unexpectedly (Wazney et al. 2018).

So far, most of the studies in northern environments have focused on seasonal to monthly time-scales flows alteration (Ashraf et al. 2018) but have not captured key components of short-term flow fluctuations (Alonso et al. 2017). Recent studies have proposed original methods for characterizing the sub-daily influence of hydropower operations on downstream hydrology in different environments. Among those, Carolli et al. (2015) proposed two simple indicators for characterizing the alteration of natural regimes due to hydropeaking. These indicators have successfully served to identify hydropeaking impacts on a large scale in Northern Europe (Ashraf et al. 2018). In order to better account for ecological criteria, Alonso et al. (2017) proposed a graphical approach to represent the alteration of sub-daily flow regimes. Despite those advances, there is still a need for a comprehensive method that characterizes both the long-term and short-term influences of hydropower operation on downstream hydro-regimes. The objective of the present study is to move forward in that direction by proposing a three-step method for capturing those influences in a Nordic environment, both at the annual and sub-daily levels. The method was tested in the Canadian section of Alsek River watershed, where adverse effects such as winter floods have been reported downstream of the Aishihik hydropower plant.

2 STUDY AREA

The Alsek River originates in southwestern Yukon and flows in the Pacific Ocean. It collects water from the highly glacierized St-Elias Mountains in the western portion of the watershed and from a flatter and almost non-glacierized area in the northern and eastern portions. The upper section of the River, as delimited by the section upstream of the gauging station 08AB001 (Figure 1), flows through Champagne and Aishihik First Nations' traditional territory and Kluane National Park and Reserve (KNPR). A 90-km long section of the Alsek River was designated as part of the Canadian Heritage Rivers System in 1986 (Finkelstein 2006). The 37 megawatt Aishihik hydro plant has been operating since 1975. The Aishihik facility is currently the only hydroelectric facility in the Yukon that can store energy during the summer, when demand is low, to be used during the winter, when demand is high (Yukon-Energy 2019).

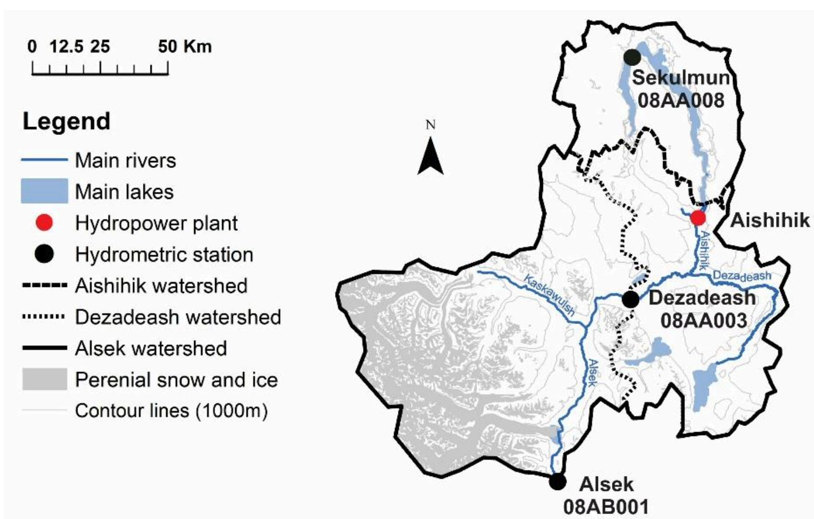

Figure 1. The Upper Alsek River watershed.

Regulation of the Aishihik River flow has been reported to have adverse effects on ecosystems and native wildlife populations since it started (Gill and Cooke 2009). From traditional knowledge of Champagne and Aishihik First Nations, fish population decline, bank erosion at heritage sites and fish habitat destruction are among the most cited negative impacts upstream of the dams (Joe 2004). Downstream of the plant, hydrological regime changes are measured tens of kilometers away from the dams (Joe 2004). Significant water volumes released during the winter are suspected of to enhance freeze-up ice jams and associated flooding. During the winter, massive ice floods in the valley impairing river access to First Nations communities and affecting mobility of wildlife have been observed in kilometers-long transects of the Aishihik River. In other Northern environments, these phenomena have been shown to be associated with hydropeaking. (Timalsina et al. 2013).

3 METHOD

The long-term and short-term influences of the operation of the Aishihik plant on hydrological regimes is assessed by comparing the plant's water release records to historical discharges at two downstream hydrometric stations: Dezadeash River (08AA003), located in Haines Junction, more than 50 km away from the plant; Alsek River (08AB001), located in the KNPR, approximately 150 km away from the plant.

The hydrological regimes of the Aishihik, Dezadeash and Alsek rivers are first characterized by calculating average monthly specific discharges. Differences from the natural regime are evaluated using two hydrometric stations as reference. The Sekulmun River station (08AA008), located just downstream of the non-regulated Sekulmun Lake within the Aishihik watershed, can be seen to be representative of what the natural regime would be at the outlet of the Aishihik lake. The Wheaton River station (09AA012), located within a primarily non-glacierized watershed at around 170 km in the southeast of the Aishihik plant, is used as a reference for the free unconstrained nival regime. Specific discharge calculations were performed for the years 2004-2015, a time window of records availability for all of the studied stations. Discharge time series and associated metadata originate from Environment and Climate Change Canada (2017) with the exception of Aishihik hydropower plant water release data, which were provided by Yukon Energy. Both daily and hourly time steps records are used in the study, although available hourly data for the Dezadeash and Alsek Stations are limited to the mid-spring to mid-fall period of the year, when the influence of the plant's releases on downstream flows is at its minimum.

Table 1. Hydrometric stations

Station #	Name	Lat. (N)	Long. (W)	Area (km^2)	% Glaciers
(Y.E.)	Aishihik plant	61° 02' 07"	137° 03' 16"	2,779	≈ 0
08AA003	Dezadeash	60° 44' 53"	137° 30' 30"	8,386	0.3
08AB001	Alsek	60° 07' 05"	137° 58' 39"	16,136	13
08AA008	Sekulmun	61° 33' 37"	137° 32' 14"	1,240	≈ 0
09AA012	Wheaton	60° 07' 40"	134° 53' 01"	864	1

Hydrological regimes were then further explored by calculating the relative contribution of the Aishihik plant's releases to the discharge measured at both the Dezadeash and Alsek Stations. Comparing monthly relative contributions to yearly ones allows for identification of the months of greatest natural flow perturbations.

Finally, the influence of the diurnal variability of the Aishihik plant's releases on the downstream stations is assessed by applying Fast Fourier Transform (FFT) filters to hourly measurements (Fleming et al. 2002). FFT filters are applied using a moving window of 128 hours. The filters extract and convolute signals of the 2 harmonics closest to the 24 hours period. The amplitude and phase angle (expressed as time to maximum discharge) of the recomposed signal are calculated for the central 24 hours of the time window for each segment of the time series (see illustration in Figure 2). Because a multiday time window is used, calculated amplitudes are anticipated to be lower than the discharge variations measured at the stations. In order to account for meaningful events only, days with very low amplitude variations (less than 1% of the average discharge) and/or days with low to moderate releases from the plant (discharges below $1m^3/s$) are removed from the dataset. A comparison is made between meaningful amplitudes of the Aishihik plant and a downstream station by conducting a correlation study on 20 days moving windows. Correlation presenting an R^2 over 0.8 and a p-value under 0.05 are considered as strong. A transit time is estimated by comparing the time to maximum discharge of both signals. Consistency in transit time results can be seen as an indicator of method robustness.

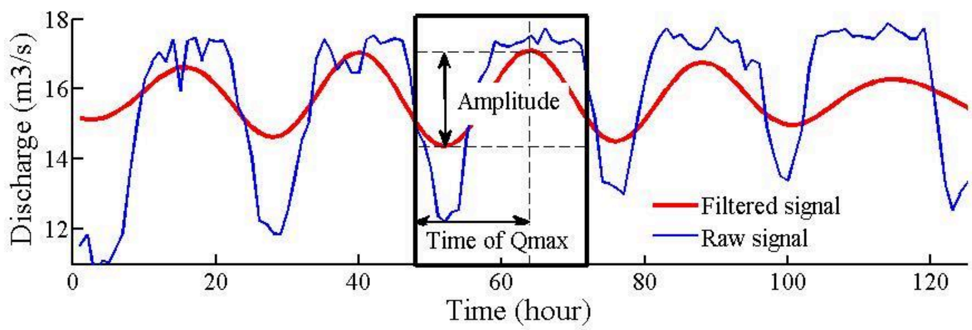

Figure 2. Illustration of FFT filter application. The black rectangle denotes the segment considered for calculation of the amplitude and of phase angle, referred to as the time of maximum discharge. The blue line represents the original signal, and the red line represents the filtered signal.

4 RESULTS AND DISCUSSION

4.1 Hydrological regimes

Figure 3 shows the average monthly specific discharges for five discharge measurement points. Station 09AA012, used as reference for the unconstrained nival regime, is characterized by a specific discharge of approximately 0.1 mm/d from December to April, followed by a peak discharge in June that corresponds to the apogee of the snow melt period. July to October discharges are characterized by a gradual decrease from 0.8 to 0.4 mm/d. The influence of a major lake within the watershed is noticeable when comparing the Station 08AA008 regime to that of Station 09AA012. Both watersheds show similar behavior during the winter and early spring. During the summer, the Sekulmun Lake buffers high flows period by storing part of the discharge associated with snow melt and releasing it during the following months.

The Aishihik plant's release regime differs from these two natural regimes. It shows specific discharges from December to March to be among the highest of the year, with values exceeding 0.4 mm/d. June, the month of highest discharge in the comparable watershed, is the lowest of the year at Aishihik plant. Because the Dezadeash watershed contains several large lakes, its specific discharge would be expected to plot between the curves for Station 08AA008 and Station

09AA012 if it were not influenced by the operations of the Aishihik plant. This is not the case during the winter months. With specific discharges between 0.25 and 0.3 mm/d, discharges at the Dezadeash Station are well above those of the two references. The situation during the summer and fall looks closer to the references. The Alsek River, which is highly glacierized, exhibits the highest specific discharge from June to October. From December to April, its specific discharge remains at the same level as that of the Dezadeash. The lack of reference for a glacierized catchment does not allow for further interpretation related to that station.

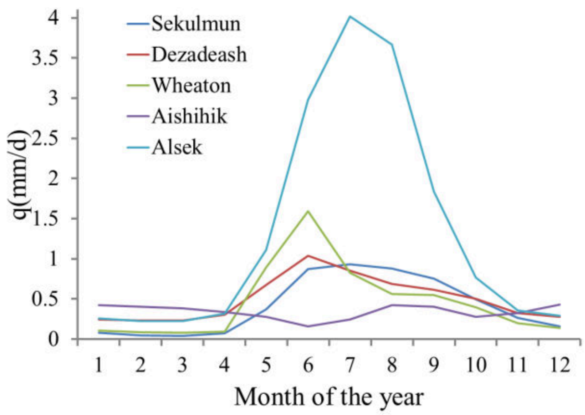

Figure 3. Average monthly specific discharges for 2004-2015.

4.2 Monthly Aishihik contributions to downstream discharge

The relative contributions of the releases from the hydropower plant to the downstream rivers at the Dezadeash and Alsek Stations are presented in Figure 4.

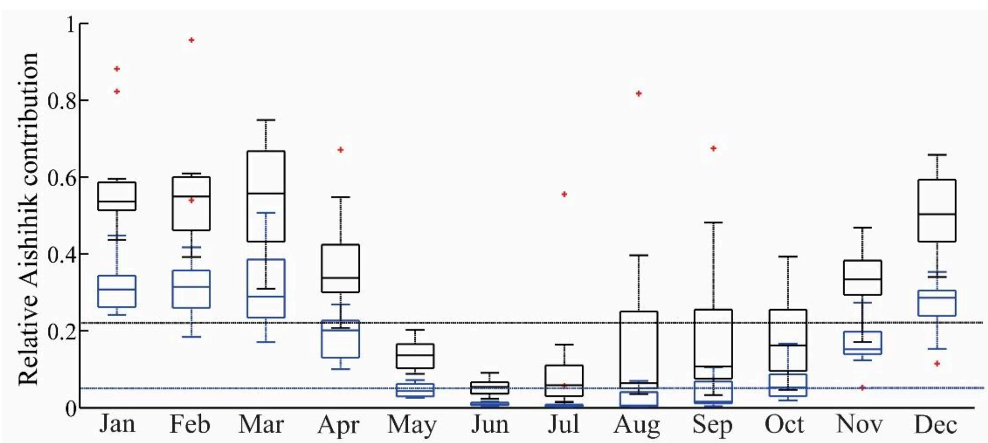

Figure 4. Relative contributions of the Aishihik plant's releases to the discharge at the Dezadeash Station (Black) and at the Alsek Station (Blue) for the 2004-2015 period. The boxes represent the 25th, 50th (median value) and 75th percentiles of the monthly contributions and the dashed lines represent yearly averages.

On a yearly basis, the Aishihik plant's releases represent approximately 23% (median value) of the total discharge measured at the Dezadeash Station. From December to March, the median contribution at Dezadeash is above 50%, which is well above the yearly average. In contrast, from May to October, the Aishihik contribution to the Dezadeash flow remains at a level lower than the yearly average. The lowest relative contribution occurs in June, the month with the lowest releases from the plant and the highest runoff in the rest of the Dezadeash watershed. Figure 3 confirms that the winter discharge at Dezadeash is highly influenced by operation of the Aishihik plant. With more than 50% (median) of its discharge consisting of Aishihik releases, the Dezadeash winter discharge is much higher than the 33% that the Aishihik watershed surface represents for that of the Dezadeash.

The relative contribution pattern at the Alsek Station is similar to that at the Dezadeash Station, although the lowest relative contribution of Aishihik to the discharge occurs in July, the month of peak discharge in glacierized catchments. At the Alsek Station, the contribution of Aishihik releases reaches 30% of the discharge between December and March, exceeding what is expected when considering that the Aishihik watershed surface represents approximately 17% of the Alsek one. The contribution during those months is well above the yearly average, which is approximately 5%.

4.3 Diurnal oscillations

Results of the FFT application are presented in two steps. Firstly, detailed results are presented for the year 2010, followed by a summary of the entire study period. The year 2010 was chosen because it is one of the years in which diurnal variations are most observable.

Figure 5a presents signal amplitudes for the three discharge measurement points for 2010. It shows a contrast between a period of low to moderate amplitudes (days 160 to 280) and a period of high amplitudes (rest of the year) for releases from the Aishihik plant. The Dezadeash and Alsek curves only cover a limited period of the year. This situation, arising from that lack of hourly data available for those stations, mainly limits the comparison of diurnal variations to the period of low to moderate amplitudes for Aishihik releases. Despites those limits, Figure 4a shows similarities in curve shapes between the Dezadeash and Aishihik watersheds between days 160 and 270. These similarities are not observable or less observable for days 120 to 160, a period that corresponds to the spring freshet, and therefore, to high natural flows in the Dezadeash watershed. Figure 5b visually confirms that a correlation exists between signal amplitudes at both measurement points, especially for low amplitudes. The average difference in time of maximum discharge for the day 160 to 270 period is 15 hours, which is a realistic number considering the distance between the two measurement points.

Similarities between the river discharge and the amplitude variations of the Aishihik plant's releases are not observed for Alsek during 2010. The absence of correlation between both datasets is confirmed by Figure 5c. This lack of similarity cannot be interpreted as an absence of hydropeaking influence at the Alsek Station as the record period is the one of highest specific discharge (Figure 3) and of high natural diurnal oscillations in glacier melt water input. No average difference in time of maximum discharge was calculable for the Alsek Station. Table 2 presents the results of an analysis of all available years following a similar procedure as for 2010. "Number of days considered" represents the number of days for which diurnal oscillations were measured at both Aishihik and at the corresponding downstream station.

"Number of correlations" represents the number of 20-day periods with strong correlation (R^2>0.8 and p-value <0.05) in diurnal fluctuation amplitudes. Finally, "Δ Time of Qmax" represents the average difference in time of maximum discharge for periods of strong correlation.

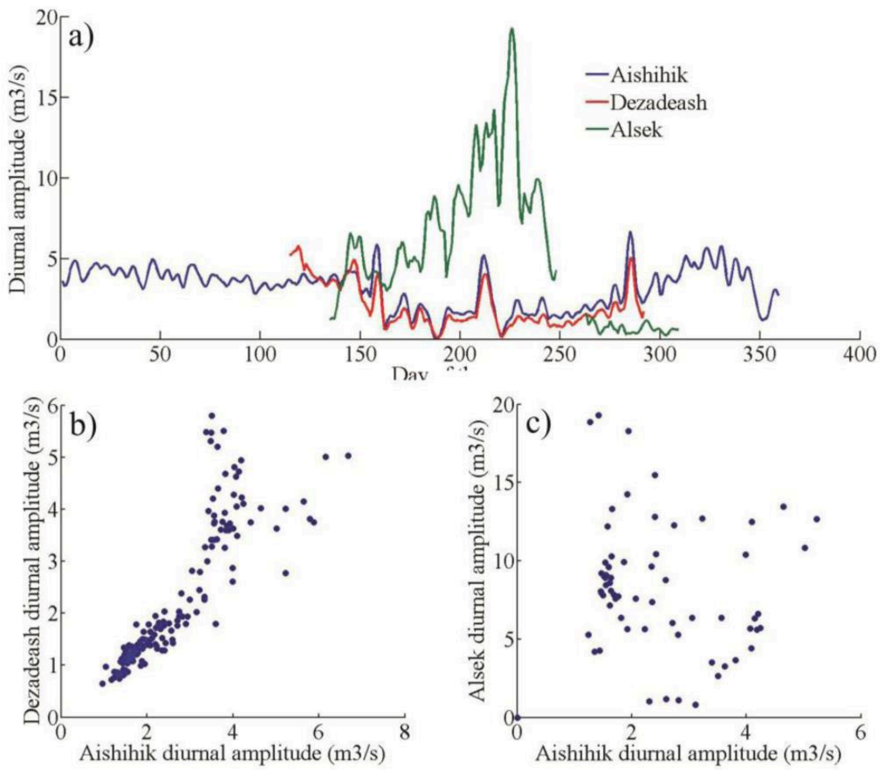

Figure 5. a) Comparison between filtered diurnal amplitude signals at the Aishihik plant (blue), Dezadeash (red) and Alsek (green) for the year 2010. b) & c) present scatter plots of the amplitude at the Aishihik plant and at Dezadeash and Alsek Stations respectively.

Table 2. Correlation of diurnal oscillations between Aishihik and downstream stations.

	Dezadeash			Alsek		
Year	# of days considered	# of correlations	Δ Time of Qmax	# of days considered	# of correlations	Δ Time of Qmax
2004	119	59	16	34	0	-
2005	116	63	14	77	1	-
2006	95	32	14	59	0	-
2007	121	30	13	94	8	-
2008	129	57	13	97	8	-
2009	122	25	17	56	7	-
2010	162	106	15	65	0	-
2011	66	29	14	88	0	-
2012	87	36	13	80	2	-
2013	62	14	13	100	4	-
2014	na	na	na	86	2	-
2015	75	26	14	50	0	-
Total	1154	**477 (41%)**		886	**32 (4%)**	

Table 2 shows that, despite data availability limitations, the influence of the daily fluctuation of water releases from the plant is detectable at Dezadeash every year during the study period. Even though 2010 was a year with a high number of strong correlations, we observe that the phenomenon described for that year occurs over the entire study period. Since the results are being highly dependent on the availability of data, the correlation periods cannot be considered as reflecting the level of influence that the Aishihik plant's water release may have on the Dezadeash flows for a given year. Interestingly, the time of maximum discharge is very consistent from year to year for both stations, thus providing confidence in the reproducibility of the method.

5 CONCLUSION

Overall, this study shows that water releases from the Aishihik plant have a high influence on the Dezadeash discharge measured at Station 09AA003 at both the monthly and sub-daily levels: i) The average Dezadeash River discharge has been more than double what its natural level would be during the winter over the study period; ii) the effects of hydropeaking are clearly present in the Dezadeash discharge time series, even for months when operation of the plant is limited. During the winter, the Alsek River discharge measured at Station 08AB001 is influenced by the Aishihik hydropower plant to. Unfortunately, the lack of data for comparison does not allow for a precise estimate of the degree to which the winter discharge exceeds its natural regime. No sign of correlation between the diurnal variations at the hydropower plant and at the Alsek Station has been observed in the available records. However, this cannot be interpreted as the non-existence of such a correlation. Further research is recommended for that site. Results show that FFT filters applied to a multiday time window can be a useful method for characterizing the influence of hydropeaking on downstream discharge.

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Geospatial Snow Estimation for Engineering Applications and Operations

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ABSTRACT

The U.S. Army Corps of Engineers supports accurate terrestrial, atmospheric, and environmental awareness from tactical to global scale in support of its national security, international development, and humanitarian functions. Moreover, the Cold Regions Research and Engineering Laboratory specifically estimates geospatial snow properties in support of the Corps civil works mission which include managing waterways in snow impacting watersheds, winter vehicle mobility, and other national intelligence functions. Snow is a spatially and temporally evolving medium that has a diverse set of impacts on engineering applications and operations. While some operational organizations provide general snow information with a regional to global perspective, the time and length scales do not match tactical or engineering requirements. Fine-scale spatial representation of snow requires observations or simulation of several snow characteristics including snow depth, density, albedo, stratigraphy, microstructure, and temperature. The Remote Snow Assessment Team at the Cold Regions Research and Engineering Laboratory has addressed user needs through the use of a combined multi-sensor, modeling framework to improve global snow characterization and enable assimilation of remotely sensed observations. Case studies from both military and civil works applications are highlighted showing successful methods developed to provide high spatial/temporal resolution snow products, snow climatologies from historical analyses, and solutions to solve snow issues with respect to water resource management, flood hazard assessment, and winter mobility modeling.

KEY WORDS: Characterization, modeling, remote sensing, snow.

1 INTRODUCTION

The U.S. Department of Defense (DoD) requires global terrestrial, atmospheric, and environmental awareness to support civil works and warfighting functions. Snow is a critical component of environmental awareness that can change rapidly and profoundly impact DoD operations. Domestically, the U.S. Army Corps of Engineers (USACE), under the auspices of the DoD, requires information on snow to develop accurate and timely hydrologic forecasts for water resource allocation, infrastructure design and construction, and flood forecasting. On 30 to 50% of Earth's land area, runoff processes are dominated by snow in mountainous, temperate, boreal, and Arctic environments. Abroad, the Army requires snow information for mission planning and operations. Army warfighter functions are impacted by snow in ways ranging from hampered mobility to limited sensor performance. These impacts are highly dynamic because snow is a spatially variable and temporally evolving boundary condition. Accurate and timely snow condition information is critical to mitigating these impacts.

2 SNOW DATA REQUIREMENTS: MILITARY AND CIVIL WORKS

The impacts of snow on the US Army's military and civil works functions are summarized in terms of three task groupings that crosscut functional areas: sensor performance, mobility, and infrastructure. Each of these task groupings requires a specific set of snow property information to mitigate impacts on operations, which are discussed in more detail below. A command structure requires tools that integrate snow information seamlessly into the planning process to maximize success across all functions. Snow information needed for domestic civil works and stability operations is similar to that required by sustainment operations, and is therefore grouped with infrastructure. The relationship between primary mission planning variables and scientific snow metrics are listed in Figure 1. Each variable is characterized by timescale requirements (i.e. real-time, forecast, and climatology) as well as specific snow variables (i.e. flux, amount, and physical properties). Snow variables related to flux include snowfall rates; those related to amount include snow-covered area (SCA), snow depth, and snow water equivalent (SWE); and those related to the physical properties of snow include optical properties across the visible through infrared portion of the electromagnetic spectrum, snow wetness related to its dielectric properties, snow microstructure at the grain scale, and indices of snow strength.

					Snow Variables							
		Timescale			Flux	Amount			Physical Properties			
Task	Decision Support Variable	Real-time	Forecast	Climatology	Snowfall Rates	Snow Covered Area (SCA)	Snow Depth	SWE	Optical Properties	Wetness	Micro-structure	Strength
Sensor Performance												
Target/Adversary Detection	Sensor efficacy, radar, electro-optical signatures	X	X		X		X	X	X	X	X	
Force Concealment	Camouflage efficacy, background electromagnetic signatures, acoustic attenuation	X	X	X	X		X	X	X	X	X	
Terrain Analysis	Ground state, terrain/ vegetation discrimination	X	X	X	X	X	X		X	X	X	
Buried Threat Detection	Thermal and radar signal attenuation	X			X		X	X		X	X	X
Surveillance Sensors/Mine performance	Burial, tripwire function	X	X				X					
Communications	Signal attenuation	X			X		X	X		X	X	
Mobility												
Austere Entry												
Over Snow Travel	Snow load bearing capacity, traction, depth	X	X	X	X	X	X			X	X	X
Avalanche Hazards	Snowpack Stability	X	X		X	X	X			X	X	X
Helicopter Landing Zones	Rotorwash/visibility, snow load bearing capacity	X	X		X	X	X				X	X
Travel on Improved Surfaces												
Surface Movements	Trafficability, Snow Removal needs, Visibility	X	X		X		X					X
Aircraft Landings	Visibility, Snow depth	X	X		X		X					X
Vehicle Design	Traction, Rolling Resistance			X		X	X				X	X
Military Infrastructure/Civil Works/Stability Operations												
Emergency/Flooding Management	Melt discharge/river flow rates	X	X	X				X		X		
Structure Design	Snow Load, Drainage needs	X	X	X			X	X				
Irrigation/Hydropower Management	Melt discharge/river flow rates	X	X	X				X		X		
Road Construction and Maintenance	Snow timing and depth	X	X	X	X	X	X					

Figure 1. The relationship between primary mission planning variables and scientific/engineering snow metrics.

3 SNOW ESTIMATION APPLICATIONS

Substantial scientific efforts have been made to understand, observe, and predict snow characteristics, including all of the identified properties required for DoD decision support. The