The Arctic Water Resource Vulnerability Index: an integrated assessment tool for community resilience and vulnerability with respect to freshwater

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ABSTRACT People in the Arctic face uncertainty in their daily lives as they contend with environmental changes at a range of scales from local to global. Freshwater is a critical resource to people and while water resource indicators have been developed that operate from regional to global scales and for mid-latitude to equatorial environments, no appropriate index exists for assessing the vulnerability of Arctic communities to changing water resources at the local scale. The Arctic Water Resource Vulnerability Index (AWRVI) is proposed as a tool that Arctic communities can use to assess their relative vulnerability – resilience to changes in their water resources from a variety of biophysical and socioeconomic processes. AWRVI is based on a social-ecological systems perspective that includes physical and social indicators of change and is demonstrated in three case study communities / watersheds in Alaska. These results highlight the value of communities engaging in the process of using AWRVI and the diagnostic capability of examining the suite of constituent physical and social scores rather than total AWRVI score alone.

Keywords: Arctic; Freshwater; Index; Resilience, Vulnerability

Introduction

The need for communities in the circum-polar Arctic to determine their relative vulnerability to changes in freshwater resources is becoming more urgent. Freshwater is critical to the sustainability of humans in the Arctic, as elsewhere on Earth. Yet, the Arctic presents a challenging set of interacting factors not commonly considered in analysis of water supply and quality, such as the combination of very remote communities with poorly developed infrastructure and high energy costs, a rapidly changing climate, and an often limited abundance of liquid water much of the year.

In the Arctic, the vulnerability of water resources to which communities are subjected occurs at the local scale of small watersheds and the constrained areas in which they traditionally obtain subsistence foods from the land and water. A unique consideration in this environment is the presence of continuous and discontinuous permafrost and corresponding complex interactions in surface water availability. While agricultural activity in the Arctic is not likely to be a factor in the next 100 years, other industrial activities, such as mining have cumulative effects downstream, potentially impacting water supply and quality of downstream communities.

Insolation and solar forcing are more variable and extreme in the Arctic than at lower latitudes due to variation in sun angle and surface albedo throughout the annual cycle. The result of these Arctic climate processes are that ice and permafrost are susceptible to highly variable radiative heating and therefore potential thawing that affect the freshwater cycle and balance. These interactions can also shift icing regimes of small rivers, thus restricting the local water supply and availability regimes.

The case for an Arctic water resource vulnerability index

Currently, no appropriate index exists to adequately assess resilience and vulnerability of people in the Arctic to changes in water resources. This paper describes an initial set of parameters used to establish an Arctic Water Resource Vulnerability Index (AWRVI – pronounced “arr-vee”), which can be used by communities to assess their relative vulnerability or resilience to factors influencing freshwater resources at the watershed scale. Resilience is defined as the magnitude of disturbance that can be absorbed by a system without fundamentally changing it, that is, more resilient systems are able to absorb larger shocks (Holling and Gunderson 2002). When massive transformations occur, resilient social-ecological systems contain the components needed for renewal and reorganization. In other words, they can cope, adapt, or reorganize without sacrificing the provision of ecosystem services. We use resilience and vulnerability as opposite ends of a spectrum denoting the ability of human communities and the ecosystems in which they live to respond to change and maintain the functionality of that social-ecological system. In this paper we propose an index that encompasses a social-ecological systems view, and develop and test the index using three case-studies from Alaskan communities and watersheds.

In the past 30 years, the climate in the Arctic has warmed appreciably and there is evidence for a significant polar amplification of global warming in the future (Overpeck and others 1997; Hinzman and others 2005). Changes in the hydrologic cycle will affect both the presence of surface water and the thermal balance in soil. While preliminary evidence suggests a changing climate will have a significant impact on the hydrologic cycle in Arctic regions (Serreze and others 2000; Hinzman and others 2005), little evidence is available to predict how the quality and quantity of freshwater available to humans is likely to change. Significant changes include later freeze-up and earlier break-up of Arctic rivers and lakes that mirror Arctic-wide and even global increases in air temperature (Magnuson and others 2000; Serreze and others 2000). Since the Arctic hydrologic system is particularly sensitive to changes in rain- and snow-fall, timing of freeze-up and break-up, and the intensity of storm activity, it is likely that much of what has been documented to date, and will be observed in the future, arises from changes in these physical drivers (Hinzman and others 2005). Climate change can be thought of as a top down set of changes which occur over long time periods and broad areas. For example, changes in upstream land use patterns may affect whether a river floods, stays the same, or eventually becomes too shallow to utilize for transport (e.g., barges). Changes in upstream habitats may affect downstream sedimentation, which further change channel form and capacity. Upstream changes to watersheds impact downstream water quantity and quality in a way that can be cumulative. This makes it critical to apply a tool at the local scale that accommodates land use and watershed changes. In developing AWRVI we have worked on an assumption of watershed stationarity in communities, that is, that many of the subsistence communities in the Arctic occupy areas of traditional subsistence gathering and hunting that, within the dynamic bounds of seasonal and annual expansion and contraction, are largely within discrete watersheds (Robards and Alessa 2004).

Little is known about how hydrologic changes will affect the health, sustainability, and culture of humans in the Arctic. Research on human social dynamics indicates that social networks play a central role in the ability of communities to respond to environmental change (Amaral and Ottini 2004). Other research, including our own research with Arctic communities in Alaska (Alessa and others 2007; Alessa and others in press), indicates that the values associated with water may be used as strong indicators of vulnerability or resilience (Reynoldson 1993). A diversity of values in a community means that if changes in a watershed make one set of values untenable, there are multiple other types which can continue to operate. For example, a community which holds a single value type (e.g., subsistence values) will be more vulnerable to change than a community that holds a diversity of values. Similarly with social networks, the more linkages a community shares, the more options it has to respond to change by moving knowledge, goods, or social capital through the network (Robards and Alessa 2004).

Existing Water resource indices

Existing approaches for assessing the vulnerability of water resources and hydrological systems to change have frequently involved global indices of water poverty (Water Poverty Index (WPI) – (Lawrence and others 2002; Sullivan and others 2003)), water scarcity (Basic Human Needs Index – (Gleick 1996; Seckler and others 1998)) or water stress (Water Stress Indicator – (Falkenmark 1989)). Finer scale indices have been developed for assessing water availability (Water Availability Index (WAI) – (Meigh and others 2004)) or water scarcity (Gleick 1996) at the regional level. These indices typically utilize measurements of water inputs, outputs and any shortfall between the two and thus operate as a variation on the water balance equation. As broad scale measures they provide useful ways of quantifying differences in water availability between countries and in some cases between regions. By inference the relative vulnerability in water availability between countries or regions can be determined. The focus of these approaches on quantification of water flow, availability or use, however, means that they are an incomplete approach for assessing the vulnerability of communities to changes affecting water resources (Brenkert and Malone

2005). Those indices that do incorporate social measures (e.g., WPI) either do so at such a broad national scale as to be inappropriate at community watershed scales (e.g., Sullivan 2001) or when applied at the community scale have little or no relevance to Arctic conditions and environments (e.g., Sullivan and others 2003).

Approaches specifically designed to measure vulnerability of water resources include the water resources vulnerability index (WRVI) at the global scale (Raskin 1997), the index of watershed indicators (IWI), (EPA 2002), the indicator of regional vulnerability of water resources to climate change in the contiguous U.S. (Hurd and others 1999), and the hydrological response model for land use and climate change in Southern Africa (Schulze 2000). These approaches help to resolve the coupled effects of global and regional scale perturbations and have been used to identify hydrologically sensitive areas at intermediate regional scales. However, they operate at broad regional scales that do not provide the fine-scale representation at the watershed scale in which communities operate on a daily basis.

The Canadian water sustainability index (CWSI) does provide a finer-scale consideration at the local level by implementing a WPI for evaluating the well-being of Canadian communities with respect to freshwater (PRI 2007). The CWSI includes community capacity indicators as well as the standard physical measures of water availability, supply and demand but does not accommodate the unique characteristics of the Arctic nor focus specifically on vulnerability since it emphases sustainability of agricultural areas of southern and central Canada (PRI 2007).

Methods

We used a framework that builds on existing water indices (including the WAI, WPI, WRVI and the IWI) as well as concepts forwarded by models in other areas of the globe. In developing AWRVI, we adopted the WPI (Sullivan and others 2003) template and established criteria that allow assessment at finer resolutions with a social-ecological perspective (Table 1). This allows a community organization without specialized equipment or training to conduct AWRVI and then identify indicators which may require further elucidation. An indicator is defined as any variable which characterizes the level of vulnerability-resilience to a community in a watershed. The approach parallels vulnerability-resilience assessments that focus on adaptive capacity of societal systems (or capability for social response) and the effects and attributes of locality (Brenkert and Malone 2005).

The details of AWRVI including the construction of sub-indices, constituent indices, indicators and the rating of indicators were arrived at using the Delphi technique (Rowe and Wright 1999) as a means for obtaining a reliable consensus of water experts (including anthropologists, ecologists, geomorphologists, hydrologists, sociologists, and water engineers) with experience in Arctic regions using a series of questionnaires with controlled feedback. The Delphi technique was developed in the 1950s (Brown 1968; Sackman 1974) and is increasingly being used in the development of assessment tools for natural resources (Linstone and Turoff 2002). It can be characterized as a method for structuring information derived from a group of experts so that consensus may be developed on the best available knowledge to deal with a complex problem.

Resilience to change in freshwater resources is a function of both the physical system that drives the functioning of water in the social-ecological system and the social system through which communities perceive, interact and regulate water as a resource and is measured as the average of two sub-indices – physical and social (Table 1). Each sub-index is divided into several constituent indices and these are represented by a series of indicators – the physical index comprises five constituent indices and a total of 17 indicators, and the social sub-index comprises four constituent indices and a total of 8 indicators. An indicator measures the degree of vulnerability (or resilience) for a parameter and is represented on a standardized rating scale that normalizes each indicator (Table 2) where the low end of the scale represents vulnerability to change in water resources, the high end of the scale represents resilience to change in water resources, and the mid part of the scale represents the threshold between vulnerability and resilience.

The criteria for the selection of indicators was relevance to the scale of interest to Arctic communities, relative ease in understanding and implementation that is clearly defined, amenability to existing data or future inventory and monitoring that is balanced and independent of other indicators to minimize redundancy. An initial set of indicators (Appendix 1) was developed by the authors based on existing broad scale water indices (e.g., Water Poverty Index, Water Availability Index, and the Index of Watershed Indicators) and then modified in an iterative process via the Delphi approach resulting in the final suite of indicators that we used (Table 4). While a large number of indicators was possible, those excluded from AWRVI were discarded because they were ambiguous or bimodal in their responses or the information they would capture was present in another indicator which was included. For example, the standard geomorphological metric of drainage density, calculated as the length of streams per unit area divided by the area of the drainage basin (Sreedevi and others 2005), provides a measure of the pattern of the stream network in a watershed. However, watershed runoff, measured as the average annual discharge per unit area, provides a measure of the hydrologic output of the watershed that covaries with drainage density (Lammers and others 2001). In this case drainage density becomes redundant. Thus, correlation between indicators has been minimized within a constituent index and to a lesser extent between indicators within different constituent indices or sub-indices. Efforts to minimize correlative effects within the entire set of indices and indicators meant balancing the development of AWRVI as a pragmatic, useable tool versus a series of completely independent indicators.

Indicators typically represent either the magnitude of a parameter, for example average annual precipitation, or the variability of a parameter, for example the coefficient of variation (CV) for annual precipitation – the ratio of the standard deviation to the mean over the time series analyzed. The break points and threshold level for an indicator were based on the expected minimum and maximum values for the typical distribution of the phenomenon measured in the region. Break points were then taken at percentiles (quintiles since we have used a five-point scale) for linear distributions (e.g., average annual precipitation) and at each order of magnitude for logarithmic distributions (e.g., annual river runoff).

Time-series analyses to support measures of variability utilized a time period greater than any interannual or interdecadal climate phenomena and so where possible a 30 year period was used, this is also the climate normal used by the World Meteorological Organization (WMO), the US National Oceanographic and Atmospheric Administration (NOAA), and the US National Weather Service (NWS). This time-series baseline is dependent on availability of time-series data and so in some situations a narrower timer-series will have to be used.

Weighting and Lack of Data

Indices for disturbance, vulnerability and resource condition often use weighted indices that apply greater importance to particular indicators than others. AWRVI does not attempt to differentially weight constituent indices because it is problematic to determine which indicators and constituent indices are more important. Similarly, it is difficult to determine the magnitude of any difference in importance. For example, it is not possible to determine whether change in precipitation is more important than change in surface water for the natural supply constituent index or whether natural supply is more important than water quality for the physical sub-index. AWRVI comprises a set of indicators that measure a range of parameters for vulnerability of human communities to change in water resources. Also, the AWRVI score alone is not necessarily critical, rather it is the process and the suite of scores that will most likely enhance resilience of a commuity. Thus the physical and social sub-indices, along with the various constituent indices taken together provide a diagnostic of which parts of the social-ecological system in which the community resides and lives contribute resilience versus those that contribute vulnerability.

In AWRVI, with absence of data for an indicator, that indicator is eliminated from the index computation to prevent biasing, by reducing the denominator in a sub-index by one for every indicator that is eliminated. However, the elimination of one or more indicator reduces the level of confidence in AWRVI. To account for this, a measure of confidence is introduced by computing a lack of data score as the proportion of indicators that have no data divided by the total number of indicators (Van Beynen and Townsend 2005). Higher lack of data scores represent less confidence in the AWRVI index rating.

Data Sources

AWRVI is implemented by using, existing public domain databases as much as possible. Examples of such databases for the Alaskan Arctic are given in Table 3. These suggested databases are not intended to be exhaustive, but rather provide examples of what was used for the case study communities where we tested AWRVI in Alaska. Other data sources may exist for some communities, while suggested data sources may be lacking or of unacceptable quality for other communities. Several indicators (e.g., landcover change and permafrost distribution) utilize spatially-explicit data and hence require the application of rudimentary geographic information systems (GIS) tools. Other indicators are based on a categorical rating system (e.g., water treatment technology scale, and water source diversity) that requires municipality or direct community input. The index itself (Tables 1, 2, and 4) is not Alaska specific but sufficiently generic that it has wide-spread applicability in the circum-polar Arctic. We demonstrate the application of AWRVI using case study communities in Alaska that utilizes Alaska specific datasets (Table 3). We acknowledge that there will be variations in the availability and suitability of datasets from country to country that will require testing of the implementation of AWRVI under these different circumstances.

The Physical sub-index

The $AWRVI_{physical}$ sub-index provides a rating of the contribution to the vulnerability of a community from biophysical drivers and moderators of freshwater in the watershed. The sub-index is defined by five constituent indices measuring natural water supply, municipal supply impounded by human infrastructure, water quality, permafrost status, and the extent of subsistence habitat that is water dependent (Tables 1 and 4).

Natural Supply

Natural supply refers to the availability of water in the landscape and includes all surface waters, such as rivers, streams, lakes, ponds, and wetlands, and also precipitation falling over them annually. This index comprises indicators representing the magnitude and variability of precipitation and surface water. Vulnerability in a watershed is exacerbated with decreasing wetland / lake area, decreasing river discharge, and decreasing precipitation (White and others 2007). Resilience in a watershed is maintained by constant or increasing surface water, constant or increasing river discharge, and constant or increasing precipitation (White and others 2007).

Precipitation. Watersheds with low rainfall or snowfall and with greater variability in that precipitation are likely to exhibit greater vulnerability than watersheds with higher precipitation and less variability. Precipitation is measured as the average annual precipitation over a 30-year time-series. Variability in precipitation is calculated by the CV for average annual precipitation over the time-series.

Surface water. Watersheds with little or no surface water and with greater variability in that surface water are likely to contribute more vulnerability than watersheds with greater surface water and less variability. The greater the increase in the percent of the landscape which is surface water, the greater the resilience of the community due to the availability of fresh water through direct access regardless of whether infrastructure currently exists. Surface water storage is calculated as the percentage of the surface area of a watershed that is of a landcover type representing lakes, ponds, rivers, wetlands and other waterbodies. Variability in surface water is calculated as CV for the percentage of surface water over time. Thematic Mapper (TM) satellite imagery provides 30m resolution coverage for some areas of the Arctic dating back to 1972 / 1973 and can provide a sufficient baseline to measure changes at the watershed scale by calculating the percent of loss or gain in wetlands and lakes (Hinzman and others 2005; Smith and others 2005). In other parts of the Arctic where adequate TM coverage is not available historical aerial photographs can provide the necessary baseline for change in surface water providing a 50 year time-series in some cases (Smith and others 2005; Riordan and others 2006).

River runoff. The average annual runoff in the watershed and the CV for that runoff over a 30 year time-series are two indicators of river flow. Watersheds with higher annual runoff and less variability in runoff are more resilient than watersheds with less runoff and greater variability (Lammers and others 2001). Observed responses of Arctic river systems to recent increases in temperature and probable increases in winter precipitation have been somewhat unexpected (ACIA 2005). Changes in summer discharge have occurred, but the summer signal is noisy because of large inter-annual variations due to differences in snow pack and extreme summer rainfall events. More distinct, however, have been changes in base flow, possibly brought about by reductions in permafrost and an increase in active layer thickness due to the warmer temperatures. For example, between 1936 and 1999 an overall pattern of increasing minimum flows were observed in a database of 111 Russian high latitude drainage basins (Smith and others 2005). This change, presumably due to increased groundwater infiltration, permafrost degradation, and possibly precipitation increases has resulted in winter flow rates considerably greater than in the past (Hinzman and others 2005). Increased winter flow rates could have a wide range of impacts, including changes in stream chemistry and aquatic habitat, and increased river icing. Increased winter flow rates may also mitigate cold season water shortages for some communities.

Seasonal variation in water supply. The difference in monthly maximum and minimum river discharge normalized by the monthly mean river discharge allows for an easily determined measure of intra-annual water supply variation. Where there is little variation in month-to-month river discharge the index will tend to 0, that is, the community will be highly resilient to seasonal water supply changes (Lammers and others 2001). In contrast, if all the flow occurred in one month then the value would be very high (approaching 12), and this would be highly vulnerable. This indicator is calculated as $(Q_{max} - Q_{min})/Q_{mean}$ based on monthly time step where Q is the monthly river discharge. Monthly river discharge is available for a large part of the pan-Arctic (Lammers and others 2001).

Municipal Supply

The municipal supply constituent index comprises the per capita water yield from infrastructure (reservoirs and wells), the number of water sources, the type of water treatment technology being used, the cost to access the nearest water source, and the proportion of water infrastructure underlain by permafrost. The greater the total water availability per person from viable wells and other water sources; the better the facilities that are available to treat water for domestic use; the greater the diversity of water supply sources, and; the nearer to a community that its water supply is, the more resilient a community is likely to be (Chambers and others 2007). Generally, the larger the total capacity of a community to store water through periods when water may not be accessible, the more resilient it is to changes in water supply. Similarly, vulnerability is likely to be greater where water availability is low, diversity of water supply is low, treatment technology is poor, and distance from supply is large.

The available water source for many communities in the Arctic is limited to shallow ponds perched on the permafrost aquaclude, seasonal streams and wetlands, or in some cases a lake or river. In most cases where groundwater wells are used, the water is derived from thaw bulbs and may be of limited extent and long-term consistency (Hinzman and others 2005). In large floodplains, wells may be drilled to below permafrost layers with some success. In most areas of the Arctic, however, the permafrost is too deep to drill a water supply well. While water surveys may be conducted in some villages prior to installation of a water collection/intake structure, little is known about the long-term sustainability of the water source or the potential effects of climate change on the quality or quantity of the water in the future. For example, in communities where snow is the source of water for year-round consumption, enough snow must be collected during the winter, treated in the summer, and then stored for consumption the following winter. Snow collection facilities, such as that in Shishmaref, are particularly vulnerable to changes in the snowfall or wind patterns requiring frequent rationing of water (Chambers and others 2007). Severe water rationing can prevent even small commercial operations, such as a tannery, from maintaining or increasing capacity. In areas where wells are drilled beneath rivers or into thaw bulbs, the water can be treated and supplied year round. Water derived from thaw bulbs may be unsustainable however, because these are considered to be highly transient features of Arctic landscapes (Hinzman and others 2005).

Per capita water yield. Yield or availability of municipal water is measured as the total combined yield per person per day from wells, reservoirs, tanks and other human infrastructure used to extract or store water. The threshold range for water yield is 20-100 litres per person per day – below this the yield is considered vulnerable and in excess of this the yield is considered resilient (Chambers and others 2007).

Water source diversity. The more options available to a community the better it is able to respond to change or crisis and so the greater the diversity of water sources a community has available the more resilient that community is (Chambers and others 2007). The categorical rating for water source diversity distinguishes between surface water sources and groundwater sources and combines a count of each type.

Treatment technology scale. Municipal water that is treated before delivery carries less health risk than untreated water and so enhances the resilience of a community. Similarly, waste water and sewage that has undergone treatment before being returned to the watershed, either into streamways or into a landfill, carries less health risk than untreated waste and so also enhances resilience. The categorical rating for treatment technology combines a rating of water treatment (i.e., filtered or not, and chlorinated or not) with waste treatment (i.e., primary, secondary or tertiary treatment) so that a community with a filtered and chlorinated water supply and that has tertiary waste treatment is categorized as highly resilient, while a community with no water treatment and no waste treatment is categorized as highly vulnerable (Chambers and others 2007).

Cost access source. Communities that have a water source nearby that requires little energy for extraction are likely to be more resilient than communities with a nearest water source that is distant from the community. A direct measure of cost is the energy per capita per day required to provide water from the nearest source. The proximity and in particular the energy requirements necessary to access municipal water will also be a function of the hydraulic head, that is the elevation between water source and its destination. As a result the indicator we use is the hydraulic gradient for a community's water source which provides a proxy for the energy necessary to access that source and is calculated as the hydraulic head divided by distance (Domenico and Schwartz 1998).

Water infrastructure on permafrost. Municipal water infrastructure in the Arctic is uniquely at risk to disruption and damage if it is located on discontinuous permafrost since discontinuous permafrost has been especially subject to thawing under recent climate warming and can be expected to be further subjected to thawing under warming projections (Hinzman and others 2005). Communities that have no water infrastructure located on discontinuous permafrost are considered to be highly resilient for this indicator while any community with more than 60% of the infrastructure located on discontinuous permafrost is considered to be highly vulnerable for this indicator.

Water Quality

The water quality of the hydrological system in a watershed is of critical importance to Arctic communities. Communities with access to good quality supplies for drinking and for supporting their subsistence foods can be considered resilient while those communities that depend on poor quality water are more vulnerable. The most direct measures of water quality are based on field and lab testing of water samples from streams and lakes to determine dissolved oxygen content, biochemical oxygen demand, temperature, pH, turbidity, conductivity, nutrient levels (especially nitrates and phosphorus), presence of fecal bacteria (using total coliforms and fecal coliforms), and dissolved organic matter (EPA 1997). However, systematic water quality testing of US Arctic rivers and lakes is rare, and even less so in other parts of the Arctic, and so indirect measures have been chosen to indicate vulnerability from water quality. Those rivers or watersheds that do have water quality data provide a better level of information and therefore decision-making capability than is the case in the absence of any data, irrespective of what that data shows. As a result the number of streams for which water quality data exists is used as one indicator. A second indicator is the number of upstream sites at which industrial activity occurs (e.g., mines) since these are potential source of pollutants.

Water quality data. The percentage of a watershed (or percentage of streams) that have water quality data provides one indirect indicator of water quality. Communities in watersheds that have no water quality data are potentially more vulnerable than a community in a watershed with extensive water quality data. However, because the availability of water quality data is time dependent, that is, available data is likely to be flawed because if it is out-of-date, we have placed a constraint that inclusive data be no more than 10 years old.

Upstream development. The total number of upstream development sites, including mines, landfills, and military sites, provide a second indicator. Greater vulnerability exists where there are more upstream development sites.

Permafrost status

Ice-rich permafrost maintains a relatively low permeability, greatly restricting infiltration of surface water to the subsurface groundwater and has a critical bearing on the vulnerability of Arctic communities with respect to freshwater (Chambers and others 2007). Geophysical surveys, including ground penetrating radar, direct boring with complementary temperature measurements, tree-ring analyses, and benchmark resurveys, reveal that the permafrost is in the process of degrading (thawing with subsequent subsidence of the surface). Extensive thermokarsting (i.e. surface expression of subsidence due to thawing permafrost) is evident in Alaska (Osterkamp and Romanovsky 1999; Hinzman and others 2005), Canada (Camill 2005), and Russia (Frauenfeld and others 2004; Pavlov 2006) although this does not develop in a uniform way.

Permafrost status. The distribution of the type of permafrost in a watershed will either promote resilience for a community or increase its vulnerability. Greater discontinuous permafrost leads to greater vulnerability while greater continuous permafrost or permfrost-free areas will lead to greater resilience (White and others 2007).

Subsistence habitat

In subsistence dependent communities of the Arctic more options for harvest species, that are either directly or indirectly dependent on freshwater resources, are likely to lead to higher resilience (Alessa and others 2008b). Species that are directly dependent on water are fish, most notably salmon, but also whitefish and numerous other aquatic species in rivers and streams. Terrestrial species such as caribou and moose depend on vegetation cover and in turn runoff and precipitation.

Aquatic habitat suitable for the community's main harvest species. A simple measure of aquatic habitat is the percentage of fish recruiting streams in the stream network for the watershed. The smaller the proportion of fish recruiting streams the higher the vulnerability while the greater the proportion of fish recruiting streams the greater the resilience (Lawson and others 2004; Hilborn and others 2007). For the Alaskan case-studies we identified all stream reaches one kilometer upstream and downstream of second and higher order stream confluences as critical salmon spawning and overwintering habitat (Alessa and others 2008b). Different aquatic habitat will need to be identified for communities in different parts of the Arctic.

Terrestrial habitat suitable for the community's main harvest species. A coarse indicator of terrestrial habitat for Alaska is the combined landcover of a watershed that is tundra (suitable caribou habitat) and boreal forest (suitable moose habitat). The more landcover that is in either of these cover types the greater the resilience (Alessa and others 2008b). Different terrestrial habitat may need to be identified for communities in other parts of the Arctic.

The Social sub-index

The $AWRVI_{social}$ sub-index provides a rating of the contribution to the vulnerability of a community from social moderators of freshwater in the watershed. The sub-index is defined by four constituent indices measuring knowledge, community wealth, regulatory capacity, and sensitivity to change (Tables 1 and 4). These indices measure the extent of knowledge, regulation, awareness, and values of change in water resources that enable or prevent communities from responding to change in the freshwater supply. Collectively these indices comprise a sub-index that provides an assessment of the social, economic, and cultural capital (Bourdieu 1996) of the community. Social capital refers to the networks and relationships of influence and support, economic capital refers to availability of economic resources such as cash and assets, and cultural capital refers to forms of knowledge, skills, and education (Bourdieu 1996).

Knowledge Capacity

Accurate and abundant information potentially increases the resilience of communities in the Arctic (Alessa and others 2008a). Indicators in this category include the quality and quantity of traditional ecological knowledge of residents of villages in a catchment and in surrounding areas. Level of education influences ability to assess data, therefore, the index indicates greater resilience with increasing levels of education. Knowledge capacity may expand or shrink with respect to the biophysical environment such that feedbacks between knowledge and the landscape contribute to synergistic or antagonistic changes in the availability of freshwater resources (Alessa and others 2008a). For example, knowledge of a water source may be strongly retained in a population but the resource could become unavailable due to hydrological changes in both quantity and quality (e.g., from upstream land use changes). Conversely, the knowledge of the source could become extinct despite the availability of water or it could emerge in the population after loss of or change in an alternate site.

Traditional knowledge. A community is likely to exhibit greater resilience if a strong cadre of Elders are present (Alessa and others 2008a). This indicator is measured by the number of indigenous people 50 years of age and older per capita (expressed as number per 1000 in Table 4).

Western knowledge. A community's capacity to respond and adapt is likely to be greater if a high level of education is present in the population (Alessa and others 2008a). This is measured by the number of college degrees per capita (expressed as number per 1000 in Table 4) in the community.

Residency. Communities with long-time residents are likely to express a stronger capacity for resiliency since in-situ longitudinal information about water sources and changes in those sources provides a stronger capacity for response (Alessa and others 2008a). This is measured by the number of people with 30 years or more residency in the local area per capita (expressed as number per 1000 in Table 4).

Economic capacity

A wealthy community can potentially buy themselves out of future problems, relative to a poor community, and is thereby more resilient than the poorer community. We use the internal wealth, that generated by households in the community, as a measure of economic capacity and resilience (Rose and Liao 2005). External wealth, for example, government subsidies and grants, does contribute to economic wealth but can also leave a community subject, and vulnerable, to withdrawl of that support so has not been included. A simple and direct measure of community wealth is the per capita income of the community. The higher the per capita income of a community is the more resilient it is likely to be (Rose and Liao 2005).

Social capacity

Institutions are social structures that govern the behavior of communities, identify with a social purpose, and develop and enforce rules that govern cooperative human behavior (North 1991). The term may also be applied to particular formal organizations of government and public service. For the purpose of AWRVI, the level and type of protection in a watershed will either enhance resilience to change or increase vulnerability (Bengtsson and others 2003). Social capacity is determined, in part, by the level of environmental protection and specifically by the extent of protected area or reserve – as used in environmental vulnerability indices (Gowrie 2003).

Protected area status. This indicator measures the proportion of land area in a watershed that is set aside in protected area, park, or reserve. The greater the proportion of land in a watershed that is in protected area status the greater the resilience that is likely (Bengtsson and others 2003). In the case of Alaska this is measured as the percentage of land area in protected area status (state or federal park or reserve) plus the land area in partial protection (e.g., multiple use lands that includes protection) weighted by a half. In other countries of the Arctic this will need to be determined based on national land tenure status.

Cultural Capacity

A number of factors predispose a community to a greater awareness and sensitivity to change, and therefore to being resilient. When water is valued more highly as a resource, communities are less likely to choose options that degrade or threaten it (Alessa and others 2007). Social networking may also increase access to information. Thus, increased links among community members, as well as between communities, that can lead to the dissemination of information is an indicator of increased resilience. Greater perception of change increases the likelihood that communities will respond to change.

Values of Water. Communities that hold diverse social values of water that include those associated with cultural identity and intangible benefits are likely to be more resilient whereas a community in which the values of water are solely utility-oriented (drinking, washing/cleaning, industry) are likely to be more vulnerable (Alessa and others 2007; Alessa and others in press). A diversity of values in a community means that if changes in a watershed make one set of values untenable, there are other types which can continue to operate. For example, if one community holds mainly subsistence values and few other values (e.g., economic diversification, recreation, biological), whereas another holds a diversity of values, then changes in salmon populations will lead to undesirable changes (vulnerability) in the first community, rendering their persistence unlikely without costly intervention, whereas the second community will experience negative effects on well-being, but will have a higher likelihood of persisting. This is measured by the importance of subsistence in a community, as an indicator of traditional and cultural values, using the per capita harvest weight of subsistence foods in the community. In Arctic Alaskan communities this data is available from the Community Profile Database (Table 3).

Network diversity. Strong social networks are likely to increase access to information as well as resource sharing and reciprocal cooperation so that increased links among community members, as well as between communities, can lead to increased resilience (Olsson 2004). Communities that have greater diversity in linkages with other communities are likely to exhibit greater resilience while those communities with few external links are likely to be more vulnerable (Alessa and others 2008a). This is measured by the total number of external community linkages per capita scaled by the logarithm of the population (to reflect increasing network size by order of magnitude of the population). In our community case studies we measured the number of linkages directly via primary data collection, In the case of Alaska there are some existing studies (e.g., Magdanz and others, 2002; Magdanz and others, 2004) that document social network linkages although there is incomplete coverage, and in other circum-polar countries such data is at least as patchy. Potentially any community could gauge this for itself.

Perception of change. Individual and collective perceptions of the environment are an important driving force in the human response and action in the environment (Messerli and others 2000; Alessa and others 2008a). Perception of change is typically a characteristic of individuals rather than entire communities and so many attitudinal measures of perception are not easily aggregated to the community level. We have used the presence in the community of a water action plan as a proxy indicator of a community's awareness and perception of change with respect to water resources. The presence of a water action plan conveys greater resilience, whereas the absence water planning indicates vulnerability. The rating of the status of a water action plan in a community requires input from the community.

Community Case Studies

The Arctic Water Resources Vulnerability Index was applied to three communities in three different locations in Alaska: Eagle River, a satellite community of Anchorage in southcentral Alaska, White Mountain, a community located on the Fish River on the Seward Peninsula, and Wales, a coastal community located on the Bering Straight (Figure 1).

The total vulnerability score for each of the communities is shown in Table 5. Using AWRVI, Eagle River was characterized as "moderately resilient" (Score=0.74), White Mountain was near the "threshold" (Score=0.48) and Wales was "moderately vulnerable" (Score=0.41). In all three cases the lack of data score was 0.04 indicating four per cent or one of 25 indicators could not be computed due to the absence of suitable data (Table 5). These scores provide an overall indication for the context of the community's vulnerability or resilience with respect to freshwater resources. However, as important as the overall AWRVI score, are the scores for the sub-indices which comprise the overall Index. Wales rated as moderately vulnerable on the physical sub-index and near the threshold on the social sub-index. White Mountain also rated as moderately vulnerable on the physical sub-index but moderately resilient on the social sub-index. Eagle River rated moderately resilient on both the physical and social sub-indices.

Evaluating AWRVI

The outcome from the application of AWRVI to the three community case studies was evaluated by community members, agency managers, and scientists using focus groups that were undertaken through a series of workshops held in the communities, the regional hub (Nome) for these communities on Seward Peninsula, and in the Alaska cities of Anchorage and Fairbanks. The qualitative assessment of each focus group corroborated the overall AWRVI scores and the Physical and Social sub-indices for each of the community watersheds.

Discussion

The location of a community is often determined by settlement histories related to the acquisition of resources (Chance and Andreeva 1995). The type of water sources present in the current day are often not under the control of the community. For example, Eagle River's watershed contains several large glaciers and rivers and receives high snowfall each winter. Both White Mountain and Wales are located in low snowfall areas of Alaska (essentially a cold desert). White Mountain's watershed has no glaciers but is located on a large river whereas Wales' watershed contains no glaciers and it is not located on a river. Thus, the Physical - Natural Supply Sub Index for each of these communities (Eagle River, 0.54, White Mountain, 0.33 and Wales, 0.42 – Table 5) reflects the inherent features of the watershed. However, the ability to store, treat and/or transport water (Physical-Municipal Supply) is controllable and may be a way to minimize an objective hazard such as low Natural Supply. For example, both White Mountain and Wales Physical-Municipal Supply scores (0.45 and 0.20, respectively – Table 5) reflect a lower level of infrastructure to store, treat and/or move freshwater resulting in more vulnerability than Eagle River which has a "highly resilient" score for this sub index (0.80 – Table 5).

Physical supply and infrastructure are only a part of the total ability of a community to be resilient. The ability to perceive and understand changes in water supply are key features of successful community responses (Alessa and others 2008a) and depend on a variety of factors which are reflected in the Social Sub Index: Knowledge, Economic, Social, and Cultural Capacities. In these indicators, Eagle River and White Mountain had similar scores reflecting "moderate resilience" (0.77 and 0.63 respectively) suggesting that, despite large physical differences, these two communities are similar in terms of the organization of social capital. Wales' score near the "threshold" (0.54) suggests that either social and cultural capital is not optimally organized or is lacking in one or more of the social key factors, such as a water action plan in the community.

Resilience is ultimately the result of factors which accumulate and interact with each other over time rather than a single or few variables which are easily identified. For example, seasonality in precipitation results in long periods of several months of wetter or drier conditions. A community may be vulnerable to this climatic variability unless they develop infrastructure which can capture and store water during the wet season, resulting in lower vulnerability or even resilience. However, the water infrastructure may also be more or less resilient since, for example, lack of maintenance, changes in permafrost affecting ground stability, and contaminants from upstream land modification, will all affect the effectiveness of infrastructure. Similarly, the use patterns and values of water may lead to more or less water conservation behaviors which feedback to the demands placed on the water infrastructure and the lifestyles of community residents living in a highly variable, seasonal water system. It is the interactions of often seemingly small factors which determine the overall resilience/vulnerability per se of a community to changes in freshwater resources. With this in mind, AWRVI is a new, Arctic-specific tool that gives communities the ability to identify the factors which can aid them in decision-making regarding the use and management of freshwater through both a total assessment as well as by identifying specific areas that contribute to overall resilience or vulnerability. AWRVI is intended to be used by an Arctic community to determine its vulnerability to changes in water resources at the watershed scale but should be used as part of a suite of indicators for assessing and responding to environmental conditions more broadly. Other indicators could include natural hazard assessments, for example. AWRVI is unique because it is designed to be used at the scale in which communities undertake their daily activities, it takes a social-ecological systems perspective by including physical and social indicators of vulnerability / resilience, and it includes measures specific to the physical characteristics of the Arctic region, including permafrost status.

While AWRVI could be applied at any time interval from which time-series and metrics of change can be determined we suggest a time-series sufficiently long enough to account for interannual and interdecadal effects. The 30-year period we have used is sufficient to account for climate cycles such as the Pacific Decadal Oscillation which has an approximately 25-year cycle, but other cyclic effects could have longer periodicity. In many Arctic communities time-series data of 30 years or longer are not be available in which case a shorter time-series would have to be used.

There are a number of ways in which AWRVI and its indicators can be refined. Further work is needed to determine how to include measures of stochasticity of a phenomena in the index, for example, measuring the timing and magnitude of precipitation or flow events would be a useful indicator since salmon runs may be affected by siltation in rivers caused by heavy rains. This vulnerability index and its indicators are the product of an ongoing expert assessment process using the Delphi technique, broader expert consensus of the index internationally would strengthen AWRVI particularly since the role of institutions has been included only to the level for which there is broad consensus in the literature and various communities of practice. Finally, AWRVI needs to be subjected to further testing, application and reiteration for a more extensive range of Arctic communities in the circumpolar Arctic. While AWRVI is designed for arctic environments we have demonstrated and tested the implementation of AWRVI in three case study communities in Alaska. This needs to be expanded to identify comparable datasets that allow the AWRVI framework and indicators to be applied in Canada, Greenland, Iceland, Norway, Sweden, Finland, and Russia.

The United Nations Millennium Development Goal 8 is to ensure environmental sustainability through a series of targets that includes access to safe drinking water and basic sanitation (United Nations 2000). AWRVI is a tool that allows communities in the Arctic to determine their own strategies to changing conditions in water resources at the scale of the watersheds in which they live, subsist, and strive. It provides a means for assessing vulnerability to critical water resource variations and to proactively respond so as to ensure the viability of our coupled social-ecological systems now and for the generations that will follow.

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Table 1: Arctic water resource vulnerability index and sub-indices.

Arctic Water Resource Vulnerability Index:

$$\mathbf{AWRVI} = [AWRVI_{physical} + AWRVI_{social}] / 2$$

Physical sub-index:

$$\mathbf{AWRVI_{physical}} = [AWRVI_{natural\_supply} + AWRVI_{municipal\_supply} + AWRVI_{water\_quality} + AWRVI_{permafrost} + AWRVI_{subsistence\_habitat}] / 5$$

Constituent sub-indices:

$AWRVI_{natural\_supply}$	= f (precipitation, surface water, river runoff)
$AWRVI_{municipal\_supply}$	= f (yield, source diversity, treatment technology, hydraulic gradient, permafrost risk)
$AWRVI_{water\_quality}$	= f (upstream modification, water quality testing)
$AWRVI_{permafrost}$	= f (permafrost distribution)
$AWRVI_{subsistence\_habitat}$	= f (aquatic habitat, terrestrial habitat)

Social sub-index:

$$\mathbf{AWRVI_{social}} = [AWRVI_{knowledge} + AWRVI_{economic} + AWRVI_{information\_capacity} + AWRVI_{sensitivity}] / 4$$

Constituent sub-indices:

$AWRVI_{knowledge}$	= f (traditional knowledge, Western knowledge, residency time)
$AWRVI_{economic}$	= f (community wealth)
$AWRVI_{information\_capacity}$	= f (protected area status)
$AWRVI_{sensitivity\_change}$	= f (subsistence values, social network diversity, perception of change)

Table 2: Rating scale for indicators used in the Arctic Water Resource Vulnerability Index

Rating	Vulnerability-resilience description
0	Highly vulnerable
0.25	Moderately vulnerable
0.50	Threshold
0.75	Moderately resilient
1.00	Highly resilient

Table 3: Data sources for selected Arctic Water Resource Vulnerability Index indicators and parameters for Alaska.

Indicator / parameter	Description	URL
Physical – Natural Supply		
Landcover change	Circumpolar Arctic Vegetation Map (north of treeline) Alaska Statewide vegetation / landcover (1991 AVHRR / NDVI)	http://www.geobotany.uaf.edu/cavm/data/ http://agdc.usgs.gov/data/projects/fhm/index.html#G
River discharge	National Water Information Service (USGS), Real-time Water Data: discharge for selected sites in Alaska	http://waterdata.usgs.gov/ak/nwis/rt
Stream network	National Hydrography Database (USGS)	http://nhd.usgs.gov/data.html
Precipitation and local climate data	National Climatic Data Center, Climate Data Online, Hourly Precipitation Data (for 57 stations across AK)	http://cdo.ncdc.noaa.gov/CDO/mapproduct
Physical – water quality		
Water quality	National Water Information Service (USGS), Water-quality Data for Alaska: field and lab analyses from 4,969 selected sites in Alaska	http://waterdata.usgs.gov/ak/nwis/qw
Physical – water origin		
Permafrost distribution	National Snow and Ice Data Center, Frozen Ground Data Center, Permafrost map of Alaska (1:2,500,000)	http://nsidc.org/data/ggd320.html
Physical – subsistence habitat		
Fish recruiting streams	National Hydrography Database (USGS)	http://nhd.usgs.gov/data.html
Tundra landcover	Alaska Statewide vegetation / landcover (1991 AVHRR / NDVI)	http://agdc.usgs.gov/data/projects/fhm/index.html#G
Social – Knowledge + Economic capacity		
Traditional knowledge Western knowledge Residence time Community wealth	US Census Bureau Decennial Census summary files	http://factfinder.census.gov/servlet/DatasetMainPageServlet?_program=DEC&_submenuId=&_lang=en&_ts=
Social – Informational capacity		
Land tenure	Alaska Department of Natural Resources. Alaska General Land Status	http://fox.dnr.state.ak.us/SpatialUtility/SUC?cmd=md&layerid=114
Social – Sensitivity to change		
Importance of subsistence	Alaska Department of Fish & Game, Subsistence Division, Community Profile Database	http://www.subsistence.adfg.state.ak.us/geninfo/publctns/cpdb.cfm

Table 4: Physical and social indicators for Arctic Water Resources Vulnerability Index

Indicator	Resilience Index rating				
	Highly vulnerable	Moderately vulnerable	Threshold	Moderately resilient	Highly resilient
	0	0.25	0.5	0.75	1.0
Physical – Natural Supply					
Average annual precipitation over recent 30 year period (mm / year)	< 100	100 – 249	250 – 499	500 – 750	>= 750
Variance in annual precipitation over recent 30 year period (σ / x)	> 0.5	0.3 – 0.49	0.2 – 0.29	0.1 – 0.19	0 – 0.09
% surface water storage in watershed	<=0.1	0.2 – 1	2 – 10	11 – 20	>20
Change in % of surface water in watershed over recent 30 year period	> +/- 10	+/- 1 – 10	+/- 0.1 – 1	<+/- 0.1	No change
Average annual river runoff over recent 30 year period (cumecs / km2 / year)	< 0.01	< 0.1	< 1	< 10	>= 10
Variance in annual river runoff over recent 30 year period (σ / x)	> 0.5	0.3 – 0.49	0.2 – 0.29	0.1 – 0.19	0 – 0.09
Seasonal variation in monthly river discharge (Q_{max} - Q_{min} / Q_{mean})	> 8	4 – 8	2 – 3.9	1 – 1.9	< 1

Indicator	Resilience Index rating				
	Highly vulnerable	Moderately vulnerable	Threshold	Moderately resilient	Highly resilient
	0	0.25	0.5	0.75	1.0
Physical – Municipal Supply					
Reservoir & well yield per capita per day (litres)	< 10	10 – 49	50 – 99	100 – 499	>500
Water-source Diversity (number and type)	1 surface or 1 ground	2 surface or 2 ground	1 surface and 1 ground	2 surface and 2 ground	>2 of each
Treatment technology scale	None	Filtered OR chlorinated	Filtered, chlorinated AND 1^{o} waste treatment	Filtered, chlorinated, AND 2^{o} waste treatment	Filtered, chlorinated, AND 3^{o} waste treatment
Water supply hydraulic gradient (m/m, hydraulic head (m) / distance (m)	<-100	<-10	-10 - +0.1	+1.0 - +9.9	>+10.0
% of water infrastructure on discontinuous permafrost	>= 50	40 – 49	30 – 39	20 – 29	< 20

Indicator	Resilience Index rating				
	Highly vulnerable	Moderately vulnerable	Threshold	Moderately resilient	Highly resilient
	0	0.25	0.5	0.75	1.0
Physical – Water Quality					
# upstream development sites (e.g., mines, dumps)	>10	6 – 10	2 – 5	1	0
% of streams with water quality data	0	1 – 24	25 – 74	75 – 89	90 – 100
Physical – Permfrost status					
Permafrost distribution	> 25% dPF	1 – 25% dPF	> 75% cPF	1 – 75% cPF AND 1-75% nPF AND 0% dPF	> 75% nPF
Physical – Subsistence Habitat					
subsistence fish recruiting streams (# per km)	< 0.05	0.05 – 0.19	0.2 – 0.29	0.3 – 0.5	> 0.5
% tundra and boreal forest cover	0 – 19	20 – 39%	40 – 59%	60 – 79%	80 – 100%

Indicator	Resilience Index rating				
	Highly vulnerable	Moderately vulnerable	Threshold	Moderately resilient	Highly resilient
	0	0.25	0.5	0.75	1.0
Social – Knowledge					
Traditional: # people 50+ years of age and Indigenous per capita	< 10	10 – 49	50 – 99	100 – 199	>= 200
Western: # college degrees per capita	< 20	20 – 49	50 – 99	100 – 249	>= 250
Residency time: # people with 30 years + residence per capita	< 50	50 – 99	100 – 249	250 – 499	>= 500
Social - Economic					
Internal community wealth: average household income	< $5,000	$5,000 – 14,999	$15,000 – 24,999	$25,000 – 49,999	> $50,000
Social – Informational Capacity					
Percentage of land area set aside in protected area status	> 5%	> 5 – 15%	>15 – 25%	>25% – 50%	> 50%
Social – Sensitivity to change					
Importance of subsistence: kg per capita of subsistence harvest	<20	20 – 49	50 – 99	100 – 249	>= 250
Network diversity: (# external community linkages / $\log_{10}$ population)	< 5.0	5.0 – 7.4	7.5 – 9.9	10.0 – 19.9	>= 20
Perception: presence of a water action plan in the community	No plan exists		Draft plan exists	Approved plan exists	Plan has been implemented

Table 5: AWRVI index and indicator values and ratings for Eagle River, White Mountain and Wales communities, Alaska.

Index or indicator	Eagle River		White Mountain		Wales	
	Value	Rating	Value	Rating	Value	Rating
AWRVI index		**0.74**		**0.48**		**0.41**
Lack of Data score	1/25	0.04	1/25	0.04	1/25	0.04
PHYSICAL sub-index		**0.72**		**0.33**		**0.27**
Physical - Natural supply		0.54		0.33		0.42
Av. ann. precip. (mm)	183	0.25	439	0.50	936	1.00
Variance in av. ann. precip.	0.24	0.50	0.21	0.50	1.03	0.00
Surface water storage (%)	22	1.00	1	0.25	2	0.50
Change in surface water	no data	X	no data	X	no data	X
Av. ann. river runoff (cumecs / km^2)	0.20	0.50	0.02	0.25	0.60	0.50
Variance in av. ann. river runoff	0.29	0.50	0.82	0.00	0.68	0.00
Seasonal variation in discharge	2.95	0.50	2.55	0.50	2.80	0.50
Physical - Municipal supply		**0.80**		**0.45**		**0.20**
Yield (l)	> 500	1.00	380	0.75	36	0.25
Water-source diversity	>10 wells >10 surface	1.00	1 surface > 2 groundw.	0.75	> 2 surface	0.25
Treatment technology	filtered chlorinated Primary	0.50	not filtered chlorinated Primary	0.25	not filtered not chlor.	0.00
Hydraulic gradient	0.01	0.50	0.36	0.50	< 0.01	0.50
Infrastructure in PF (%)	0	1.00	80	0.00		0.00
Physical - water quality		**0.50**		**0.13**		**0.25**
# upstream development sites	4	0.50	15	0.00	9	0.25
% streams water qual. data	60	0.50	12	0.25	10	0.25
Physical - permafrost		**1.00**		**0.00**		**0.00**
PF distribution	100% nPF	1.00	20% cPF, 80% dPF	0.00	5% cPF, 95% dPF	0.00
Physical - subsistence habitat		**0.75**		**0.75**		**0.50**
Aquatic habitat (%)	0.23	0.75	0.11	0.50	0.08	0.25
Terrestrial habitat (%)	63	0.75	93	1.00	67	0.75
SOCIAL sub-index		**0.77**		**0.63**		**0.54**
Social - knowledge		**0.58**		**0.75**		**0.67**
Traditional (per 1000)	5	0.00	181	0.75	156	0.50
Western (per 1000)	313	1.00	52	0.50	125	0.75
Residency (per 1000)	263	0.75	682	1.00	449	0.75
Social - economic		**0.75**		**0.25**		**0.50**
Per capita income ($)	27000	0.75	10000	0.25	15,000	0.50
Social – inform. cap.		**1.00**		**1.00**		**1.00**
% area in protected status		1.00		1.00		0.75
Social - sensitivity		**0.75**		**0.50**		**0.25**
Subsistence	86	0.50	93	0.50	88	0.50
Network diversity	11.6	0.75	9.5	0.50	7.3	0.25
Perception		1.00		0.50		0.00

Figure 1: Location map of case-study watersheds in Alaska and maps of each watershed; A. Wales; B. White Mountain, and; C. Eagle River.