure water resources of White Mountain to the vulnerable water resources at Golovin. These two communities are only about 40 km apart.

6. Conclusions

[32] This study has considered the vulnerability of a broad range of surface water sources on the Seward Peninsula. Communities with larger groundwater contributions to their water supply, either as base flow in source streams or from wells, should be less vulnerable to hydrologic changes owing to permafrost loss. Not surprisingly, the availability of groundwater in these communities is manifest in their current exploitation of the resource. Conversely, communities that are at risk owing to vulnerable surface water sources do not have groundwater sources available to them. As degrading permafrost may lead to greater surface water loss to infiltration, their future vulnerability may require further exploration of groundwater sources or to establish access to more distant surface waters to augment the water supply.

[33] Five Seward Peninsula communities were evaluated for water resource vulnerability using a vulnerability index. The study results are representative of the Seward Peninsula water resources. However, the methods are generally applicable across the Arctic, and the study has broader implications. Use of the vulnerability index across this region illustrated a framework for classifying a wider range of arctic communities with respect to water resources under a changing climate.

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References


