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GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8401

Contemporary glacier area changes in the Ragged Range, Northwest Territories, including Nahanni National Park Reserve of Canada

M. Ednie and M.N. Demuth

2018

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Summary

Geological Survey of Canada Open File 8401 presents an analysis of recently documented glacier area changes for the Ragged Range, Northwest Territory, including the glaciers of Nahanni National Park Reserve of Canada. Utilizing uniform methods from a previous analysis – 1982-2008 – glacier morphometry was updated with 2017 satellite imagery. Analysis reveals that currently there are 345 individual glaciers in the Ragged Range region covering a total area of 204.5 km^2. Between 2008 and 2017, the overall surface area decreased by ~34 km^2 while the population increased by 4 glaciers. The increase in the number of glaciers during the last 8 years is attributed to fragmentation of larger glaciers into multiple smaller glaciers. It has also been determined that the rate of total area contraction has increased – from -2.9 km^2 a^{-1} during 1982-2008 to -3.8 km^2 a^{-1} during 2008-2017.

Terminal region of the Bologna Glacier, Nahanni National Park Reserve of Canada. Dana Haggerty photograph, 2008-August-30.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Changes in the configuration of glaciers in many of Canada's Arctic and alpine regions play a significant role in regional and global sea-level change (f.ex., UNEP/WGMS, 2010; IPCC, 2013; Van Wychen et al., 2014; Clarke et al., 2015; Zemp et al., 2015) and modulate mountain runoff that impacts natural and human system functioning (f.ex., for Canada's western Cordillera, see Moore and Demuth, 2001; Demuth et al., 2008; Comeau et al., 2009; Moore et al., 2009; Marshall et al., 2013). Employing its Reference Glacier-Climate Observing System (Appendix A), the Geological Survey of Canada (GSC) issues data reports and research on the state of Canada's glaciers. These efforts, in part, contribute to Canada's international commitments towards the goals of the United Nations Framework Convention on Climate Change.

As it concerns protected areas generally and Canada's system of National Parks and Reserves specifically, decadal changes in the glacier cover configuration has landscape, public safety, visitor experience and ecological significance. Such changes will modify the thermal and hydraulic properties of streams and rivers derived from glacier melt and wastage which, in turn, exert a significant regulation of water quality for highly adapted biota, as well as influencing stream morphometry and related habitats (Petts et al., 2006). Further, glaciers are significant to the distribution of grazing and predator species; their presence generating strong katabatic wind flow which helps to reduce insect harassment of ungulate populations. Glaciers that flow over significant topographic barriers may also provide travel corridors for wildlife and humans between valleys that are preferentially sought out during seasonal fluctuations in the weather (f. ex., Demuth et al., 2014).

A component of the GSC's monitoring strategy is based on periodic glacier inventory measurements, where glacier morphometry and situation in the landscape are documented using remote sensing. Such data compliments more detailed assessments of the nature of the climate forcing that modulates the seasonal and annual mass balance of glaciers and ultimately leads to dynamic readjustment of the glacier surface and its margins (details in Demuth and Ednie, 2016). Using recently documented glacier area delineations for 2017, this report details the morphometric changes in the glaciers of the Ragged Range since the 1982-2008 analysis provided by Demuth et al., 2014; and further illustrates the control that glacier size and landscape situation appears to have on those changes.

2. Definitions – Quantifying Glacier Fluctuations

The fluctuation of a glacier under the influence of climate (precipitation, air temperature, solar radiation and cloud cover) can be described using various measures and metrics associated with its geometry (length, area and thickness), flow, surface facies expressions/glaciological zones, and mass change (*Figure* 1).

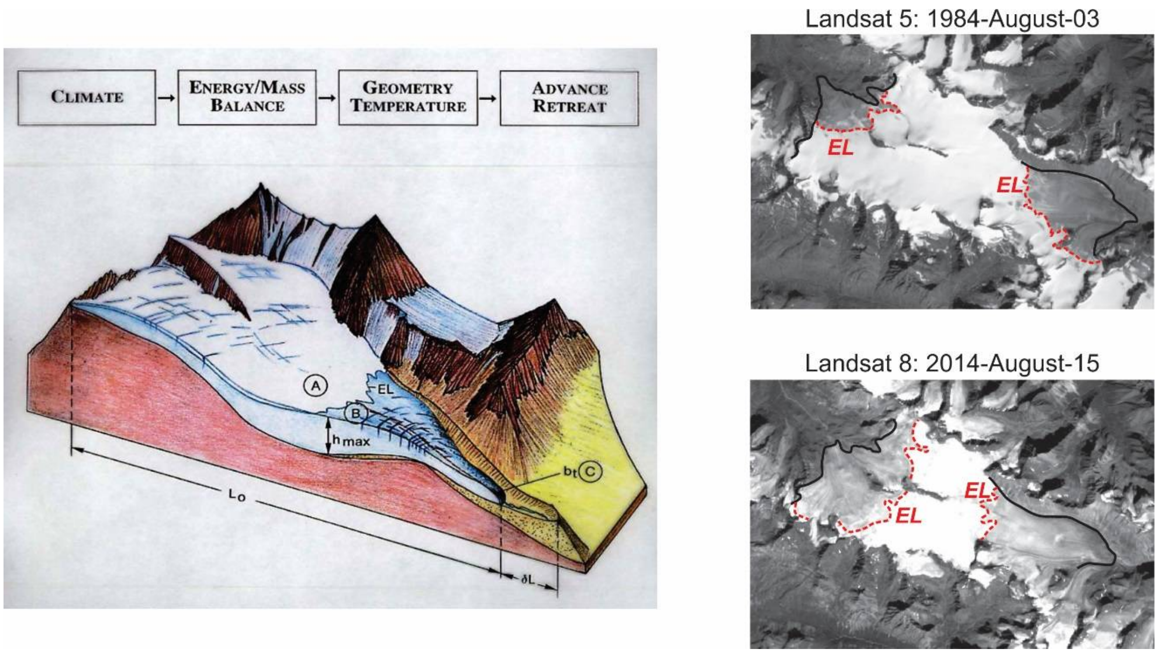

*FIGURE 1. A TYPICAL ALPINE GLACIER FEATURES NET ACCUMULATION AND NET ABLATION ZONES DIFFERENTIATED BY AN EQUILIBRIUM LINE (**EL**). ABOVE THE EL LAY THE SNOW AND FIRN FACIES OF THE ACCUMULATION AREA Ⓐ; BELOW IT THE ICE FACIES OF THE ABLATION AREA Ⓑ. LATE-SUMMER LANDSAT IMAGES OF THE BRINTNELL-BOLOGNA ICEFIELD IN NAHANNI NATIONAL PARK RESERVE ILLUSTRATE CONTRASTING FACIES CONFIGURATIONS AND ACCUMULATION AREA SIZES (DEMUTH AND EDNIE, 2016)*

2.1. Glacier Area

Repeat inventories of glacier area, along with extensive process oriented mass balance studies, are important components in coordinated glacier observation networks (Haeberli et al., 2000). Changes in a glacier's area are the net result of dynamic readjustment following mass being added and taken away by the processes of accumulation and ablation respectively. Accumulation can result from precipitation, condensation, drift snow or avalanching; while ablation results from melt, sublimation, or avalanching (commonly ice calving from the glacier margins). Measurements of glacier area spanning sufficiently long time intervals reflect a low-pass filtered perspective of a glacier's health which is linked to climate (f.ex., Barry, 2006; Pelto, 2006). A glacier's size and its situation in the landscape can, amongst other factors, control its rate of growth or contraction and therefore, glacier area changes must be assessed with complimentary information describing large-scale topography and its effects. Examples include shading from short-wave solar radiation, long-wave emissivity from surrounding terrain that is snow-free, and the role of drift and avalanching snow accumulations as discussed by Demuth and Pietroniro, 2002; Granshaw and Fountain, 2006; DeBeer and Sharp, 2007; Demuth et al., 2014 and Steiner et al., 2015).

3. Study Region – Ragged Range and Nahanni National Park Reserve of Canada

Nahanni National Park Reserve (NNPR) of Canada is located at ca. 61° 30' N, 125° 30' W in the northern section of the cordilleran physiographic region, in the southwest corner of the Northwest Territories (NT), and extends generally along the Yukon-NT border Figure 2). Covering an area of approximately 30,055 km^2, and ranging in elevation from 180 to 2,773 m asl., NNPR exhibits a wide diversity of flora and fauna that reside in three dominant *life zones* or landscape units – montane, subalpine and alpine. The large altitudinal range within NNPR is the main agent of variability as it concerns the differences in biodiversity between these units, though local terrain characteristics can create local micro-climates and hydrological and ecological niches.

NNPR includes in its northwestern extent, the Ragged Range, the Sunblood and Dall Ranges to the northeast, the Ram Plateau and Tlogotsho Range to the East, and the northward flowing source tributaries of a portion of the Flat River to the South. After leaving its alpine headwaters, the South Nahanni River flows east-southeast through the broad gap between the Ram Plateau and the Tlogotsho Range, and empties into the Liard River near Nahanni Butte. The Liard River joins the Mackenzie River at Fort Simpson, eventually flowing through the Mackenzie Delta, and out into the Beaufort Sea and the Arctic Ocean.

The region supports several hundred glaciers – the majority of which are small mountain glaciers that surround the region's only icefield, the Brintnell-Bologna Icefield [1] (Figure 2).

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[1]The name "Brintnell-Bologna Icefield was coined in Demuth et al., 2014 to colloquially represent this feature, and is not vetted as an official feature/place name by the Canadian Geographical Names Board.

Small niche and hanging glaciers are found to the northwest and southeast of aforementioned main concentration of glacier cover.

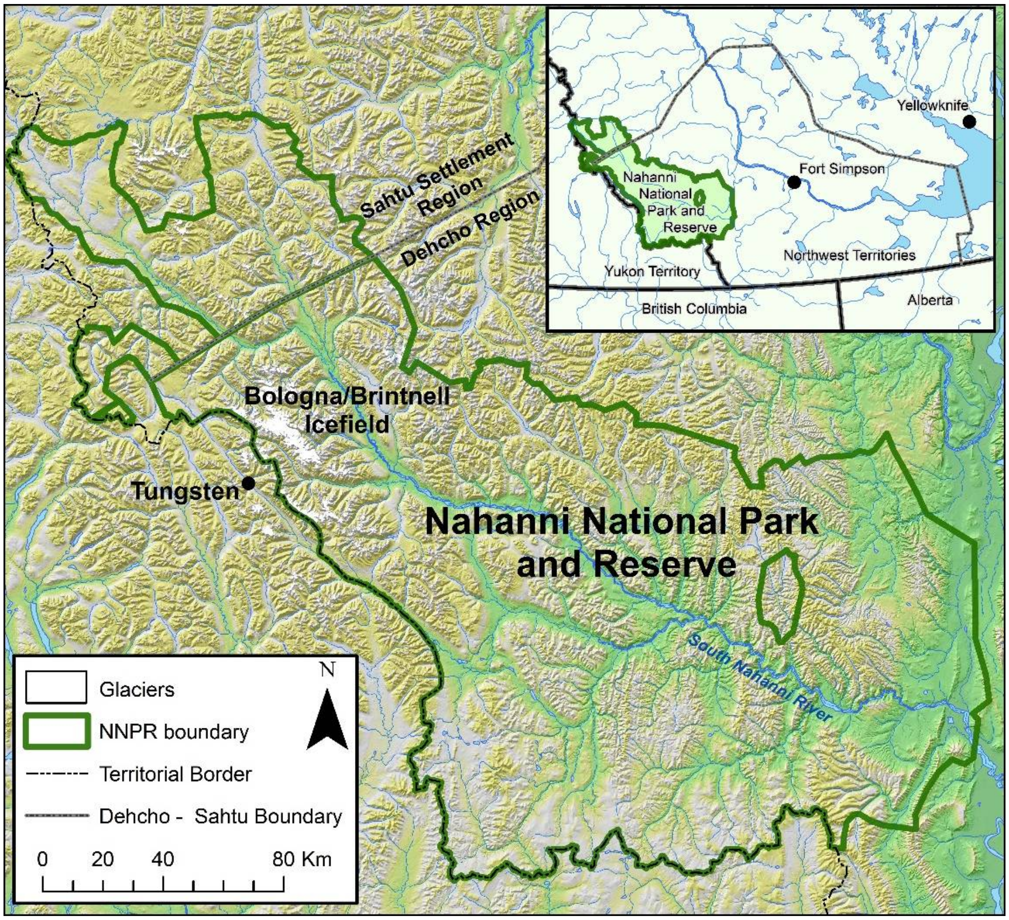

FIGURE 2. LOCATION OF NAHANNI NATIONAL PARK RESERVE AND THE BOLOGAN-BRINTNELL ICEFIELD REGION

The mean annual air temperature within the main concentration of glacier cover is estimated to be c. –6.5 °C (see Anderson, 2017 for details). The region's snow cover can be described as generally *continental* with the region's glaciers typically receiving c. 600 mm w.e. annually (see f.ex. Anderson, 2017). Recent work, however, has determined that, at the storm cycle scale, it is maritime moisture plumes having their origins in the Gulf of Alaska that account for the majority of sub-seasonal snow accumulation events (Courtin, 2018).

Additional details on the glaciers of the Ragged Range can be found in Demuth (2007), Demuth et al., (2014) and Anderson (2017).

4. METHODS

The present study builds on previous Ragged Range glacier inventories and change detection analyses conducted by Demuth et al. (2014) between 1982 and 2008.

4.1. REMOTE SENSING

Glacier extents in 2017 were delineated from Landsat 8 OLI imagery obtained from the USGS Global Visualization Viewer (GloVis) courtesy of U.S. Geological Survey. The two Landsat 8 L1TP type scenes used were acquired on September 7, 2017 (path 54, row 16) and September 30, 2017 (path 55, row 16). The selected scenes were acquired in late summer to ensure minimum snow cover that would potentially obscure glacier boundaries. The two scenes were corrected for top of atmosphere reflectance and ground reflectance using PCI Geomatica.

A Normalized-Difference-Snow-Index (Hall et al., 1988) and a false color composite image (bands 6, 5, 4) were used to identify exposed and debris covered glacier ice to delineate glacier boundaries. Glacier inventory information (f.ex. Figure 3) for 1982 and 2008 was then updated for 2017.

Notably, the 2017 inventory identified 112 glaciers amounting to 28.4 km^2 not previously delineated in the 2008 inventory. According to Demuth et al. (2014), who used late summer Landsat 5 imagery, "*rock glaciers, misclassified features and features confounded by spectral ambiguity (e.g., cloud, shadow, debris cover) were parsed*" in the generation of their 1982 and 2008 comparative data set. For the purposes of this study therefore, the 2017 delineation was homogenized for change detection purposes, but a version was retained to provide a complete representation of the region's current glacier cover configuration and for future change detection.

Decadal-scale changes in glacier populations and surface areas were quantified by comparing the three homogenous inventories within a GIS environment.

4.2. ERROR CHARACTERIZATION

Potential sources of error in glacier surface area calculations include the resolution and accuracy of background imagery and the accuracy and precision of delineated glacier margins (shadows, cloud cover and debris-covered margins).

Error budget considerations are provided in Appendix B and based on a 12 m circular error of Landsat 8 OLI imagery (Irons et al., 2012) and a glacier delineation error assumed to be no greater than the pixel size (30 m).

The work of Bolch et al. (2010), Carisio (2012) and Beason (2017) is also considered in deriving the total error budget.

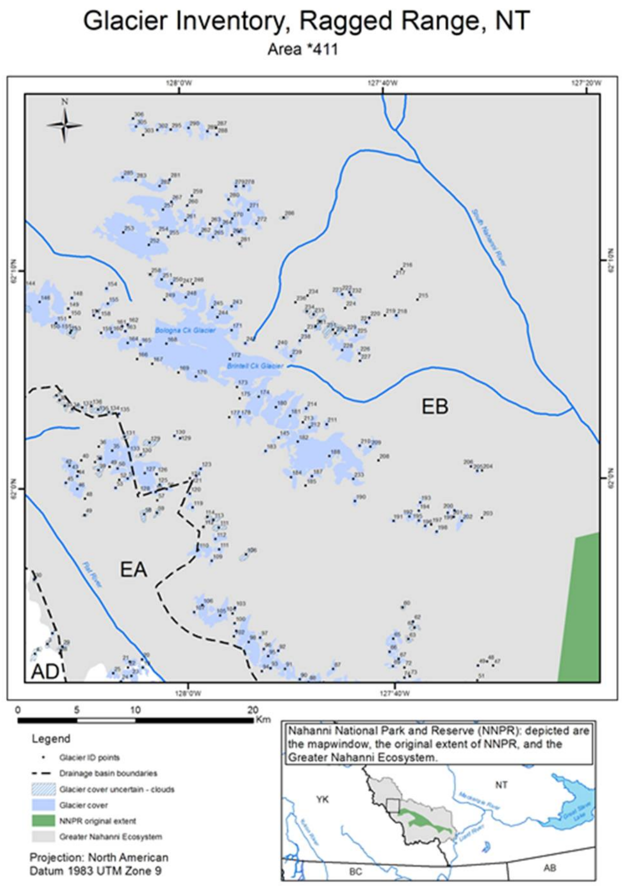

FIGURE 3. SAMPLE GLACIER INVENTORY MAP OF THE RAGGED RANGE (SOURCE: DEMUTH ET AL. 2014)

5. Data Reduction and Results

5.1. Glacier Cover Delineation 2017

In 2017, 345 individual glaciers covering a total area of 204.5 km^2 ±17.8 km^2 were identified in NNPR and the surrounding region (Table 1). The glaciers range in size between 0.004 km^2 and 18.6 km^2., with an average size of 0.6 km^2. The majority of the glaciers are small in size with 86% the population composed of glaciers less than 1.0 km^2 in surface area. The two largest glaciers in the region are the north-west flowing Bologna Glacier (15.8 ±0.71 km^2) and the south-east flowing Brintnell Glacier (18.6 ±0.81 km^2)

which make up the Brintnell-Bologna Icefield. This icefield represents 17% of the total regional glacier cover.

TABLE 1. REGIONAL NNPR GLACIER AREA AND POPULATION BY SIZE CLASS FOR 2017

Glacier area class (km^2)	Area (km^2)	Area %	N	N %
0.01 – 0.1	5.9 ±1.7	2.9	117	33.9
0.1 – 1.0	55.3 ±7.3	27.1	180	52.2
1.0 – 10	108.8 ±7.3	53.2	46	13.3
10 – 100	34.4 ±1.5	16.8	2	0.6
Total	204.5 ±17.8	100	345	100

5.2. Glacier Area Changes – Relative to the 1982 and 2008 Inventories

To quantify and characterize changes in glacier extent since the 1982-2008 inventory, the 2017 glacier inventory was compared to those for 1982 and 2008 using a homogenous dataset (Table 2).

TABLE 2. HOMOGENOUS GLACIER INVENTORY AREAS AND POPULATIONS FOR 1982, 2008 AND 2017

	1982 Glacier Inventory			2008 Glacier Inventory			2017 Glacier Inventory		
Glacier area class (km^2)	Area (km^2)	Area %	N	Area (km^2)	Area %	N	Area (km^2)	Area %	N
0.01 – 0.1	1.8 ±0.4	0.6	23	3.0 ±0.7	1.6	50	3.4 ±1.0	2.1	76
0.1 – 1.0	63.0 ±7.8	22.1	172	42.2 ±5.1	18.3	130	35.5 ±4.3	21.2	110
1.0 – 10	166.7 ±10.9	58.4	65	116.5 ±7.0	54.7	47	102.4 ±6.8	61.1	46
10 – 100	54.1 ±2.4	18.9	3	48.2 ±2.2	25.4	3	34.4 ±1.5	20.5	2
Total	285.7 ±21.5	100	263	209.9 ±14.9	100	230	175.7 ±13.7	100	234

A Wilcoxon signed-rank test (Wilcoxon, 1945) was used to determine significant changes between repeated glacier areas measurements periods 1982-2008 and 2008-2017. The tests were conducted on each area class. Test results found that within each glacier class, glacier surface area distribution around the mean were significantly different between the periods. P-values are presented in Table 3. The limited number of glaciers in the largest class (10-100 km^2) prevented the use of the Wilcoxon signed-rank test.

TABLE 3. SIGNIFICANCE OF PAIRED WILCOXON TESTS FOR CHANGES IN THE MEAN AREA OF THE GLACIERS IN THE RAGGED RANGE – H0: MEAN VALUES ARE INDISTINGUISHABLE (0.05%)

Area class (km^2)	1982-2008	2008-2017

0.01 – 0.1	0.0095	*P* <0.001
0.1- 1.0	*P* <0.001	*P* <0.001
1.0 – 10	*P* <0.001	*P* <0.001
10 – 100	n/a	n/a

Between 1982 and 2017 glacier extent in the NNPR and surrounding region lost 110 km^2 from 285.7 ±21.5 km^2 in 1982 to 175.7 ±13.7 km^2 equaling a loss of 39% (Table 2). Figure 4 provides examples of glacier surface area contraction between 1982, 2008 and 2017. Since 1982, the surface area of the regions smallest glaciers (0.01-0.1 km^2) increased from 1.8 km^2 to 3.4 km^2 while glaciers larger than 0.1 km^2 lost surface area (Table 2). While the largest glaciers in the region exhibited the greatest absolute loss of overall surface area, the number of glaciers in the 0.1-1.0 km^2 class was reduced by 62.

Overall, the population of glaciers decreased during the 35 year period from 263 in 1982 to 234 by 2017, a loss of 73 glaciers. The population total for 2017 includes 32 glaciers that fragmented into two or three smaller glaciers since 1982 (see f.ex., Figure 4a).

The Fractional Area Change (FAC), the change in area between time periods divided by the original surface area, was used to identify the relation between glacier contraction and size. Between 1982 and 2008 the majority of glaciers shrank in size with smaller glaciers shrinking more than larger glaciers such as Bologna or Brintnell (Figure 5). A small number of glaciers showed a modest growth in size (0-20%) during this time period. During this first period, glacier in the 0.1-1.0 km^2 size class experienced the greatest average surface area change of -48.9% (Table 4).

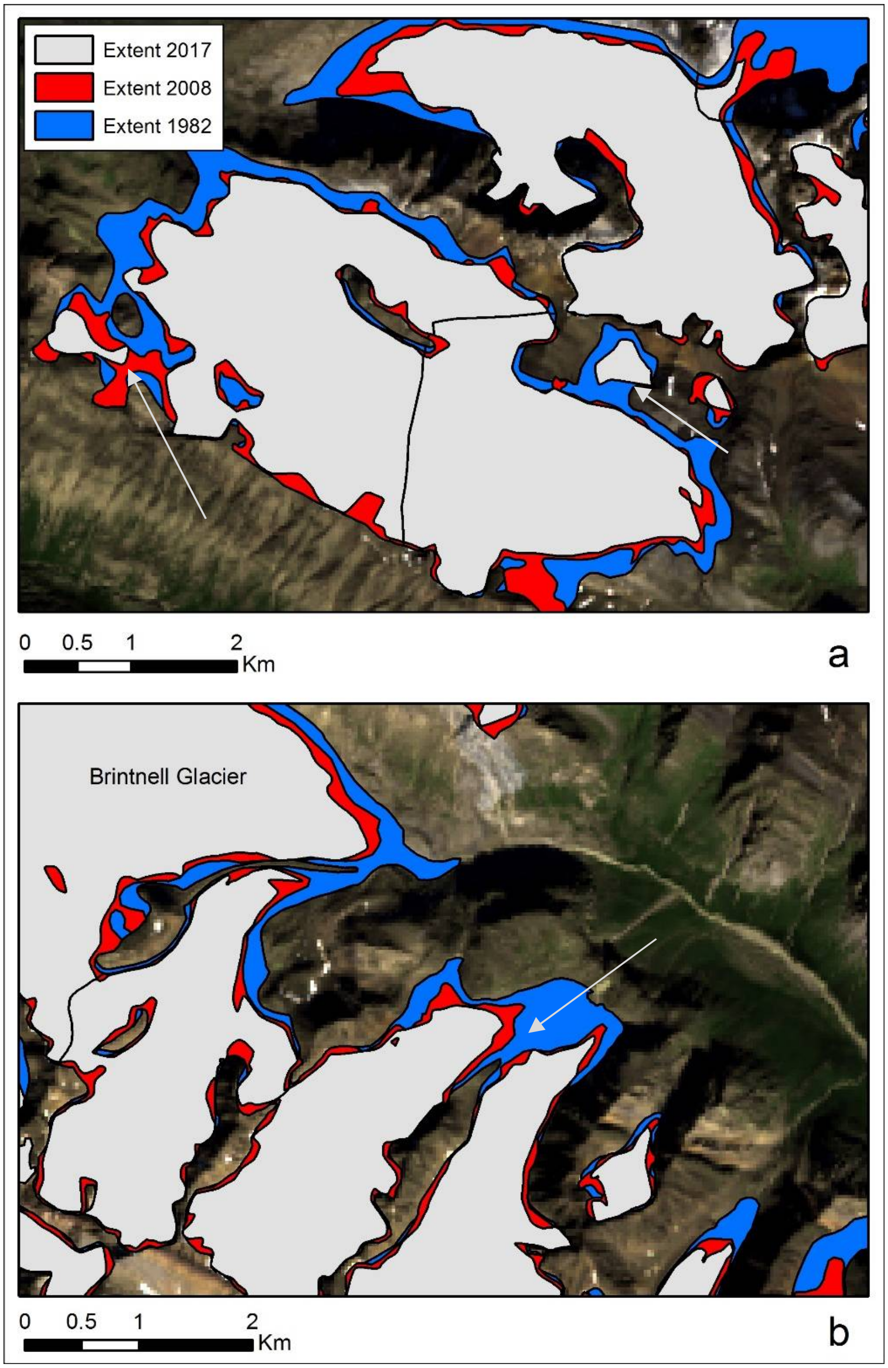

FIGURE 4. GLACIER AREA CHANGES BETWEEN 1982 – 2008 – 2017 FOR REGIONS NORTH OF BOLOGNA GLACIER (A) AND BRINTNELL GLACIER (B). NOTE EVIDENCE OF FRAGMENTATION AND INSTANCES WHERE GLACIER TERMINII NO LONGER COALESCE

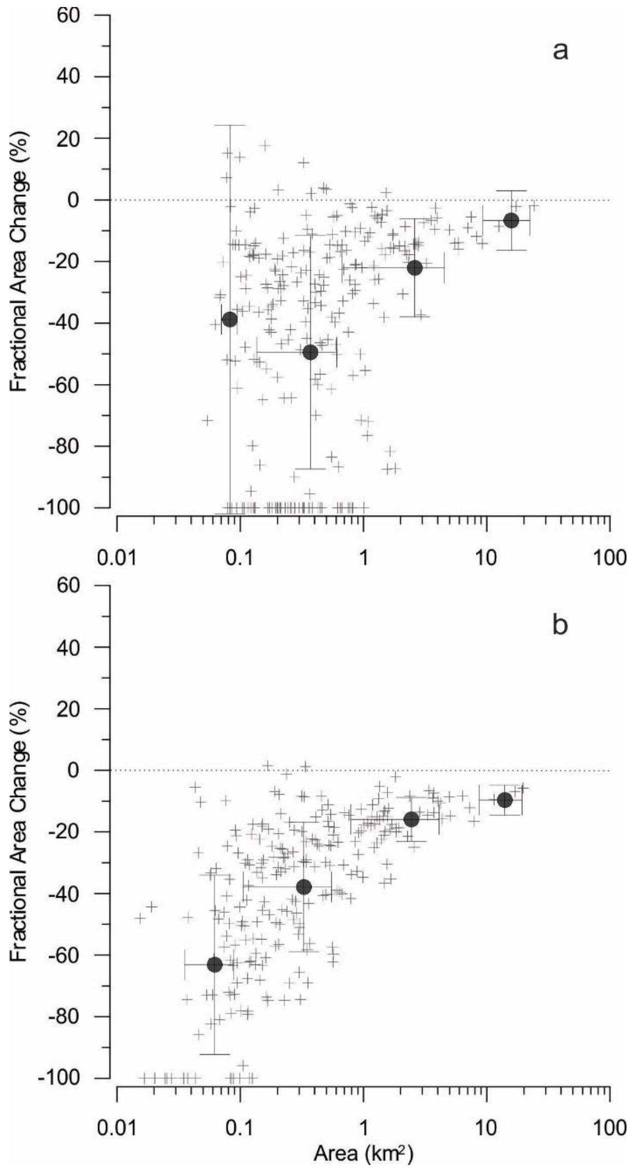

FIGURE 5. FRACTIONAL AREA CHANGE (FAC) 1982-2008 (A) AS A FUNCTION OF 1982 GLACIER AREA AND FAC 2008-2017 (B) AS A FUNCTION OF 2008 GLACIER AREA. INDIVIDUAL OBSERVATIONS AND AREA CLASS MEANS AND SINGLE STANDARD DEVIATIONS ARE SHOWN

Between 2008 and 2017, the majority of glaciers lost surface area with larger glaciers shrinking less than small glaciers (Figure 5b). Although glaciers in the smallest class (0.01 – 0.1 km^2) had the largest increase in population in the last 9 years it also had the largest negative fractional area change; -63.1% between 2008 and 2017 (Table 4). In contrast, the two largest glaciers (Brintnell and Bologna Glaciers) had a fractional area change of only -9.6%.

TABLE 4. FRACTIONAL AREA CHANGE BY GLACIER SIZE CLASS FOR 1982-2008 AND 2008-2017

Area class (km^2)	Average FAC 1982-2008 (%)	Average FAC 2008-2017 (%)
0.01 - 0.1	-27.0	-63.1
0.1 - 1.0	-48.9	-37.9
1.0 - 10	-31.7	-15.9
10 - 100	-6.7	-9.6

After concepts laid out in Shook et al (1993) and applied by Demuth and Pietroniro (2002) and Demuth et al. (2018) for several headwater basins in the Canadian Rocky Mountains, the character of glacier area fluctuations is further illustrated by plotting the *cumulative hyper-geometric size frequency distribution* for 1982, 2008 and 2017 (Figure 6). The aforementioned *size migration* phenomenon is well illustrated by a superimposition of the successive size-frequency distributions. Shrinking glacier surface areas can be seen in each successive distribution, with the least change among larger glaciers and an overall increase in the number of small glaciers (<0.1 km^2). Moreover, the increase in the number of glaciers less than 1.0 km^2 is most pronounced between 1982 and 2008.

6. DISCUSSION

Currently, the majority of the glaciers (~86%) in the Ragged Range are composed of small isolated glaciers less than 1 km^2 in size. Glaciers in the 1-10 km^2 size class represent over half of the total glacier surface area in the region but only 13% of the population. The regions only icefield covers 34 km^2 and represents ~17% of the total regional glacier surface area.

Over the past 35 years, glacier surface area has decrease from ~286 km^2 to ~176 km^2 with the majority of that loss from glaciers in 1-10 km^2 class which lost ~65 km^2. These relatively large glaciers most likely have lower elevation terminus and ablation zones and thus experience greater melt rates (f.ex., Demuth and Pietroniro, 2002; DeBeer and Sharp, 2007; Tennant and Menounos, 2013). Despite that the majority of the glaciers that disappeared during this period were originally less than 0.01 km^2 in area, the 0.01-0.1 km^2 class expanded in surface area, from 1.8 km^2 to 3.4 km^2, with 26 new glaciers – something that is attributed to by a number of factors. First, the population increase appears to be caused by an increasing rate of glacier redistribution amongst the size classes considered, f.ex., from those >1 km^2 to those <1 km^2. During the first interval, 27 glaciers were added to the smallest class (~1.0 glaciers a^{-1}) while during the last 9 years, 26 glaciers had contracted so as to count within the smallest class (2.9 glaciers a^{-1}).

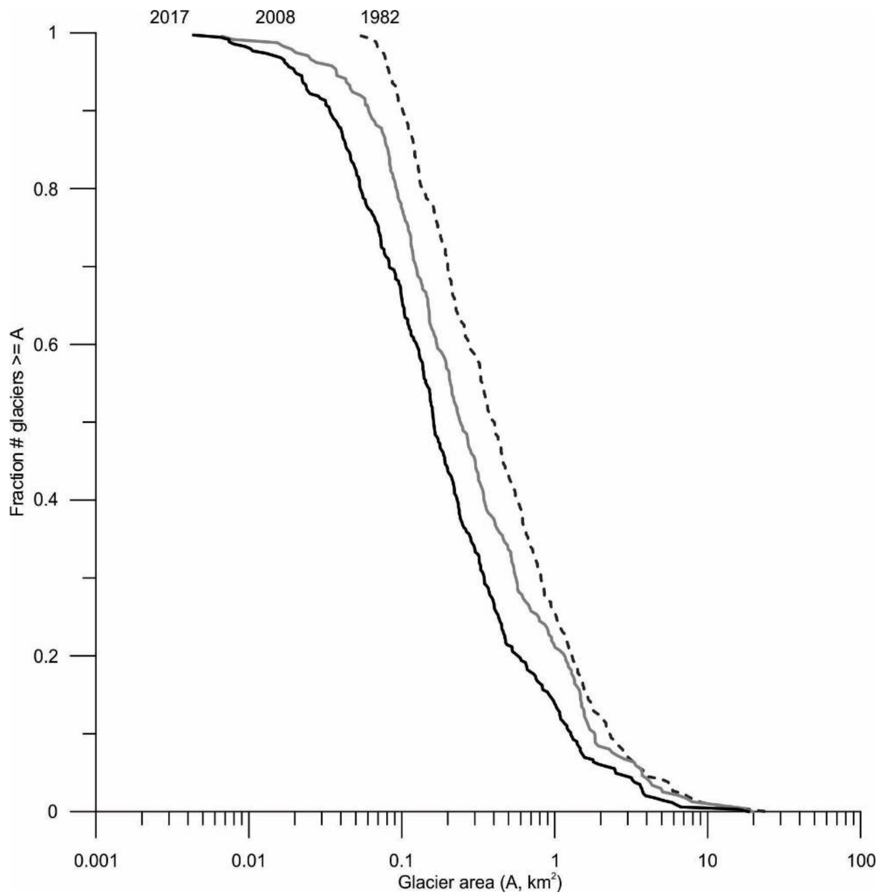

FIGURE 6. CUMULATIVE HYPER-GEOMETRIC SIZE-FREQUENCY DISTRIBUTION FOR GLACIERS IN THE RAGGED RANGE FOR 1982, 2008 AND 2017

Second, the increase may be driven by fragmentation - from 24 additional glaciers by 2008 and another 11 by 2017. Glacier fragmentation could have resulted from even minor surface lowering leading to the exposure of ridges and topographical divides. These additional glacier margins and a “patchier” landscape generally would give rise to accelerated melt and contraction through, for example, the advection of energy derived from short-wave radiation receipts over the newly exposed ground. Demuth and Pietroniro (2002) and Demuth et al., (2008) illustrated this size and fragmentation effect by plotting the contraction of glaciers in the eastern slopes of the Canadian Rocky Mountains using a perimeter-area characteristic.

As it concerns the size-frequency distribution (Tables 1 and 2, Figure 6), it is clear there are relatively few larger glaciers and numerous smaller glaciers; and that these larger glaciers contribute more to the total area fraction than do the more numerous smaller glaciers (f.ex. the 1 km^2 cut-off shown in Tables 1 and 2). Further, inflections in the slope of the distribution confirm that the planform geometric properties of the glacier are different for different size ranges, and thus are likely controlled by factors that scale in different directions (i.e., self affine). For example Demuth et al. 2014 determined a significant relationship between area and major flow-line length – suggesting that additional factors other than simple planform area need to be considered when interpreting or perhaps even parameterizing and thereby predicting future glacier cover configurations on the landscape.

The rate of overall glacier surface area contraction in the Ragged Range increased from -2.9 km^2 a^{-1} for the period 1982-2008 to -3.8 km^2 a^{-1} for the period 2008-2017 with an overall contraction rate of -3.1 km^2 a^{-1}. Bolch et al. (2010) found a similar rate of annual contraction of glaciers in the northern Canadian Rockies (-3.94 km^2 a^{-1}) between 1985 and 2005. The rate of area-wise contraction for glaciers between 0.01 and 10 km^2 remained stable through both periods. The greatest increase in the rate of contraction occurred on the region's largest glaciers (10-100 km^2) where a rate of -0.2 km^2 a^{-1} was observed for the 1982-2008 period compared to a rate of -1.5 km^2 a^{-1} for the 2008-2017 period. This large rate increase can be attributed to the fragmentation of a large glacier to the southeast of Brintnell glacier, originally 11.5 km^2 , into two sections measuring 6.7 km^2 and 3.7 km^2. Without the fragmentation of this glacier, the rate of surface area change exhibited in the two time intervals would have been similar.

As identified in Demuth et al. (2014) smaller glaciers in the Ragged Range underwent greater fractional change than larger glaciers with FAC scatter increasing with decreasing area. In the past 9 years (1998-2017), a similar trend was observed but with a more distinct increasingly negative FAC with decreasing glacier size. The relation between glacier contraction and size has been identified in other regions; for example, the Canadian Rockies (Demuth and Pietroniro, 2002; Demuth et al., 2008; Tennant and Menounos, 2013) and the northern Cascades (Granshaw and Fountain, 2006).

The overall population of glaciers in the Ragged Ranged region declined through the first period but increased slightly during the second period. The rate of glacier fragmentation increases from 0.9 a^{-1} for the period 1982-2008 to 1.2 a^{-1} for the period 2008-2017. The rate that these small glaciers completely disappear is relatively stable for both periods with an average of -2.2 glaciers a^{-1} disappearing between 1982 and 2008 while -1.8 glaciers a^{-1} disappeared between 2008 and 2017. The rate of population loss of glaciers in the 0.1 – 1.0 km^2 class was observed to increase slightly from 1.6 glaciers a^{-1} between 1982 and 2008, to 2.2 glaciers a^{-1} between 2008 and 2017.

7. Conclusion

Geological Survey of Canada Open File 8401 has presented an analysis of recently documented glacier area changes in the Ragged Range, NT and Nahanni National Park Reserve to illustrate decadal trends as controlled by size and situation in the topography. It has been determined that approximately 110 km^2 of glacier cover has been lost over the last 35 years - i.e., approximately 3.4 km^2 a^{-1}. Further, the average rate of annual glacier contraction increased from 2.9 km^2 a^{-1} between 1982 and 2008 to 3.8 km^2 a^{-1} between 2008 and 2017. Similar to the findings of other studies predating this work, many of the smallest glaciers may have become relatively immune to the influences of climate change and warming by becoming topographically preserved – i.e., by retreating into higher elevation regimes and terrain niches where glacier nourishment may be reliably provided by blowing and drifting snow, and melting is supressed because of lower receipts of short-wave solar radiation. Fragmentation of larger glaciers also increases the population of smaller glaciers; and with the increasing rate of fragmentation seen over the last 35 years, the population of the regions smallest glaciers may continue to increase. It is suggested that additional work be conducted on the geometrical properties of these glaciers so as to further illustrate the influence of large-scale landscape topography and other processes on the rates of glacier contraction, their interpretation and possibly their prediction.

APPENDIX A. GEOLOGICAL SURVEY OF CANADA'S REFERENCE GLACIER-CLIMATE OBSERVING SYSTEM IN THE CORDILLERA.

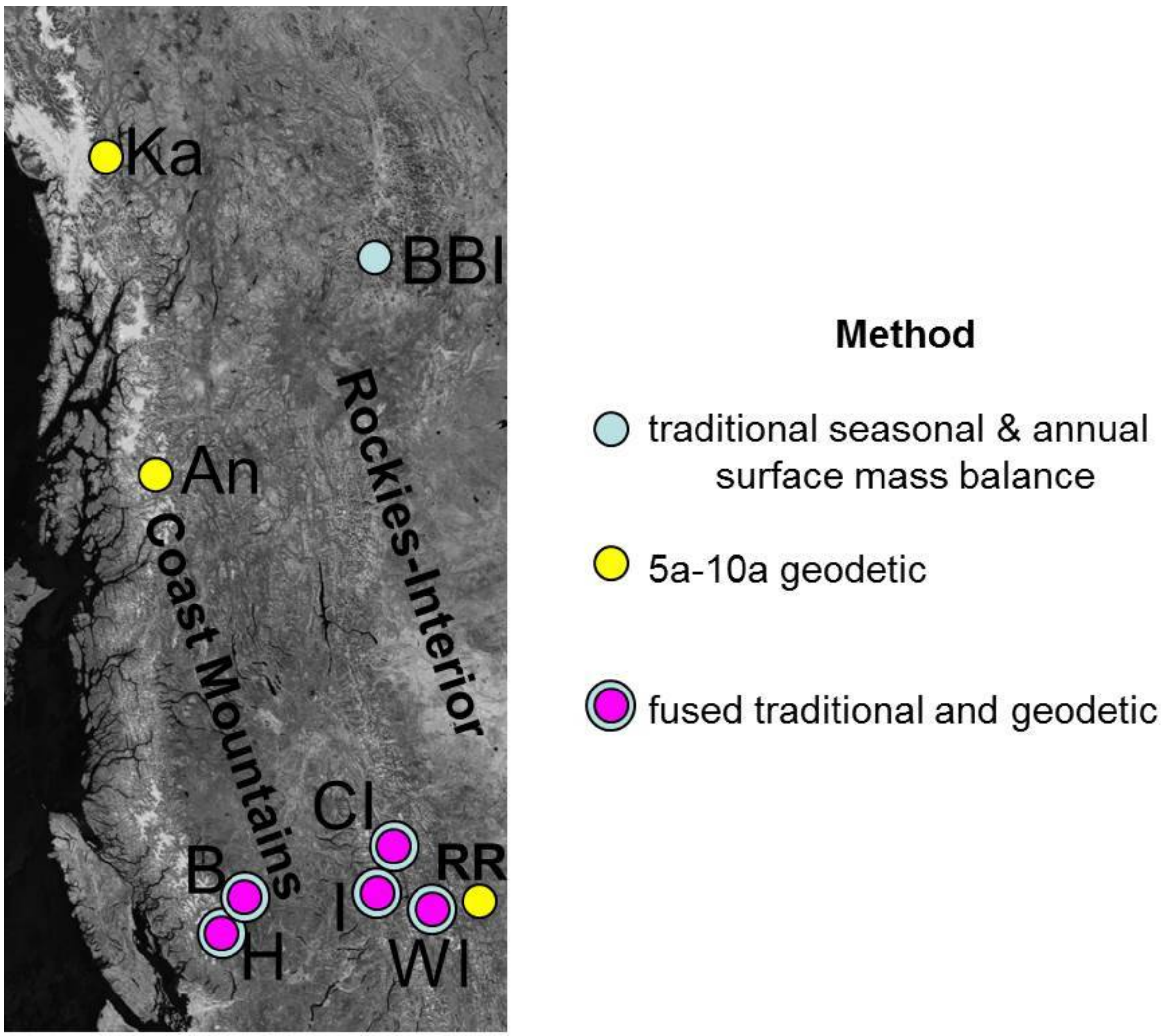

FIGURE A 1. REFERENCE MASS BALANCE OBSERVING SITES FOR THE CORDILLERA: WI = WAPTA ICEFIELD (PEYTO AND YOHO); RR = RAM RIVER; CI = COLUMBIA ICEFIELD (ATHABASCA AND SASKATCHEWAN); I = ILLECILLEWAET; BBI = BRINTNELL-BOLOGNA ICEFIELD (BOLOGNA); KA = KASKAWULSH; AN = ANDREI; B = PLACE; H = HELM.

Mountain National Parks:

Wapta Icefield is located in ***Banff*** (Peyto Glacier) and ***Yoho*** (Yoho Glacier) *National Parks*.

Columbia Icefield is located in ***Jasper*** (Athabasca Glacier) and ***Banff*** (Saskatchewan Glacier) *National Parks*.

Illecillewaet Glacier is located in ***Glacier and Mount Revelstoke National Park***.

Northern Bioregion Parks and Reserves:

Kaskawulsh Glacier is located in ***Kluane National Park Reserve***.

Brintnell-Bologna Icefield (Bologna Glacier) is located in ***Nahanni National Park Reserve***.

British Columbia Provincial Parks:

Helm Glacier is located in ***Garibaldi Provincial Park***

Metadata for each glacier/icefield site, including details on observing and research partnerships, measurement infrastructure and First Nations territorial references, are available from: mark.ednie@canada.ca

Appendix B. Error Budget Characterization – On-screen Digitization of Glacier Boundaries

The following is adapted from Demuth et al. (2018) - on-line supplementary material in support of the following research articles: Demuth et al. (2008) and Demuth et al. (2014).

When manually digitizing an object (portrayed in raster format) to estimate its area, the uncertainty is a function of raster resolution. In relation to digital vertex placement error along a glacier margin, there is an uncertainty associated with both the unambiguous margin, and the portions that are obscured by cloud, shadow, late lying snow-cover, or debris cover. Careful image selection can minimize some of these problems, but others are inherent in the nature of an alpine landscape.

The vertex placement uncertainty along unambiguous ice margins was assumed to be no greater than the pixel size (e_p) of the image being digitized; 30 meters for Landsat 8 OLI (Table B 1). The resulting digitizing uncertainty was then estimated as the area of a buffer around each glacier object:

$$E_{uo} = \pm e_p (l_T - l_o) \tag{1}$$

where l_T is the total perimeter and l_o is the length of the obscured margin (= l_{cloud} + l_{snow} + l_{shdw}+ l_{debris}).

The uncertainty associated with ambiguous margins was estimated as the product of the ambiguous margin length and an estimated vertex offset value associated with each type of ambiguity (Table B1).

For the 2017 inventory delineation, obscuration by cloud was insignificant. The glacier margins were generally clear of late-lying snow and the ice facies configuration indicated a relatively high transient snow line. Margin ambiguity caused by shadow and debris-covered ice was considered, with the former most prevalent in situations where glaciers were bounded by steep headwalls or in cirque-like settings

TABLE B 1 THE UNCERTAINTY ASSOCIATED WITH VERTEX PLACEMENT

	Vertex placement uncertainty (± m)
Error source	LS8 OLI
Digitizing	30
Shadow	75
Debris	75

Imperfect image co-registration is another source of potential uncertainty, and was estimated as the product of the digitized perimeter and the image resolution (i.e., the ortho-modeling algorithm used fits the GCPs exactly). DeBeer and Sharp (2007) comment that because this error is assumed to be independent and randomly distributed, it is reasonably to estimate it at 50% of this value

Total uncertainty was calculated as the root sum square of the individual uncertainties, with the following considerations and techniques employed in the data collection stream assisting to ameliorate the uncertainty:

- Work based on repeat digitizing experiments (e.g., Dunn *et al*. 1990 and this study) has demonstrated that errors associated with locating vertexes along the perimeter of a polygon are limited to a statistically derived error band which is significantly smaller than a commonly prescribed vertex buffer width. Notably, the anticipation that all vertexes will move in the worst possible direction simultaneously, to lie along the inner and outer buffer limits, is highly unlikely (personal communication, Hans Skov-Peterson). Using a Monte Carlo randomization approach, and assuming a Gaussian model to describe the inaccuracy of capturing individual vertices, this effort and that of Skov-Peterson demonstrated that the actual area uncertainty is approximately an order of magnitude less than that estimated by the buffer approach.

- *Digital roughness* (e.g., Paul *et al*. 2002) is ameliorated by vector smoothing and compression.

- Magnification to the pixel level for vertex collection

- Application of a contrast stretching to offset obscuration by shadow

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