Yukon

Occasional Papers in Archaeology No. 22

Detecting and Monitoring Change to an Arctic Heritage Site Using UAV Photogrammetry: A Case Study From Qikiqtaruk / Herschel Island, YT

Katelyn O'Keefe

Archaeology Program | Government of Yukon | Hudę Hudā̲n Series

Archaeology Program
Government of Yukon
Hudę̄ Hudǟn Series

Hudę̄ Hudǟn – Long Ago People (Northern Tutchone)

Objectives of the Series

The Occasional Papers in Archaeology Series is designed to provide for the timely dissemination of technical reports, conference workshop proceedings, and dissertations relating to archaeological research in the Yukon. The publication of these materials contributes to the realization of Yukon Tourism and Culture's heritage programming mandate: to develop, enhance and preserve the Yukon's heritage resources and communicate an appreciation and understanding of the Yukon's heritage to Yukoners and Yukon visitors.

In order to expedite timely publication of research results and keep publication costs to a minimum, manuscripts are submitted ready for printing. Errors are the responsibility of the author(s).

UNIVERSITY OF CALGARY

Detecting and Monitoring Change to an Arctic Heritage Site Using UAV Photogrammetry:

A Case Study From Qikiqtaruk / Herschel Island, YT

by

Katelyn O'Keefe

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF ARTS

GRADUATE PROGRAM IN ARCHAEOLOGY

CALGARY, ALBERTA

APRIL, 2022

Abstract

Arctic heritage sites are increasingly at risk due to modern climate change. Traditional documentation and monitoring of valuable heritage resources are time-consuming. In recent years, UAV (drone) photogrammetry has become a powerful tool for visualizing heritage sites. This research goes beyond visualization by evaluating the suitability of UAV data, acquired for documenting heritage resources, and for other reasons, to perform change detection analysis on Arctic cultural landscapes. The procedures developed throughout this research can also be used to create a heritage monitoring strategy. The case study used in this research is Simpson Point on *Qikiqtaruk* (Herschel Island), the most western Canadian Arctic island and the only island on the Yukon coast. Within *Herschel Island – Qikiqtaruk Territorial Park*, the heritage resources represent 800 years of continuous occupation by Inuvialuit, their ancestors, the Thule, and Euro-North Americans. UAV imagery of Simpson Point from July 2017 and 2019 was processed using photogrammetric software. The outputs (orthomosaics and point clouds) were prepared prior to employing two highly compatible change detection methods. The results of the change detection analysis were used to explore short-term change to the heritage features and the landscape, some of which are the result of climate change-induced overland flooding and coastal erosion. Other changes required confirmation from heritage restoration personnel. The framework of a heritage monitoring strategy for the territorial park, improvements to the future UAV data collection strategy, and the advantages and disadvantages of the change detection methods used are discussed. In addition, an emphasis is placed on the importance of data sharing, the reuse of found data, and the long-term curation of digital data.

Key words: *Aerial Photogrammetry, UAV, Change Detection, Heritage Monitoring, Heritage At-Risk, Data Sharing, Climate Change, Inuvialuit, Yukon, Arctic Archaeology*

Preface

Digital files associated with the 2019 UAV data collection can be found at ScholarsPortal in the *Digitally Preserving Herschel Island – Qikiqtaruk Territorial Park, Yukon Territory* Dataverse. Metadata for the UAV datasets used in this research is appended to this thesis.

Acknowledgments

Firstly, I would like to thank my supervisor Dr. Peter Dawson, who provided endless support and mentorship, interlaced with grand stories of northern fieldwork and unusual film recommendations. I would also like to thank my committee, Dr. Gerald Oetelaar, and Dr. Derek Lichti, for their guidance. Thank you to Dr. Elizabeth Paris for serving as my neutral chair. In addition, I would like to thank Dr. Gerald Oetelaar for bringing this research opportunity to my attention. I want to thank Christian Thomas, Senior Projects Archaeologist with Yukon Cultural Services, for his continuous assistance and the opportunities his collaboration with my supervisor has brought me throughout this project. Thank you to Brent Riley and Gisli Balzer of the Yukon Historic Sites Unit for supplying records of their restoration work on Qikiqtaruk. Furthermore, I would like to thank the *Herschel Island – Qikiqtaruk Territorial Park* rangers and the Aklavik Hunters and Trappers Committee members for their hospitality and support of my research.

This project would not have been possible without the funding support of my supervisor; the Cultural Services Branch, Government of Yukon; *Inuvialuit Final Agreement* funding administered by the Department of Environment, Government of Yukon; the Royal Canadian Geographic Society; the Alberta Graduate Excellence Scholarship (AGES); and various other University of Calgary scholarships.

My greatest thank you goes to my parents for always encouraging me to do my best and fostering my love for history and the outdoors from an early age. Dad, your strong work ethic, generosity, and problem-solving skills have worn off me. Mom, your intelligence, confidence, and organizational skills will always inspire me. Another huge thank you is owed to Jefferey Cornish for repeatedly sharing his geospatial knowledge and for always believing in me. I would like to thank Tom Strachan, Matt Rawluk, and Dr. Elizabeth Robertson for squashing any selfdoubt I had throughout the writing process. I would also like to thank Kaylee Baxter for her friendship and her unrelenting encouragement in the last year of my MA. Thank you to my many friends and family members who offered words of support throughout my time in school.

Thank you to my managers and colleagues at Stantec Consulting for the words of wisdom and continuous support. Lastly, I would like to show appreciation toward members of the University of Calgary staff, my colleagues, and my research group, including Peter Peller, Dr. Darren Bender, Madelyn Knaub, Zachary Jacobson, Christina Robinson, Madisen Hvidberg, Kelsey Pennanen, Matt Munro, Matt Moors, Jeremy Leyden and the students and faculty within the Department of Anthropology and Archaeology.

In loving memory of Elsie Barbara O'Keefe,

my family's first *-ologist*

Table of Contents

List of Tables

Appendix

List of Maps, Figures, and Illustrations

List of Symbols, Abbreviations and Nomenclature

Abbreviation	Definition, Page First Used
2.5D	Two-and-a-half dimensional, 15
3D	Three-dimensional, 1
AL	Atlantic Layer, 36
ALT	Active Layer Thickness, 44
C2C	Cloud-to-Cloud Distance Computation, 4
CCD	Charge-coupled Devices, 11
CESMLE	Community Earth System Model Large Ensemble, 37
CMOS	Complimentary Metal-oxide Semiconductor, 11
COPE	Committee for Original Peoples Entitlement, 67
DSM	Digital Surface Model, 1
DEW	Distant Early Warning Line, 67
FOV	Field of View, 11
GCP	Ground Control Point, 14
GIS	Geographic Information Systems, 4
GNSS	Global Navigation Satellite System, 10
GPS	Global Positioning System, 189
GSD	Ground Sampling Distance, 10
HBC	Hudson's Bay Company, 72
IFA	*Inuvialuit Final Agreement*, 27
IPCC	Intergovernmental Panel on Climate Change, 33
IRC	Inuvialuit Regional Corporation, 68
ISR	Inuvialuit Settlement Region, 1
LULC	Land Use Land Cover Change, 18
MOU	Memorandum of Understanding, 196
NOGAP	Northern Oil and Gas Action Program, 100
NWMP	North-West Mounted Police, 4

PML	Polar Mixed Layer, 37
PPK	Post-processing Kinematic Solution, 191
PPP	Precise Point Positioning, 189
PSWC	Pacific Steam Whaling Company, 74
RCMP	Royal Canadian Mounted Police, 51
RMS	Root Mean Square Error, 116
RTK	Real-time Kinematic, 108
SAT	Surface Air Temperature, 34
TLS	Terrestrial Laser Scanner, 4
UAV	Unmanned Aerial Vehicle, 1
VIA	Visual Inspection Analysis, 4

1 INTRODUCTION

The Arctic coast is particularly susceptible to environmental changes associated with modern climate change (Manson and Solomon, 2007; Barnhart et al., 2014; Irrgang et al., 2019). The Inuvialuit Settlement Region (ISR) is experiencing rapid coastal erosion, sea-level rise, and frequent flooding associated with storm surge events. Coastal heritage sites in the region, including those in the Mackenzie Delta, Yukon North Slope, and *Herschel Island – Qikiqtaruk Territorial Park*, are being damaged or destroyed (Irrgang et al., 2019). For Inuvialuit in the communities of Inuvik, Tuktoyaktuk, and especially Aklavik, the loss of heritage sites equates to the loss of culture and connections to the landscape.

Collecting aerial imagery of landscapes using unmanned aerial vehicles (UAVs or drones) has become increasingly common in the environmental sciences and heritage management. UAV data collection is lower cost than traditional aerial photography, making it more widely accessible. Heritage professionals have recognized the value of UAV imagery for visualizing large heritage sites, documenting excavations, performing archaeological reconnaissance, and documenting heritage in remote or challenging to reach areas (Rinaudo et al., 2012; Hamilton and Stephenson, 2016; Nikolakopoulos, 2017; Berquist et al., 2018; Themistocleous, 2020; van der Sluijs et al., 2020). However, the employment of UAV imagery by heritage professionals for heritage monitoring is not as widespread in the literature.

Photogrammetry is the art and science of making measurements from photographs (Wolf et al., 2014:1). Photogrammetry can be used to scale and stitch together imagery into a single high-quality aerial "photo," called an orthomosaic. Other high-quality data products generated using photogrammetric software include three-dimensional (3D) point clouds and digital surface models (DSM) (Wolf et al., 2014:1, 11). These data products can be used for visualization and, if multi-temporal data is available, for change detection analysis. Change detection analysis is a technique that uses remote sensing datasets (imagery, point cloud data[1], etc.) to detect differences by comparing the same subject matter at different times (Singh, 1989:989). Change detection analysis is widely applicable for heritage management and archaeological research. For example, change detection can be used to compare point clouds to identify change and monitor heritage sites.

This research is a case study of multi-temporal UAV imagery products to detect and monitor change to heritage resources and the natural and cultural landscapes at an Arctic heritage site in the ISR. The heritage site used for this case study is Simpson Point, an area containing an assortment of diverse heritage resources. Simpson Point is on *Qikiqtaruk* (also known as Herschel Island), an island off the Yukon coast. The entire island is within *Herschel Island – Qikiqtaruk Territorial Park*. In this thesis, the Inuvialuktun term for the island, Qikiqtaruk, is used in reference to *Herschel Island – Qikiqtaruk Territorial Park.*

Multi-temporal UAV imagery of Simpson Point was used to perform change detection analysis to detect change to heritage resources such as buildings and archaeological features and the overall natural and cultural landscape. The intent of this research was three-fold. The first goal was to evaluate the suitability of UAV data, acquired for the purposes of documenting heritage resources, as well as for other reasons, to perform change detection analysis on Arctic cultural landscapes. The second goal was to re-purpose “found data,” previously collected and shared by other researchers. Found data is beneficial for several reasons. Firstly, shared data is cost-efficient compared to repetitive data collection of the same target area by several research groups. Along these same lines, it reduces the environmental impact researchers have on delicate

[1] A point cloud is a dataset comprised of a collection of 3D data points that represent a 3D landscape or subject.

ecosystems by reducing the frequency of data collection. Thirdly, found data fosters interdisciplinary opportunities and generates new research questions.

The third goal of this research was to develop procedures that could be used to create a heritage monitoring strategy for *Herschel Island – Qikiqtaruk Territorial Park* that could also be applied to other heritage sites in the Canadian Arctic. The heritage resources on *Qikiqtaruk* are unique because they include pre-contact and post-contact Inuvialuit sod houses and Euro-North American structures from the late 19th and early 20th centuries (Friesen, 2012). Due to the low topographic relief of Simpson Point, overland flooding and erosion are continuously threatening these heritage features[2], making the Simpson Point an ideal study location for change detection analysis and monitoring.

Chapter 2 summarizes the background of the technology used in this research, including UAVs, photogrammetry, change detection analysis, and their applications for heritage research. Chapter 3 provides an overview of the physical geography and climate change in the Inuvialuit Settlement Region, emphasizing *Qikiqtaruk* and the rest of the Yukon North Slope. The overview of the interrelated processes associated with climate change in the region includes increased atmospheric temperature, sea-level rise, sea-ice loss, permafrost melt and overland flooding due to storm surge events, and coastal erosion. The chapter concludes with a summary of the impacts these processes have on heritage sites.

Chapter 4 provides the necessary cultural context for the research presented in this thesis. The first portion of this chapter summarizes the culture history of the Yukon North Slope, from the Paleo-Inuit to the Inuvialuit, including a detailed summary of the traditional lifeways of the pre-contact Inuvialuit (Mackenzie Inuit). The third section of this chapter summarizes the

[2] The term heritage feature is used in reference to a building, site or other resource that has heritage value.

activities of Euro-North Americans on *Qikiqtaruk*, including those by early explorers, whalers, traders, missionaries, and the Northwest Mounted Police (NWMP, later becoming the RCMP). In addition, the interaction between these outside groups and Inuvialuit is discussed. The fourth section of this chapter describes the tangible heritage on *Qikiqtaruk*, emphasizing the heritage on Simpson Point, adjacent to Pauline Cove. The fifth section of this chapter stresses the cultural significance of these heritage features and provides a rationale for preservation. The final segment of this chapter describes the Inuvialuit and Yukon Government co-management of *Herschel Island – Qikiqtaruk Territorial Park*, the heritage management practices for the park according to the park management plan, heritage protection and documentation efforts already undertaken in the park, and the history of archaeological research on the island.

Chapter 5 outlines the methods used in this research, including the steps taken during data collection, data processing, data preparation, and the two change detection methods used, Cloud-to-Cloud distance computation (C2C) in CloudCompare© and visual inspection analysis (VIA), undertaken using a geographic information system (GIS). The results chapter is broken into five sections. The first section provides the technical specifications for the processed 2017 and 2019 point clouds and the orthomosaics. It compares the accuracy of the orthomosaics of Study Area 1 to a high-quality point cloud dataset created using a terrestrial laser scanner (TLS) in 2018. The second section of this chapter provides the re-colorized point clouds (change maps) from the C2C method for study areas 1 and 2 and includes initial interpretations of the change based on color, size, shape, and pattern. In the third section of the chapter, the results of the C2C method are verified and explained using VIA of the orthomosaic imagery for the study areas. Additional changes caught during VIA but not in the C2C are described. The final section of this chapter describes widespread patterns of change detected using the two change detection methods and uses climate data and other research to explain these changes.

Chapter 6 summarizes the results of this research. The chapter summarizes the advantages and disadvantages of the change detection methods used in this research, emphasizing their compatibility. Next, the expected change to Simpson Point should an additional flight be flown in 2022 is outlined. The next topic that is addressed is the rationale for protecting the heritage on *Qikiqtaruk* and efforts to preserve said heritage. How this research addresses several of the heritage management goals of the *Herschel Island – Qikiqtaruk Territorial Park Management Plan* is also included. The most significant component of this chapter is a discussion on the use of the procedures created in this research towards developing a heritage monitoring strategy for the territorial park. This section provides the steps towards an ideal monitoring strategy and suggestions to improve the future data collection strategy. The last section of this chapter is a brief overview of the importance of found data, academic data sharing, and long-term data curation. The last segment of this thesis is the conclusion, which provides a concise summary of the content and results of this research.

2 TECHNOLOGY

This chapter serves as the background for the techniques used in this research: aerial photogrammetry and change detection analysis. The first section explains photogrammetry, followed by a summary of aerial photography principles, the aerial photogrammetric process, and the applications of aerial photogrammetry in heritage. The following section provides an overview of change detection analysis and two techniques used in this research: visual inspection and cloud-to-cloud distance computation. Overall, this chapter provides essential background about the data collection and change detection methods used in this research.

2.1 Aerial Photogrammetry

The term photogrammetry is derived from *phot*, *gramma*, and *metrein,* meaning light, something drawn, and to measure (Schenk, 2005:9). Photogrammetry is the art and science of acquiring reliable measurements of objects or the environment from photographs (Wolf et al., 2014:1). The fundamental principle used in photogrammetry is triangulation, which uses sight lines present within two or more overlapping photographs to mathematically calculate the coordinates of points of interest (Wolf et al., 2014:398). The discipline has two distinct branches: metric photogrammetry and interpretative photogrammetry. Metric photogrammetry concentrates on making precise measurements from photographs to determine the relative location of points in the photographs. Interpretative photogrammetry is the identification and recognition of objects within photographs and the analysis of the significance of these objects (Wolf et al., 2014:1). Photographs used for photogrammetry can be captured on the ground, a technique that is called close-range or terrestrial photogrammetry, or from the air, a technique that is called aerial photogrammetry (Wolf et al., 2014:1). Aerial photogrammetry is closely related to the discipline of remote sensing since it collects information about a subject without contact with that subject (Bettinger et al., 2017:67). Because aerial photogrammetry is used within the research presented in this thesis, the following subsections will focus on this form of photogrammetry. These sections summarize the history of aerial photogrammetry, the basic principles of aerial photogrammetry, the products created using aerial photogrammetry, and the uses of aerial photogrammetry in heritage.

2.1.1 The History of Aerial Photogrammetry

The development of aerial photogrammetry has always been highly dependent on technological advancement. Long before the invention of photography, photogrammetric techniques were being conceptualized. In 350 BC, Aristotle contemplated the projection of images optically. In the 18th Century, mathematicians Dr. Brook Taylor and J.H. Lambert wrote about linear perspective and utilized this perspective to make topographic maps. By the mid-19th Century, the invention of photography and stereoscopy (the technique of using two or more different images containing matching points to create a single photograph with depth) set the stage for modern photogrammetric techniques (McGlone et al., 2004; Kraus, 2011). This section describes the four phases of photogrammetry, as shown in Figure 1. During this first phase of photogrammetry, an experienced photogrammetric operator used expensive instruments to reconstruct the orientation of photographs, perform all measurements and create all maps by hand (Linder 2006:7).

Aimé Laussedat, Colonel of the French Army Corps of Engineers, was the first to experiment with aerial photogrammetry, using kites and balloons as aerial platforms (McGlone et al., 2004; Kraus, 2011; Wolf et al., 2014). In the 1880s and 1890s, photogrammetry was used for the first time in North America to map the mountainous areas of Western Canada and the

Alaska-Canada border (Wolf et al., 2014:2). However, most photogrammetry up until this time had been terrestrial due to the lack of a practical means of obtaining aerial photos (Wolf et al., 2014:3).

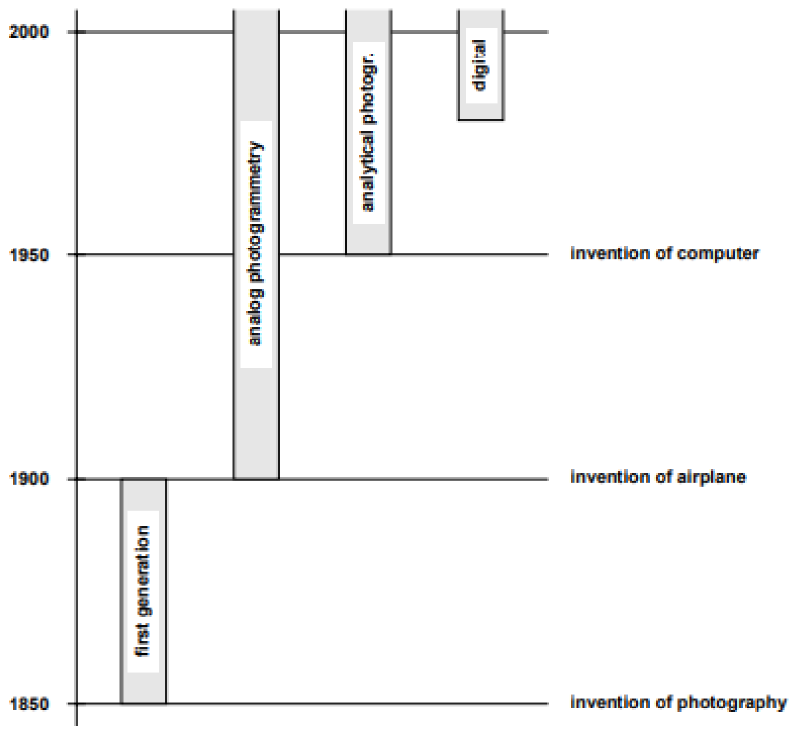


Figure 1. *Timeline of the major phases and technological developments in photogrammetry (Schenk, 2005:8).*

The invention and popularization of the airplane in the early 20th Century solved many of the difficulties that plagued early aerial photogrammetrists since it provided a dependable aerial platform. The airplane helped solidify aerial photogrammetric survey as the primary technique to create detailed topographic and mass-produced maps (Wolf et al., 2014:3). This phase is known as analog photogrammetry. During this time, photogrammetry was primarily used for analog methods since extensive manual computation was required (Schenk, 2005:13). With the advent and commercialization of the computer in the mid-20th Century, analytical computer models were developed to statistically estimate camera calibration, space resection, and interior and exterior camera orientation, which are the basis of an adjustment method called bundle adjustment (Klinkenberg, 2009). This phase, called analytical photogrammetry, still relied on analog, physical imagery and an analytical plotter, a piece of mechanical equipment that compares two photographs simultaneously to determine elevation; however, the mathematical component of photogrammetry was streamlined (Linder, 2006:7). As a result of technological advancements, analytical photogrammetry blossomed (Aber et al., 2010:19; Booysen et al., 2021).

Technology has continued to improve in recent decades, and with the invention of the digital camera, analytical photogrammetry has been gradually replaced with digital photogrammetry. A digital camera uses a digital sensor to capture the image rather than using exposure on film (Graham and Koh, 2002:19). Digital sensors were not immediately adopted, and the transition from analogue sensors took place over multiple decades. It was only in 2000 that the first airborne metric digital cameras began to be released. Therefore, high-resolution scans of film imagery were used for aerial photogrammetry while digital technology progressed (D. Lichti, pers. comm. 2022). There are many benefits to digital photogrammetry; there is no need to process film, and the data is already prepared for computer processing, data can be accessed immediately post-capture, digital files are easier to store and share than traditional film, and lastly, digital cameras are less expensive than film cameras of equal quality (Graham and Koh, 2002:5). The invention and rapid adoption of a new aerial platform, the unmanned aerial vehicle (UAV, i.e., drone), has dramatically improved aerial survey, lowering data collection and platform maintenance costs and decreasing the aviation expertise required (Green and Gómez, 2020:21-22). Together, digital cameras and UAVs have shaped modern aerial photogrammetric practices and have made photogrammetry more accessible to industry, government, academics, and members of the public (Nikolakopoulos et al., 2017; Murison, 2020). When coupled with soft-copy photogrammetric software and global navigation satellite system (GNSS) technology, UAV data collection is a sophisticated approach to acquire high-resolution imagery and 3D point cloud datasets (Green and Gómez, 2020:14).

2.1.2 Principles of Aerial Photography

An understanding of aerial photogrammetry relies on knowledge of the principles and geometry of aerial photography. The geometry of a vertical analog photograph is shown in Figure 2 below. In Figure 2, the negative and positive of the image are shown. The negative is the reversal of geometry, situated equidistant to the focal length above the rear anode of the camera. The positive is obtained from the negative’s information, and the positive's geometry is the same as the scene or object being photographed (Wolf et al., 2014:137). The focal length is the distance between the camera lens and the image sensor when the subject is in focus. This is typically measured in millimeters (mm). The principal point (P) is the geometric center of the photograph. (Wolf et al., 2014:68). The x-axis of the photograph indicates the direction of flight, and the y-axis runs perpendicular to the direction of flight (Payne and Kiser, 2003:31). Similar geometry is assumed for photos taken with a digital camera; however, digital imagery is broken down into a grid, where each square is known as a pixel. Figure 3 depicts the geometry of a digital photograph (Wolf et al., 2014:75).

The scale of a traditional aerial photograph is determined by the ratio of the focal length (f) and the flying height (H) (Graham and Koh, 2002:8). The scale is related to a digital image's ground sampling distance (GSD). GSD is the size of a pixel on the ground in meters and is related to focal length, flying height, and the sensor's size (O'Connor et al., 2017:326; Pepe et al., 2022:125). The formulae below can be used to calculate the scale for any format of aerial imagery.

$$Scale = \frac{f}{H} \qquad GSD = \frac{Sensor\ Pixel\ Size}{Ground\ Pixel\ Size} \qquad Scale = \frac{f}{H} = \frac{Sensor\ Pixel\ Size}{Ground\ Pixel\ Size}$$

Focal length directly influences image magnification. Longer focal lengths result in greater image magnification, while shorter focal lengths result in lower magnification. The field of view (FOV), the area captured by a camera in a particular photograph customarily expressed in degrees, is also influenced by focal length (Panavision, 2015). A camera with a short focal length captures a more extensive area than one with a longer focal length. In digital cameras, the field of view is also influenced by the sensor's width and height. If using a smaller sensor, a shorter focal length is required to capture the same FOV as a camera with a larger sensor and a longer focal length (Panavision, 2015). The quality of digital imagery also depends on the type of camera sensor. The sensors are made of detectors, which detect electromagnetic energy. There are two types of commonly used detectors: charge-coupled devices (CCD) and Complementary Metal-Oxide Semiconductor (CMOS) (Wolf et al., 2014:73). CCD sensors were the preferred sensor for quite some time as they yield high quality, low noise photographs (Hain et al., 2007). However, CMOS sensors are becoming increasingly prevalent in recent years because they are smaller, consume less power, and are more cost-efficient than CCD sensors. Additionally, the newest CMOS sensors rival the image quality of the once preferred CCD (Do and Yoo, 2018:112).

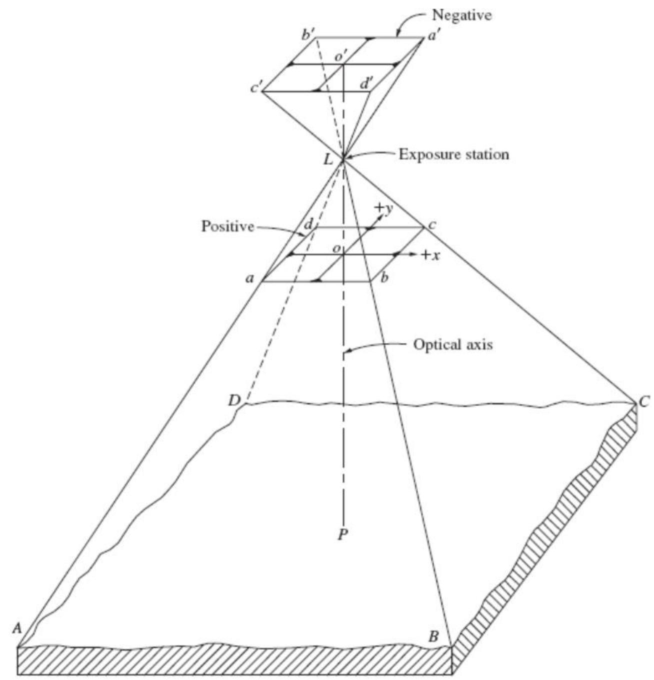


Figure 2. *The geometry of a vertical photograph (Wolf et al., 2014:138).*

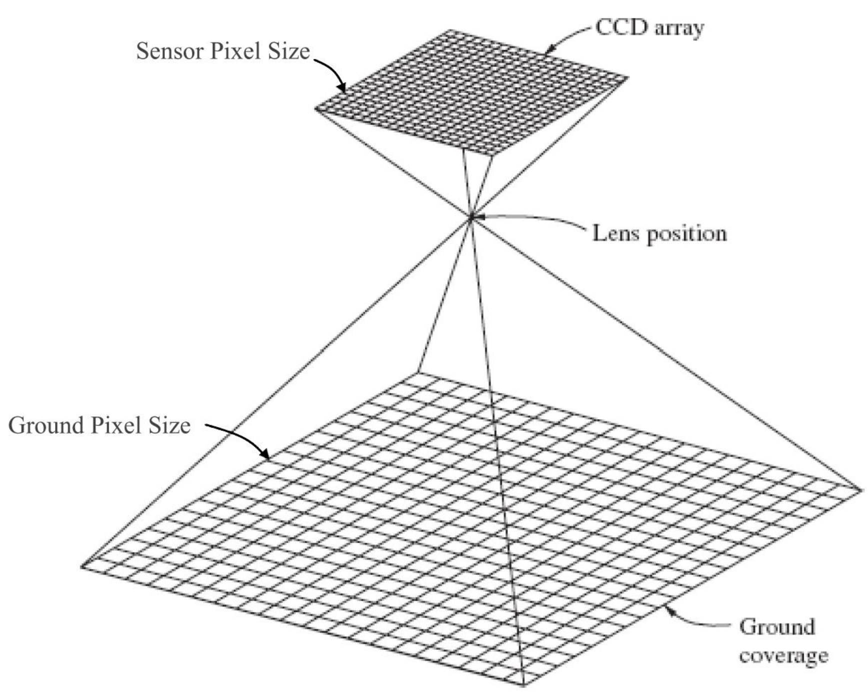


Figure 3. *The geometry of a vertical photograph using a digital camera. Modified from original, published in Wolf et al. (2014:75).*

2.1.3 Photogrammetric Data Collection

The photogrammetric process begins with the logistics and mission planning phase, followed by data capture and then data processing and map production (Graham and Koh, 2002:173). In the planning stage, it is vital to consider the size and topography of the study area, the desired data, and the available equipment. The nature of the study area determines the minimum overlap of the photos and the height of the flight since both will influence the resolution and accuracy of the data (Ahmad and Samad, 2010:3; Tal and Altschuld, 2021:120). Longitudinal overlap, also called frontal overlap, is the overlap between the images in the direction of flight. Horizontal overlap, also called side overlap, is the overlap between the image's perpendicular to the direction of flight (see fig. 4). The type of aerial platform being used is a strong factor when determining overlap, as aerial platform stability differs between platform types. UAVs are less stable than manned fixed-wing airplanes, so more image overlap is needed (D. Lichti, pers. comm. 2022). For most UAV image capture projects, a minimum of a 75 percent longitudinal overlap and a 60 percent horizontal overlap is sufficient; however, landscapes with limited identifiable features require even more overlap (Pix4D, n.d.a; Tal and Altschuld, 2021:125).

The texture of the image greatly influences overlap requirements. More overlap is required if there is low texture, such as on a homogenous landscape (Pix4D, n.d.a). Should the study area be too large for one flight, overlap is also required between flight blocks. Another important consideration in the planning process is whether the dataset will need to be georeferenced. Georeferencing, also called ground registration, is the process in which the internal coordinate system of a map is related to the geographic coordinates of the ground. When using an aerial platform with a built-in GNSS, each photo captured is tagged with geographical coordinates. Imagery that has these embedded coordinates is called geolocated or geotagged imagery. Additionally, georeferencing can be done by setting up ground control points (GCP) with known coordinates that are detectable in the aerial imagery collected (USGS, n.d.a.; Wolf et al., 2014:212). These coordinates have a higher overall degree of accuracy and precision than geotagged imagery (Pix4D, n.d.d; Meinen and Robinson, 2020; Tal and Altschuld, 2021:130).

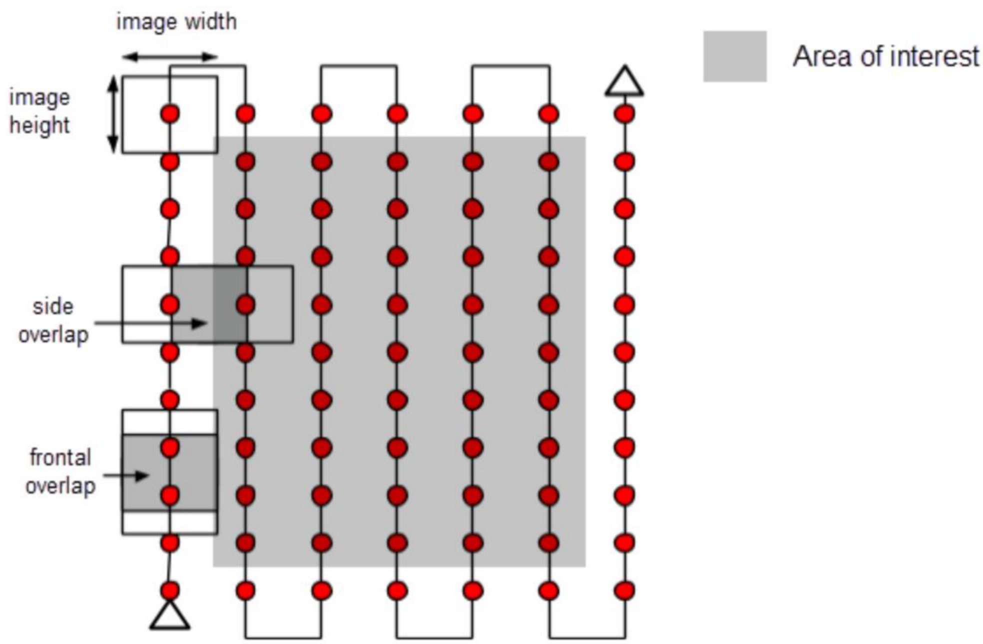


Figure 4. *Overlap requirements for an aerial survey (Pix4D, n.d.a).*

For the data processing software to identify the relationship between the images, several parameters must be known to the software. These parameters can be split into two categories: internal and external camera orientation parameters. The internal operating parameters are the focal length, lens distortion, pixel size (also called sampling size), imaging size (sensor size), and principal point (Aber et al., 2010:22). The external orientation parameters are the camera's x, y, and z position in space and the three angles of rotation compared to the ground (Aber et al., 2010:23). During the flight mission, the external orientation parameters are collected and stored within the metadata of the mission file. The photogrammetric software uses the internal and external operating parameters to calculate precise 3D coordinates for points in the imagery (Aber et al., 2010:22).

Several photogrammetric products can be created using the processed data. These include orthomosaics (also called orthophotos), colorized point clouds, and DSMs (Wolf et al., 2014:11). An orthomosaic is a photographic map produced through orthorectification, the technique of removing perspective distortions by incorporating information from the corresponding DSM, to create a 2D map with uniform scale throughout (Wolf et al., 2014:1; Payne and Kiser, 2003:162). A point cloud is a collection of 3D data points representing a 3D landscape or subject. Lastly, DSM is a 2.5D model that represents the natural and constructed features of the landscape (Pix4D, n.d.e). A 2.5D model is a two-dimensional model that uses perspective to portray a 3D environment by assigning an elevation value for each pixel on the 2D image surface (Sima and Kay, 2007:58).

2.1.4 Applications of Aerial Photogrammetry in Heritage and Other Disciplines

Aerial photogrammetry has been used most extensively by government organizations for topographic survey and the production of topographic maps. In addition, it is a valuable tool for preliminary surveys, military intelligence, highway planning, traffic management, architectural projects, environmental conservation, vegetation studies, hydrological studies, and much more (Aber et al., 2010; Wolf et al., 2014). Most importantly for this research, photogrammetry is an invaluable research tool in archaeology (Wolf et al., 2014:13).

The use of aerial photogrammetry in archaeology can be traced back over a hundred years, beginning with the use of balloons and kites (Reeves, 1936:106). In the years that followed, the invention and rapid popularization of the airplane, the advancement of photography, and the improvement of photogrammetric techniques for military purposes, modernized the discipline of photogrammetry. These advancements made capturing aerial photographs of heritage sites faster and easier (Nikolakopoulos et al., 2017). In addition, the airplane sped up the collection process and provided more control over the desired height and spatial extent captured, both of which are beneficial when recording archaeological sites (Reeves, 1936). Since the 1920s, sites worldwide have been photographed from the air, and Reeves (1936) specifies that this technique is especially beneficial for locating sites that are not easily visible from the ground. Today, airplanes are being replaced by UAVs for archaeological photogrammetry, primarily because they are relatively inexpensive and readily available (Hamilton and Stephenson 2016; Hill 2019). UAVs have been used in many ways for heritage and archaeological work. These uses include preliminary surveys, excavation, site monitoring, historic site relocation and reconstruction, and 3D modeling (Rinaudo et al., 2012; Saleri et al., 2013; Hamilton and Stephenson, 2016; Lasaponara et al., 2017; Nikolakopoulos et al., 2017; Berquist et al., 2018; Manajitprasert et al. 2019; Themistocleous, 2020; van der Sluijs et al., 2020).

UAVs, like airplanes, are excellent for finding archaeological sites, particularly in scenarios where these sites are difficult to recognize from the ground, such as tipi rings. However, the small size of UAVs also means that photogrammetry can be completed for sites in small or difficult to access locations, such as pictographs on rock faces or sites that are otherwise inaccessible to larger aerial platforms (Hamilton and Stephenson, 2016; Berquist et al., 2018). Photogrammetry is particularly useful when surveying large areas, which can be done quickly, saving time and effort for the archaeologist. An example of a widespread archaeological survey using UAV photogrammetry is mapping caribou fences in the Yukon (van der Sluijs et al., 2020). Another purpose for UAV photogrammetry is to document an excavation. The imagery obtained from the UAV mission can document the excavation process and, along with photogrammetric software, can provide scaled aerial imagery of the finalized excavation (Campana, 2017). The third use for photogrammetry in archaeology is site monitoring. Strategies include repeat photogrammetry at a particular heritage site to monitor change (Rinaudo et al., 2012). This change may be due to natural hazards, human interaction, or a combination of these two factors (Themistocleous, 2017).

Lastly, the photogrammetric imagery obtained using UAVs can be used to make 3D models of heritage sites or structures, used in museum displays, as research tools, and for general educational purposes (Fernández-Hernandez et al., 2015). Overall, there are many applications of aerial photogrammetry, and it has been proven to be a reliable method of aerial survey in archaeology and heritage.

2.2 Change Detection Analysis

Change detection analysis is a remote sensing technique that identifies differences in a subject, often a geographical landscape, by observing that subject at different times (Singh, 1989: 989). Change detection is closely associated with the advancement of military technology in the first half of the 20th Century and, during this time, relied heavily on aerial photography. Early change detection performed by civilians was analog and limited by the availability of suitable data since much of the military data remained classified until the 1970s and 1980s (Théau, 2008:77). The launch of Landsat-1 in 1972 and the continuing advancement of modern computers had a significant impact on the development of change detection in the latter 20th Century, ensuring the rapid development of new change detection techniques. During this time, image data became more widely available, and the applications of change detection shifted from purely analog to analytical and, most recently, to digital (Théau, 2008:77). Change detection analysis is related to aerial photogrammetry, discussed in the previous section. Photogrammetric outputs (orthomosaics, point clouds, etc.) can be used to observe landscapes, and multi-temporal photogrammetric imagery is well-suited for comparison. Change detection analysis has been successfully used as a research tool for land-use and land-cover (LULC) change studies, vegetation change studies, wetland, and environmentally sensitive region assessments, forestry management, forest fire and disaster impact assessments, landscape change studies, climate change research, urban planning, and heritage monitoring and management (Mouat et al., 1993; Coppin and Bauer, 1996; Civco et al., 2002; Lu et al., 2004; Tapete, 2018; Krauß and Tian, 2020).

Change detection analysis can be done manually, by visually inspecting image data, or by using specialized computer software. Examples of software with change detection capabilities are CloudCompare©, ESRI's ArcGIS Pro©, and ERDAS IMAGINE© by Hexagon Geospatial (ESRI, n.d.a; CloudCompare, 2015; Hexagon GPS, 2021).

There are two broad categories of change detection techniques: pre-classification and post-classification (Al-doski et al., 2013:39). Classification, or more specifically, image classification, is a procedure that automatically categorizes an image's pixels into land cover classes or themes (Lillesand et al., 2008:484). Pre-classification techniques are performed directly on multi-temporal imagery to produce a change vs. no change map based on changes in radiance (Al-doski et al., 2013:39). A disadvantage of pre-classification techniques is that they cannot provide insight into the cause of the change, and obtaining that information requires further analysis. The advantages of pre-classification techniques are that they are relatively simple to implement and effectively identify and locate change (Al-doski et al., 2013:41).

Post-classification comparison techniques are approaches based on comparing two or more independently classified images, then used to generate thematic maps (Al-doski et al., 2013:41). With post-classification techniques, the nature of the results can be determined, meaning that the analyst can precisely determine what change has occurred (Al-doski et al., 2013:41). Overall, many different techniques fall within the umbrella of change detection; however, describing them all is beyond the scope of this chapter. For further information on different change detection techniques, see Coppin et al. (2004), Lu et al. (2004), and Al-doski et al. (2013). The following subsections provide background information on the two pre-classification change detection techniques used in this thesis: Cloud-to-Cloud distance computation (C2C) and visual inspection analysis (VIA). The final subsection summarizes the application of change detection in heritage.

2.2.1 Cloud-to-Cloud Distance Computation

Numerous computational algorithms have been employed in engineering and other scientific research areas for change detection purposes (Singh, 1989). With digital datasets in the form of raster imagery, digital elevation models, or point clouds, these algorithms can compare the data, measuring the change in the scene between one dataset and the other (Coppin et al., 2004; Girardeau-Montaut et al., 2005). One way that 3D point data can be compared is through a form of nearest neighbor analysis. Nearest neighbor analysis is a spatial analysis tool that determines the spatial patterning of a dataset (Bishop et al., 2020). Hausdorff distance, a form of nearest neighbor analysis, is particularly suitable for sizeable 3D point sets change detection analysis. Hausdorff distance calculates the maximum deviation between two or more 3D point models, essentially quantifying the distance between the location of each point from the reference datasets to another dataset (Zhang et al., 2017; Girardeau-Montaut et al., 2005).

CloudCompare© is a software developed for 3D deviation analysis capable of managing 3D point clouds and 3D mesh (Girardeau-Montaut, 2016). The software has a built-in tool that uses Hausdorff distance in the way described above, using the Cloud-to-Cloud distance tool (Cloud Compare 2015). The tool requires at least two point clouds, with one being used as the reference cloud, from which other point clouds are compared. For each 3D point in one dataset, the distance to the closest point in the other dataset is computed. The result of the tool is a re-colorized point cloud, called a scalar index, which indicates locations with measurable change, and the quantity of change, as indicated by different colors on the map.

2.2.2 Visual Inspection Analysis

Visual inspection analysis (VIA) is a straightforward change detection technique in which the analyst visually examines multi-temporal image data for change (Lu et al., 2004:2381). Visual inspection incorporates the technique of repeat photography and the principles of photo interpretation to identify the change in the scene. The following paragraph provides further detail regarding repeat photography and photo interpretation.

Repeat photography, also called photographic monitoring, is the process of duplicating the camera station of a previous photographer, whether than photo is taken from the ground or the air (Webb et al., 2010:1). Repeat photography has long been a valuable tool for landscape monitoring and is also used in urban planning, vegetation research, climate change monitoring, and heritage management (Webb et al., 2010; Smith, 2007; Klett, 2011). Figure 5, below, is an example of repeat landscape photography. Photo interpretation is the process of determining the nature of objects within a photo and judging their significance (Payne and Kiser, 2003:1; American Society of Photogrammetry, 1966). While interpretation is more common using air photos, terrestrial photos can also be used. Interpretation of objects is completed using the basic

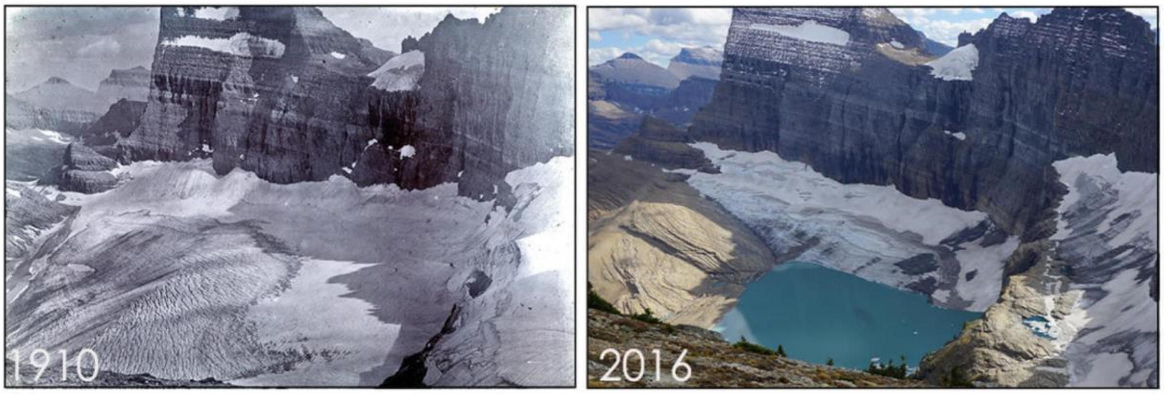


Figure 5. *Repeat photography of Grinnell Glacier in Montana (USGS Repeat Photography Project, n.d.b.).*

principles of photo interpretation: size, shape, shadow, tone (or color), texture, pattern, and lastly, the location and association of the object within the scene. Using these principles, the analyst can discern valuable information about the scene (Payne and Kiser, 2003:286-293). Historically, air photo interpretation has been crucial in creating topographic maps and has a long history of use in various research disciplines, including landscape monitoring and archaeological survey (Payne and Kiser, 2003:409). Together, repeated photography of a subject or landscape over time and interpretation of the landscape can inform the analyst of changes occurring between the photographs, which is the basis of visual inspection. Parks Canada has used this technique to monitor Fort Conger, a heritage site on Ellesmere Island in the Canadian Arctic. Challenges with repeat photography at Fort Conger include difficulties replicating camera location and angle, as well as exposure ((P. Dawson, pers. comm. 2021).

Visual inspection can be completed using non-digitized photographs or a computer tool (GIS, Autodesk Recap, etc.) to view and compare the data. This process may be undertaken with physical copies of imagery, or it may be done digitally with the assistance of computer software. The latter is more time-efficient due to the ability to toggle imagery on and off throughout the process. Before commencing the inspection, it is helpful to overlay a grid on top of the imagery, which aids in the systematic review of the data. The grid size should be selected to reflect the study area size and the nature of the research. The analyst manually flips between the photographs or toggles between the superimposed digital imagery, looking for change. With the advancement of specialized change detection software, this method is used less frequently than in the past (Lu et al., 2004:2387). Regardless, visual analysis remains valuable as a qualitative method due to its low cost and practicality (Lu et al., 2004:2387). Additionally, visual analysis is instrumental when picking out texture, shape, and size patterns, elements that are often difficult for change detection software to detect (though this is improving) (Lu et al., 2004: 2387). VIA has been used for disaster recovery and monitoring, forestry, land-cover change, and shoreline detection (Stone and Lefebvre, 1998; Slater and Brown, 2000; Asner et al., 2002; Boak and Turner, 2005; Burton et al., 2011).

2.2.3 Applications of Change Detection in Heritage and Other Disciplines

Change detection analysis is used in many industries, including ecology, urban planning, civil engineering, hazard mitigation, and heritage management. In ecological research, change detection has been used to detect LULC change and change in vegetation cover. For example, research from Carpino et al. (2018: 3) compared historic aerial photographs from 1970 and 1971 with satellite imagery from 2010 and 2011 to determine forest cover change for ten areas of interest in northern British Columbia and the Northwest Territories. The imagery was classified according to landcover type (forested or wetland), which is indicative of permafrost composition (Carpino et al., 2018:3). This study calculated the amount of land cover change by comparing the proportion of forested area to wetland area in 1970-71 and 2010-11 (Carpino et al., 2018:7-8).

Urban planners use change detection analysis to document changes in LULC, including urban sprawl and land degradation. An example of change detection in urban planning is

Amhara, Ethiopia, where 86 percent of forested highlands have been cleared for human use (Ayele et al., 2018:1). Researchers compared satellite imagery from 1995 to 2014 using multiple methods, one of which is image subtraction, a post-classification method (Ayele et al., 2018:3). Changes detected included increased cultivated land and built-up areas for infrastructure development. Monitoring land cover change in urban areas is essential for managing natural resources (Ayele et al., 2018:17).

As previously mentioned, change detection analysis is also used in civil engineering. A standard change detection procedure for routine bridge inspection is visual inspection of multi-temporal imagery (Phares et al. 2001:1; Adhikari et al., 2013:1). Another change detection method used is image differencing which can identify changes in bridge integrity and inspect defects (Adhikari et al., 2013).

Change detection analysis has been used in hazard mitigation (Eckerstorfer et al., 2016; Macciotta and Hendry, 2021). Some examples include avalanche mapping and landslide monitoring. Avalanches are dangerous mass movements of snow that cause fatalities and damage to infrastructure (Eckerstorfer and Malnes, 2015:1). Traditionally, avalanche activity has been mapped through on-site survey, which is hazardous. Recently researchers have begun comparing multi-temporal satellite radar imagery to detect changes in backscatter in avalanche-prone areas. Backscatter, the amount of energy reflected by a target, is higher in areas with rough snow texture, indicating recent avalanche activity (Eckerstorfer et al., 2016:135). Identifying avalanche debris improves avalanche forecasting for these regions, improving safety for backcountry users, and reducing the need for in-person avalanche mapping. Landslides are the mass movement of sediment and rock that can cause damage to roadways and communities. In Western Canada, change detection has been used to monitor geomorphological changes to slope faces (Macciotta and Hendry, 2021). The Chin Coulee landslide near Taber, Alberta, is an example of a landslide impacting the stability of the adjacent highway. Macciotta and Hendry (2021:4) compared point cloud data of Chin Coulee from 1982 and 2019 to measure the displacement and deformation of sediment. The data gathered in this study has provided useful information that can be used to improve risk management framework.

In heritage management and archaeology, change detection has been used to detect, monitor, and measure change to historic and archaeological sites and cultural landscapes (Barlindhaug et al., 2007; Tapete et al., 2013; Boguck and Osińska-Skotak, 2016; Abate, 2019; Hvidberg, 2019; Lercari, 2019, Pennanen, 2019; Agapiou, 2020). An example of the use of change detection to record change is the documentation of the restoration of valuable paintings. Abate (2019) used terrestrial photogrammetry to create point clouds and orthomosaics of an 18th Century painting throughout the restoration process. The point clouds and orthomosaics were then compared using multivariate alteration detection (MAD), a technique that uses an algorithm to determine the relationship between groups of variables (Abate 2019:2).

Another example of change detection used in heritage is recording the deconstruction of the Perrenoud Homestead in Alberta (Hvidberg, 2019). This case study used UAV photogrammetry and TLS to record the deconstruction process of a historic homestead. These methods were used daily, and the orthomosaics and point clouds were compared to document the deconstruction process (Hvidberg, 2019:81).

Change detection analysis is also used to monitor ongoing landscape and environmental changes to heritage sites. In 2013, a bison jump site in southern Alberta was affected by severe flooding (Pennanen, 2019). As a result, faunal material was being actively eroded from the site. The site was scanned using TLS in 2016 and 2017, and the data was compared to quantify the erosional changes (Pennanen, 2019:15). Other heritage researchers have used change detection to detect landscape changes, such as the change to the Royal Castle Gardens in Warsaw (Boguck and Osińska-Skotak, 2016). Historic maps, aerial photographs, and orthomosaic imagery were used to visually document change and record the changes to the garden landscape from 1700 to 2015 (Boguck and Osińska-Skotak, 2016:1).

Additional examples of change detection for monitoring heritage sites include research done on the site of Catalhöyük and near ancient Nazca aqueducts (Lercari, 2019; Tapete et al., 2013). At Catalhöyük, repeat TLS has been used to monitor and quantify the deterioration of wall features of earthen mounds (Lercari, 2019:1). In Peru, researchers used satellite imagery to monitor vegetation growth over archaeological features associated with the Nazca civilization, including aqueducts, the Nazca Lines, and the site of Cahuachi (Tapete et al. 2013:135).

Change detection is also helpful in documenting change to heritage sites in remote areas such as the Arctic or areas of conflict. An example of change detection in the Arctic is change detection in Norway, where the re-growth of forests poses a threat to local archaeological sites (Barlindhaug et al., 2007). Researchers used multi-temporal satellite imagery and vegetation indices to measure vegetation biomass for two study areas to monitor regrowth around archaeological farms (Barlindhaug et al., 2007:235). In Syria, researchers are investigating the potential of time-stamped medium-resolution satellite imagery to detect looting (Agapiou, 2020). While this has been done successfully with high-resolution imagery, such imagery is costly (Agapiou, 2020: 219).

In summary, change detection analysis has been used extensively in various disciplines, including those described above. In heritage, change detection applications include detecting change to heritage sites, documenting the deconstruction of built heritage, and monitoring purposes.

2.3 Chapter Summary

Discussed in this chapter were the technological fundamentals that have been used in this research. These include the principles of aerial photogrammetry and aerial photography, UAV photogrammetry, steps in the photogrammetric process, and the use of photogrammetry in heritage. Change detection was defined, and the types of change detection were briefly summarized. Also included is background information about the two change detection methods used in this research, VIA, and C2C. Change detection analysis and photogrammetry are closely related to remote sensing, and it is crucial to recognize that neither would be viable without considerable advancement in computing and spatial technologies. Data products, such as orthomosaics and point clouds, obtained using aerial photogrammetry, provide excellent data for change detection analysis. Both aerial photogrammetry and change detection analysis are widely applicable to heritage management and archaeology research. Overall, this chapter has provided the reader with the necessary background on the technology and analysis used in this research.

3 CLIMATE CHANGE IN THE CANADIAN BEAUFORT SEA REGION

This chapter describes the impact of modern climate change on the Western Canadian Arctic, specifically the Beaufort Sea coastline within the Inuvialuit Settlement Region (ISR), from the Alaskan border to the eastern reaches of the Mackenzie Delta. While the study area of interest in this research is *Qikiqtaruk* on the Yukon North Slope (see fig. 6), the processes taking place throughout the entire region are highly similar. The first section of this paper outlines the physical environment of the areas discussed in the rest of the chapter, including the Mackenzie Delta, Yukon North Slope, and *Qikiqtaruk*. The second section of this chapter is split into four subsections, each summarizing different environmental processes associated with climate change. These are grouped into warming processes and responses (atmospheric warming, oceanic warming, sea-ice loss), flooding processes (sea-level rise, overland flooding, and storm surge events), permafrost thaw, and coastal erosion. While these processes have been separated in this chapter, it is essential to recognize that they are highly interrelated. The final section of this chapter discusses these environmental processes' impact on heritage in the ISR.

3.1 The Physical Geography of the Beaufort Sea Coast

The ISR is the geographical area covered under the *Inuvialuit Final Agreement* (IFA). It spans several subregions of the Northwest Territories and Yukon, including the Beaufort Sea, Mackenzie Delta, Yukon North Slope, and *Qikiqtaruk* (IRC, n.d.b). Figure 6 below and Figure 15 in section 4.1.2 depict the extent of the ISR. The Mackenzie Delta is situated at the northern margin of North America and the northwestern margin of the Northwest Territories, Canada. To the west of the Makenzie Delta are the Richardson Mountains and the Yukon coastal plain (also commonly called the Yukon North Slope). To the east are the Tuktoyaktuk coastlands and the

Anderson Plain (Burn and Kokelj, 2009:85). The Mackenzie Delta covers an area of 13,000 km^2, with an alluvial fan that is 210 km in length and 65 km in width on average, making it the world's second-largest delta in the Arctic. The delta is underlain with discontinuous permafrost due to the shifting and warming of the numerous river channels (Burn and Kokelj, 2009:83). The interior of the delta is low-lying, with the highest point being 15 m above sea level.

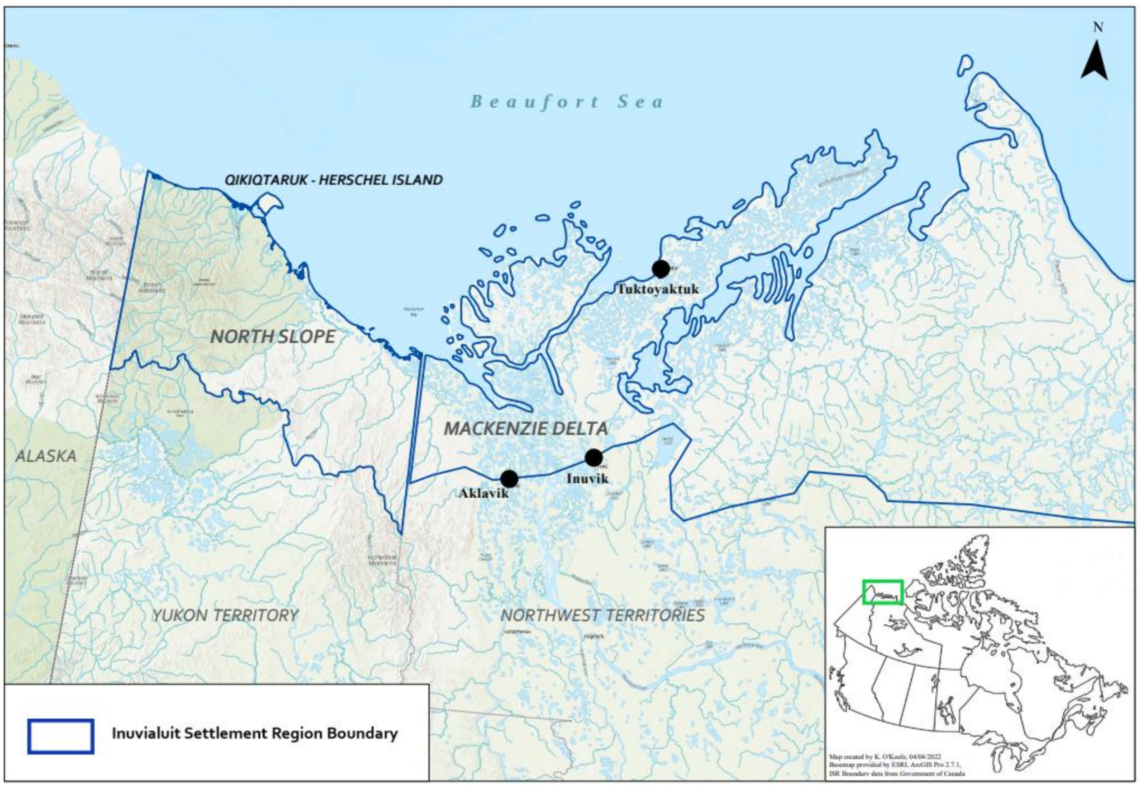


Figure 6. *Map of Beaufort Sea coast including geographical, territorial and ISR boundaries.*
© Katelyn O'Keefe, 2022.

The Delta is a post-glacial feature, having been covered in ice until 14,500 years; however, the outer fringes of the delta, including the area where Inuvik is today, were ice-free throughout much of the last glaciation (Burn and Kokelj, 2009:87). The Delta is covered by sediment from spring meltwaters and Wisconsian till, which overlay thick shale and sandstone bedrock containing significant oil and gas deposits (Burn and Kokelj, 2009:87). The climate of the Mackenzie Delta is characterized by brief warm summers and long cold winters; however, this pattern is changing in response to climate change (Dyke, 2000; Burn and Kokelj, 2009). Most importantly, the Mackenzie Delta is an extensive wetland area that provides habitat for many species of fish, mammals, and migratory birds (Dyke, 2000). For time immemorial, many of these species have formed the basis of traditional subsistence for the Inuvialuit (formerly called the Mackenzie Inuit).

The Yukon North Slope runs along the entire length of the north Yukon coast and is comprised of three distinct physiographic regions, the Yukon coastal shelf, the Yukon coastal plain, and the Yukon coastal slope (see fig. 7). The coastal plain is a narrow strip of land 25 km wide at the Blow River and 10 km wide at the Yukon-Alaska boundary (Yorga, 1980:9). To the south of the coastal plain is the coastal slope, which consists of rolling hills and terraces until reaching the base of the mountains (Yukon Ecoregions Working Group, 2004:64). Near the Alaska border, these mountains are the British Mountains, whereas, in the eastern part of the Yukon North Slope, the coastal slope extends further towards the Richardson Mountains. Where the coastal plain intersects the Beaufort Sea, the edge of the plain is marked with steep, low cliffs and narrow beaches. To the west of the Yukon North Slope is the Alaska-Canada border, where the coastal slope widens towards the Brooks Range. The waters along the coastal shelf remain shallow, and the discharge from the Mackenzie River keeps the water warm relative to further off the coast (Williams and Carmack, 2012:55).

The Yukon North Slope is composed of 80 percent tundra and 20 percent lakes and wetlands. Elevation throughout the plain is on average less than 30 m above sea level and increases to the east towards the Mackenzie Delta (Yukon Ecoregions Working Group, 2004:64). The eastern portion of the Yukon North Slope was glaciated during the Wisconsian, but the western portion, beginning 12 km west of *Qikiqtaruk*, was not (Yukon Ecoregions Working Group, 2004:65). While permafrost is continuous throughout the North Slope, it is thicker in the west, where the base is estimated to be up to 700 m below the surface (Yukon Ecoregions Working Group, 2004:67). Glacial deposits, combined with colluvium and alluvium, cover the bedrock throughout the eastern Yukon North Slope. Throughout the Yukon North Slope, the landscape is greatly influenced by fluvial and shoreline processes (Yukon Ecoregions Working Group, 2004:64). Retrogressive thaw slumps, permafrost polygons, thermokarst lakes, and pingos are common features, and numerous large rivers flow into the Beaufort Sea. From east to west, these rivers are the Big Fish, Blow, Babbage, Firth, and the Malcolm (Yukon Ecoregions Working Group, 2004:64).

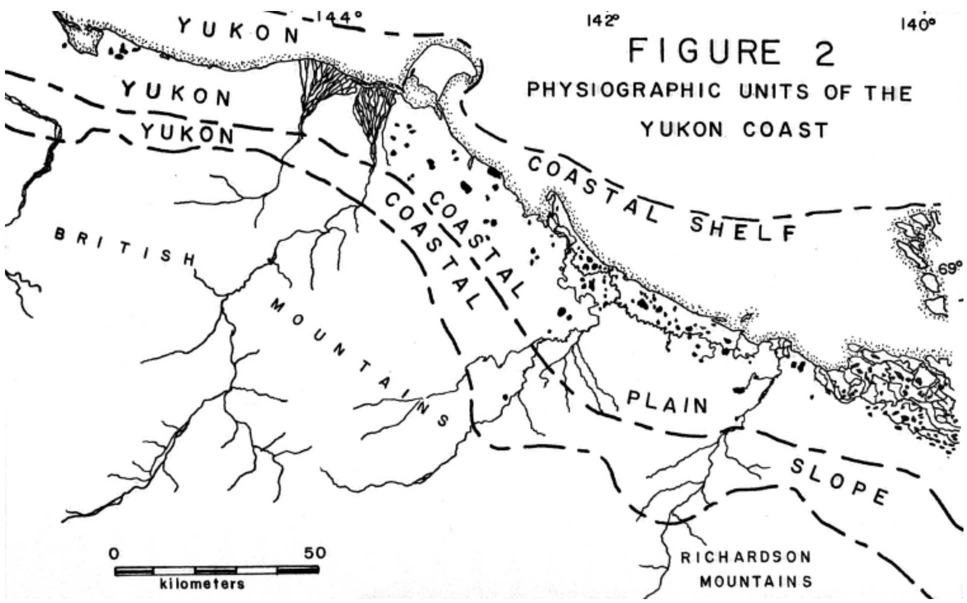


Figure 7. *The physical geography of the Yukon North Slope (Yorga, 1980:8).*

The massive alluvial fans generated by the large rivers are gradually vegetated. The coastal margin is covered in thick peat, and vegetation is dominated by low tundra vegetation, including shrubs, lichens, and willows (Yukon Ecoregions Working Group 2004:68-69). There are no trees on the Yukon Coastal plain, but there is a significant amount of driftwood along the coast, supplied by the Mackenzie River and the Firth River (Kindle, 1921; Eggertsson, 1994; Yukon Ecoregions Working Group, 2004:63). Like the Mackenzie Delta, winters are prolonged and are followed by brief warm summers. The Yukon North Slope coast winds are persistently strong, keeping the coast cooler than several kilometers inland (Yukon Ecoregions Working Group, 2004:67). The western portion of the Yukon North Slope is within Ivvavik National Park, created to protect the calving grounds of the Porcupine Caribou herd. Other species found in the Yukon North Slope include arctic fox, polar bear, grizzly bear, muskoxen, and numerous rodent species (Yukon Ecoregions Working Group, 2004). Additionally, the Yukon North Slope is one of the richest areas for migrating bird species, including many species that do not nest elsewhere in the Yukon (Yukon Ecoregions Working Group, 2004:72).

Qikiqtaruk is the only island off the Yukon Coast and is Canada's most northern island in the Western Arctic (Burn et al., 2012a:3). The island was formed when submerged ice-rich sediments from the adjacent oceanic basin (Herschel Basin) were thrust into a moraine ridge by a lobe of the advancing Laurentide Ice Sheet, called the Buckland Glaciation (Zazula, 2012:62-63). This lobe receded eastward by 16,000 years BP, leaving the moraine exposed, becoming a viable environment for ice-age megafauna. As a result, many ice-age fossils continue to be found on *Qikiqtaruk* (Zazula, 2012:63). The peninsula formed by the moraine was severed by post-glacial sea-level rise within the last 1,600 years (Zazula, 2012:63). The island has an area of 116 km^2 with steep cliffs along its periphery, and these cliffs surround gently rolling hills. The cliffs are 60 m above sea level, and the highest point on the island is 182 m above sea level, making it higher than the mainland across the passage (Burn, 2012:30-31). There are several low-lying spits on the southern end of the island, including Simpson Point (adjacent to Pauline Cove), Osbourn Point, Lopez Point, and *Avadlek* Spit. Figure 8 is a map of *Qikiqtaruk*.

The climate mimics the mainland, and the vegetation is dominated by low-lying tundra vegetation and small willows. However, research indicates that the willow canopies have been expanding (Myers-Smith et al., 2011a). Most of the official place names on *Qikiqtaruk* and the Yukon North Slope were given by Captain John Franklin in 1826 or by Lt. Cdr. Charles Stockton, commander of the U.S.S. *Thetis*, during a survey in 1889 (Burn and Hattendorf, 2011). All the geographic features on *Qikiqtaruk* have English names, except for *Avadlek* Spit, which is Inuvialuktun. See Table 12 in the appendix for a list of the English and Inuvialuktun place names, with meanings, for *Qikiqtaruk* and the Yukon North Slope.

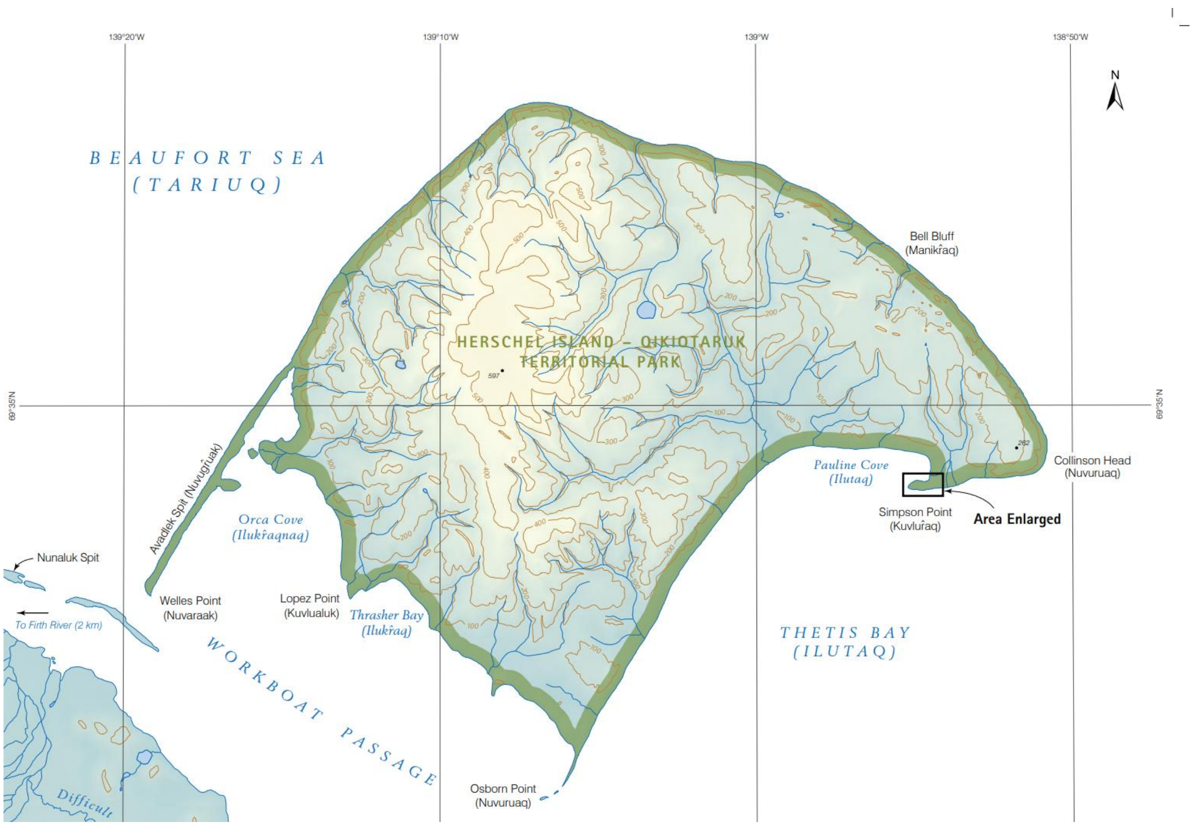


Figure 8. *Locations of landforms on Qikiqtaruk. Modified from original published in Yukon Government (2019a:vii).*

3.2 Climate Change

Modern climate change is defined as climate change greatly influenced by human activity (Karl and Trenberth, 2003:1719). Modern climate change is complex, making it challenging to study using traditional scientific methodology. As such, it has been termed a "wicked problem," defined as a problem or situation that cannot easily be studied because of its complicated inter-related components or processes and lack of stopping point (Rittel and Webber,1973:161-162; Ludwig, 2001:759). As a result, it overwhelms existing solutions. The change resulting from these processes is the feedback from climate forcing mechanisms, which alter the earth's energy balance (National Research Council, 2001:6). The most significant forcing mechanism is radiative forcing, which is when natural or anthropogenic drivers force a change in the earth's energy equilibrium (National Research Council, 2001; Myhre et al., 2013). Radiative forcing disproportionately impacts the Arctic. According to the United Nations International Panel on Climate Change (IPCC), this is causing the Arctic to change faster than anywhere else on earth (IPCC, 2014). Radiative forcing is directly related to higher sea levels and longer ice-free seasons, leading to increased erosion and increasingly frequent storm events (IPCC, 2014). The Western Canadian Arctic, including the Yukon North Slope and the Mackenzie Delta (see fig. 6), is of grave concern because of its permafrost-rich coastline and low-lying coastal morphology, intensifying coastal processes (Shaw et al., 1998; Ford et al., 2017). Climate change impacts the physical environment and changes the cultural landscape, destroying archaeological sites (Friesen et al., 2012; Irrgang et al., 2019).

There is ongoing research into the impacts of climate change in the Western Canadian Arctic on the physical and cultural environment (Bonsal and Kochtubajda, 2009; Lamoureux et al., 2015; Ford et al., 2017; O'Rourke, 2017; Lim et al., 2020). Indigenous communities in the

Arctic have documented the change happening in and around their traditional lands, and as a result, recent research has included emic perspectives (Riedlinger, 2001; Nichols et al., 2004; Waugh et al., 2018). This section summarizes climate change-related processes impacting the Beaufort Sea coastline, including atmospheric warming, oceanic warming, sea ice loss, sea-level rise, storm surge events, permafrost thaw, and coastal erosion.

3.2.1 Atmospheric Warming, Oceanic Warming, and Sea Ice Loss

Greenhouse gases are released naturally and through human activity (Guilyardi et al., 2018:4). These gases trap heat, preventing it from leaving the atmosphere. The most significant greenhouse gases are water vapor, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Dessler, 2016:67-68). Since the Industrial Revolution, human activity has drastically increased the quantity of greenhouse gases entering the atmosphere, causing an increase in global temperatures (Shine, 2010). This process is called radiative forcing, which creates feedback that impacts all other climate processes discussed in this section (Shine, 2010). There has been an increase of 1.5 degrees Celsius globally since the industrial revolution; however, a further increase of 0.5 degrees Celsius is expected between 2030 and 2052 (Guilyardi et al., 2018:4). In northern Canada, temperatures have already warmed by an average of 2.3 degrees Celsius since 1948, with the Western Canadian Arctic warming the fastest (Zhang et al., 2019:116). Figure 9 is a map of the recorded atmospheric warming in Canada from 1948 to 2016.

The Arctic is warming faster than anywhere else on earth due to high sensitivity to surface air temperature (SAT) change, a concept called Arctic amplification (Serreze et al., 2009; Overland et al., 2011; Stretletskiy et al., 2015). Arctic amplification results from a positive feedback loop due to sea ice loss and ice-albedo feedback (Serreze et al., 2009; Overland et al., 2011). This feedback occurs as follows; high SAT in the summer months causes an increase in sea ice melt, leaving the ocean exposed to solar radiation. Albedo is the ability of a surface to reflect solar energy, represented by a unitless number from zero to one, with one denoting a surface that reflects 100 percent of incoming radiation (National Snow and Ice Data Center, 2020). The ice-free ocean has an albedo of 0.06, meaning that it reflects six percent and absorbs ninety-four percent of incoming solar radiation. The albedo of sea ice, while varying due to thickness and snow cover, has a much higher albedo, ranging from 0.5 to 0.7 (National Snow and Ice Data Center, 2020). As a result, the ocean surface temperature increases and remains warm longer due to high heat capacity (Serreze et al., 2009).

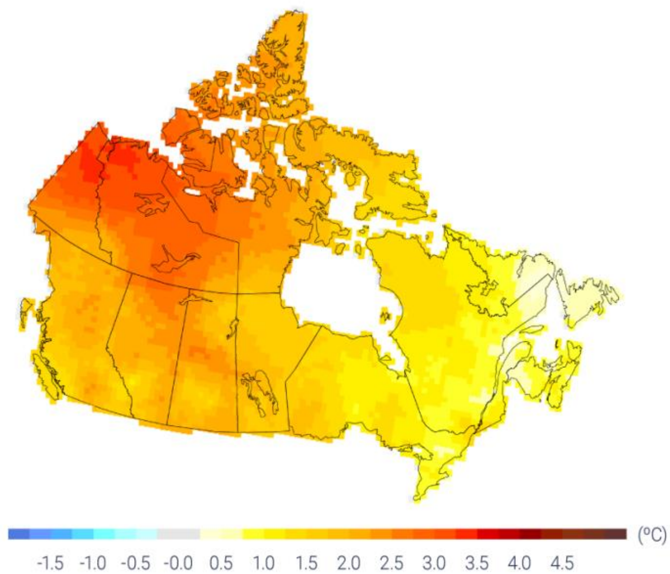


Figure 9. *Atmospheric warming in Canada from 1948 to 2016 (Zhang et al., 2019:126).*

The ocean retains the heat for an extended period and, in the fall, warms the air in contact with its surface, which delays sea ice formation. Open water promotes vertical heat flux with minimal vertical atmospheric mixing, causing temperatures to increase further (Serreze et al., 2009). As a result of this positive feedback loop, SAT has risen by 5.0 degrees Celsius in the Beaufort Sea region (Dumas et al., 2005). Since the 1990s, surface air temperature anomalies have shifted from negative to strongly positive, with the strongest positive anomalies found along the Beaufort Sea coastline in the autumn months (September-November), exceeding 5.0 degrees Celsius (Serreze et al., 2009). A temperature anomaly is the difference from a baseline temperature, typically computed by averaging temperature data over multiple decades (Dessler, 2016:17). In the last century, mean air temperatures in the Mackenzie Delta have risen 1.9 degrees Celsius, and there are 14.3 additional days where maximum air temperature reached 20.0 degrees Celsius (Lantz and Kokelj, 2008). On *Qikiqtaruk*, historic air temperatures from 1899 and 1905 have been compared to modern temperature data. The results indicate a 2.5 degrees Celsius increase in the last 100 years (Burn and Zhang, 2009:15). Overall, the Mackenzie Delta and the Yukon North Slope are particularly vulnerable to atmospheric temperature changes due to greenhouse gas emissions.

Ocean temperature is increasing in the Western Canadian Arctic, primarily due to atmospheric warming, as discussed in the previous subsection (IPCC, 2014; Ford et al., 2017). Oceanic temperatures in the Beaufort Sea have fluctuated throughout time and are well documented (Farmer et al., 2011). Research from Farmer et al. (2011) measured oceanic temperature fluctuation through time using sediment core analysis for cores covering the last 8000 years. Various microorganisms present within the oceanic sediment cores were used to determine the subsurface Atlantic Layer (AL) temperature over time. Changes in the relative abundance of certain species of microorganisms were then correlated with the temperature of the AL layer at periods in history (Farmer et al., 2011). The study results were that the AL layer has fluctuated between minus 1.0 to positive 1.5 degrees Celsius, with warm periods occurring 6500 years ago, 3500 years ago, 1800 years ago, and 500 years ago (Farmer et al., 2011). This information is valuable because the AL layer is known to warm when it mixes with the ocean's uppermost layer, called the Polar Mixed Layer (PML). When the atmospheric temperature warms the ocean via the PML, the AL is warmed upon contact. Higher AL temperatures result in an increase in water volume, which causes the upwelling of the AL into the PML (Farmer et al., 2011:4). These layers hold a significant amount of heat, which is then released into the cooler atmosphere in the autumn, completing the feedback loop. At present, ocean temperatures in the AL are warmer than in the last 1000 years, likely due to anthropogenic influences (Farmer et al., 2011). Given the positive feedback loop described above, oceanic warming will likely continue to increase.

Changes in SAT and oceanic temperature are directly linked to changes in the sea-ice melt, formation, type, extent, and mobility (Overland et al., 2011; Barnhart et al., 2014; Barnhart et al., 2016). The Western Canadian Arctic is becoming ice-free earlier in the year, and freeze-up occurs later in autumn than in the past (Overland et al., 2011:1). The open ocean season on the Canadian Beaufort Sea coastline increases by 1.5 to 2.5 days/year (Barnhart et al., 2016:284). Simulations based upon the Community Earth System Model Large Ensemble (CESMLE), a climate model used to project future climate based upon user imputed variables, predict that the entire arctic coastline will experience elongating ice-free seasons (Barnhart et al., 2016:280). By 2050 most Arctic regions will have an additional 60 days of open water, though some areas may have 100 additional ice-free days. By 2100, the average open water season is expected to expand by 150 days (Barnhart et al., 2016:280). For the Beaufort Sea, CESMLE predicts a sharp increase in the number of ice-free days, with as many as 350 by the year 2100 (Barnhart et al., 2016:281). The remaining ice is also thinner than in the past. Across the Canadian Arctic, sea ice has already thinned by a mean of 0.70 m (Overland et al., 2011:5). The amount of multi-year ice is also declining, and in just a short four-year period, multi-year ice in the Arctic declined by 42 percent (Overland et al., 2011:5).

Additionally, advection, the transfer of heat by fluid flow, continually shifts the extent of multi-year ice northward (Overland et al., 2011:5). In the Beaufort Sea region, seasonal ice is becoming the dominant form; land-fast ice is melting earlier, forming later, and thinning extremely quickly (Dumas et al., 2005). Variables affecting sea ice include atmospheric temperature, oceanic temperature, and snowfall. High atmospheric temperature delays snowfall accumulation on ice, shortening its duration (Dumas et al., 2005). Dumas et al. (2005) created a model designed to project future ice conditions in the Beaufort Sea based upon IPCC predictions of temperature increase. The model projects that an increase in average atmospheric temperature of 4.0 degrees Celsius and an increase in snowfall of between 20 percent and 100 percent will result in thinning equivalent to 24 to 39 cm. In addition, a warming of 4.0 degrees Celsius results in a three-week reduction in sea ice duration (Dumas et al., 2005:50).

Inuvialuit have witnessed changes to sea ice firsthand. Sea ice is critical for travel, which is necessary for traditional hunting activities (Nichols et al., 2004; Waugh et al., 2018). Community members have described the ice as being thinner and more dangerous to travel on, resulting in changes to hunting activities. Additionally, Inuvialuit respondents noted that multi-year ice is being replaced with thin, single-year ice. It was also observed that there had been delays in ice formation in the fall. Ice breakup was stated to be occurring significantly faster than in the last few decades, with breakup happening in mid-June instead of late June or early July (Nichols et al., 2004; Pearce et al., 2011).

In summary, the Arctic is warming due to Arctic Amplification, and atmospheric and oceanic temperature increases drastically impact the Western Canadian Arctic. These temperature changes result in changes to sea ice. Atmospheric temperature increases are linked to oceanic temperature increases, and precipitation is related to sea ice thickness, extent, and duration. Models based upon IPCC predictions for SAT increase show that sea ice in the Beaufort Sea will continue to be drastically reduced.

3.2.2 Sea-level Rise, Flooding, Storm Surges, and Driftwood Deposition

As mentioned previously, climate change processes are highly interconnected. Sea-level rise is most directly related to oceanic and atmospheric temperature change; however, globally, sea-level rise can be attributed to three main eustatic components. These components are 1) the addition of fresh water from melting glaciers, 2) thermal expansion, and 3) mass wasting of the Greenland and Antarctic ice sheets (Church et al., 2013; McKay et al., 2011). Glaciers account for less than one percent of global land ice but are significant contributors to sea-level rise due to their high sensitivity to change. The glaciers act as the most significant contributors to future sea-level rise in the Canadian Arctic, Alaska, Russia, Svalbard, and the peripheries of Greenland and Antarctica (Huss and Hock, 2015). Glaciers are expected to recede significantly before the year 2100, and according to relatively simplified models, this melt will result in a 102 to 242 mm global sea-level increase (Huss and Hock, 2015:2). Stemming from research by Huss and Hock (2015), a new model called GloGEM was created. This model incorporates melting calculations for 200,000 individual glaciers and continuously updates using the latest climate data. This model suggests a global glacier volume loss of 25 to 48 percent by 2100; however, some melt stems from glaciers presently below the waterline (Huss and Hock, 2015:1).

When accounting for submerged glaciers presently displacing water, Huss and Hock (2015:1) calculate that global sea levels will rise by 79±24 mm, 108±28 mm, or 157±31 mm, respectively, for the three common emission scenarios put forward by Meinshausen et al. (2011).

The second reason for widespread sea-level rise is thermal expansion, which is the volumetric increase of the ocean in response to higher temperatures (Wigley and Raper, 1987; Church et al., 2013). From 1993 to 2003, approximately 30 percent of the observed sea-level rise can be attributed to thermal expansion (Domingues et al., 2008). Since the 1970s, thermal expansion from atmospheric warming combined with glacial melt has been responsible for 75 percent of the observed global mean sea-level rise (IPCC, 2014). Melt from the Antarctic and Greenland ice sheets is relatively recent, occurring only since the 1970s (Church et al., 2013). Current projections for global sea level are most influenced by thermal expansion, which accounts for up to 55 percent of the projected change, followed by glaciers, which account for up to 35 percent of the projected change. The IPCC projects that by 2046-2065, the expected global average sea-level rise is between 0.24 m to 0.30 m, relative to levels from 1986-2005. For the year 2100, the expected global average sea-level rise is projected to be between 0.44 m and 0.74 m, relative to the levels from 1986 to 2005 (Church et al., 2013:11). In some regions like the Western Canadian Arctic, the rate of sea-level rise will exceed the global average due to localized phenomena.

Sea-level rise is hastened by isostatic subsistence along the Yukon North Slope and the Mackenzie Delta (Shaw et al., 1998; Manson and Solomon, 2007). Isostatic subsidence, a slow decline in elevation due to the sinking of the earth's crust, contributes to relative sea-level rise (Shaw et al., 1998; Manson and Solomon, 2007). According to IPCC's Fifth Assessment Report, global sea-level rise is measured in reference to the surface of the solid earth (Church et al., 2013). The Beaufort Sea region's localized sea-level rise is currently 0.015 m/year (Andersen and Piccioni, 2016:5). By multiplying the yearly change by the number of years until 2100, the yearly change can be calculated as a localized average sea-level rise of over 1.2 m by 2100. This figure is likely an underestimation since the factors contributing to sea-level rise are not linear in nature but rather change exponentially in response to exponentially increasing forces, like glacier melt and thermal expansion (Church et al., 2013). Overall, Canada's coastline adjacent to the Beaufort Sea is dramatically impacted by relative sea-level rise due to both eustatic sea-level rise and isostatic subsidence. An increase in sea level makes the coastal regions more susceptible to overland flooding events (Church et al., 2013). The submergence of the coastline will amplify eustatic sea-level rise and further impact low-lying areas such as Pauline Cove on *Qikiqtaruk* and the Mackenzie Delta.

Sea-level rise is not the only cause of flooding in the Western Canadian Arctic. Storm surge events are becoming more frequent (Danard et al., 2003). A storm surge is a surge of water that occurs in response to a low-pressure system, which slopes the ocean surface and physically draws the ocean upwards. Alternatively, high winds can create a pilling effect because of significant wind stress on the ocean surface (Danard et al., 2003:408). Large expanses of ice-free ocean (known as fetch) are conducive to piling. Storm surges that result in water being pulled toward a neighboring land body are called positive storm surges. When the water is pulled away from a land body, sometimes before the positive surge arrives, it is called a negative storm surge or a reverse storm surge (Danard et al., 2003). The strongest storm surges occur when a combination of high winds and high astronomical tides are associated with a low-pressure system. Other variables that influence storm intensity and duration are ocean bathymetry, shoreline geometry, and ice-free extent (Kowalik, 1984; Hudak and Young, 2002; Danard et al., 2003).

In the Beaufort Sea, northwesterly winds create a positive surge, whereas easterly winds cause negative surges (Remnitz and Maurer, 1979; Radosavljevic et al., 2015). The Beaufort Sea is microtidal, so the wind is more significant in storm surge development in the region (Radosavljevic et al., 2015). Storm surges in the region are unique in that they are concentrated in the summer and the fall when the ocean is partially ice-free (Kowalik, 1984). As previously discussed, increasing atmospheric and oceanic temperatures are causing reductions in sea ice and an extended ice-free season. Sea ice is no longer a limiting factor for wind-driven maximum wave height (Vermaire et al., 2013). Combined with an extended ice-free season, storm surges are becoming more frequent (Overeem et al., 2011). This pattern is being detected in the fall in the Beaufort Sea due to a disproportionately elongated ice-free season. As a result, the quantity of storm surge events is increasing during September and October (Vermaire et al., 2013).

There have been two notable storm surges in the Beaufort Sea within 50 years (Remnitz and Maurer, 1979). The first of these occurred in the fall of 1970, before freeze-up. The winds blew from the northwest at 130 km/hr (Remnitz and Maurer, 1979:331). There was a large ice-free area, with the ice pack located 150 km off the coast. These conditions were ideal for a significant surge. The storm in the fall of 1970 resulted in a 2.4m-high water surge, striking the outer Mackenzie Delta with waves larger than 3 m and reversing the flow of the Mackenzie River (Remnitz and Maurer, 1979:331). Aerial imagery documented extensive driftwood deposition and coastal erosion (Department of Public Works, 1971; Remnitz and Maurer, 1979). In September of 1999, another storm in the Beaufort Sea occurred. The surge impacted the outer Mackenzie Delta and is the largest documented surge in the last 1000 years (Lapka, 2013). The floodwaters swept inward up to 30 km in the Mackenzie Delta (Pisaric et al., 2011). Storm surges in the Beaufort Sea impact the coastline by hastening coastal erosion and increasing the frequency of overland flooding (Terenzi et al., 2014; Thomson and Rogers, 2014). A longer open water season and, therefore, more storm surges cause an increase in overland flooding events

(Terenzi et al., 2014). As mentioned previously, overland flooding inundates inland vegetation with salt, which devastates sensitive Arctic tundra plant species, which require extensive recovery periods (Lapka, 2013). In summary, storm surges are becoming more frequent in the Western Canadian Arctic due to a reduction of sea ice and an ever-expanding ice-free season. These surges are destructive to the coastline and cause erosion, flooding, and vegetation loss.

Driftwood is brought to the Mackenzie Delta by the Mackenzie River and to the North Slope by the Mackenzie River and the Firth River (Kindle, 1921; Eggertsson, 1994; Kramer and Wohl, 2015). Storms and other flooding events deposit driftwood further up the beach (Kramer and Wohl, 2015). During large storms, coastal regions with high bluffs are damaged by the repeated contact with driftwood at the bluff's base. Driftwood can cause damage to infrastructure and the environment by way of coastal erosion (Doong et al., 2011). Conversely, driftwood deposition on low-lying beaches can cause beach accretion because sediment and, eventually, vegetation can build up behind the driftwood deposits (Doong et al., 2011; Kramer and Wohl, 2015).

3.2.3 Permafrost Distribution and Thaw

Permafrost is a ground that remains frozen year-round for more than one year (Burn et al., 2012b; Short et al., 2011; Streletskiy et al., 2015). The Western Canadian Arctic is dominated by continuous permafrost degraded by climate change (Streletskiy et al., 2015; Cunliffe et al., 2019). The Mackenzie Delta is comprised of continuous permafrost, and the outer coastline of the delta and the Yukon North Slope are comprised of both continuous permafrost and subsea permafrost (Burn and Zhang, 2009). Permafrost distribution is related to climate gradient. The warmer the ground is at the surface, the warmer the permafrost and the thicker the active layer (Burn et al., 2012b). The active layer is the layer above the permafrost that thaws in the summertime. In the high arctic, the active layer is thinner than in the southern reaches of the permafrost zone, where it can be up to 2.0 m thick (Streletskiy et al., 2015). Variables that affect active layer thickness (ALT) are temperature, precipitation, topography, vegetation, and soil properties (Streletskiy et al., 2015). Increasing temperatures cause an increase in ALT and an increase in permafrost temperature. This pattern was documented on *Qikiqtaruk* by Burn and Zhang (2009), who found that permafrost had warmed 2 degrees Celsius in the last century, resulting in a 20cm increase in ATL. An increase in rain also increases ALT (Streletskiy et al., 2015). The relationship between ALT and topography is another crucial factor to consider because topographical differences such as slope, elevation, and exposure cause variation in permafrost thaw (Stretletskiy et al., 2015). For example, increased elevation corresponds to a decrease in ALT. Vegetation cover also contributes to the ALT since it has an insulative effect on the land surface. Moss acts as a buffer for heat exchange because of its low thermal conductivity in the summertime, keeping soil temperatures lower than they would be without moss cover (Streletskiy et al., 2015). The relationship between ALT and soil type is more complex. Different soils have different thermal conductivity and heat capacities. In dry conditions, soils made of larger particles, such as sand, have higher thermal conductivity, linked to thicker permafrost development (Streletskiy et al., 2015). However, adding moisture to any soil type increases thermal conductivity, resulting in a thinner permafrost layer. The loss of permafrost, especially on coastlines, is problematic in the Western Canadian Arctic because the land gets rapidly eroded (Lantuit and Pollard, 2008; Cunliffe et al., 2019). Permafrost thaw mass wasting occurs in three main ways, block failure, retrogressive thaw slumping, and active layer detachments, all of which appear on the landscape as characteristic landforms (Lantuit and Pollard, 2008; Burn and Zhang, 2009; Burn et al., 2012b; Cunliffe et al., 2019;). Block failure is the detachment of a block-sized section of the coastline resting on an ice wedge, usually due to thermal erosion caused by waves (Overeem et al., 2011; Hoque and Pollard, 2016). Retrogressive thaw slumping occurs on slopes where permafrost becomes exposed due to coastal erosion (Obu et al., 2016). The exposed massive ice on the slope begins to melt. If the slope melts faster than the rate of erosion of the coastline, a steep semicircular headwall is created. This headwall continues to retreat due to exposure to the sun, and the eroded material at the base of this landform gets deposited at the base of the slump or runs into the ocean (Lantuit and Pollard, 2008). Active layer detachment occurs when the active layer detaches from the underlying permafrost and gets released down a slope (Lewkowicz, 1990). A viable technique to measure ground displacement as a function of permafrost thaw is synthetic aperture radar interferometry (InSAR), a remote sensing technique (Short et al., 2011).

Permafrost acts as a reservoir for methane, a potent greenhouse gas (McGuire et al., 2009). Currently, methane released from permafrost makes up 20 to 30 percent of global carbon emissions (McGuire et al., 2009). Methane is the net product produced by methanogens (methane generating species) and methanotrophs (methane consuming bacteria) communities present within the permafrost substrate, under waterlogged and anoxic conditions (Barbier et al. 2012). On *Qikiqtaruk*, microbial communities have been studied and found to create varying methane concentrations within the permafrost substrate (Barbier et al., 2012). The knowledge acquired from the results of this research is valuable because it means that the amount of methane released depends on the type of microbial community present within that permafrost. Therefore, microbial communities can be studied to inform scientists about the magnitude of possible methane release for individual sections of the permafrost coastline in the Arctic (Barbier et al., 2012).

3.2.4 Coastal Erosion

Coastal erosion removes sediment from a coastline by erosional processes (Burn et al., 2012b). As part of an interconnected system, the climate change processes discussed previously in this system all contribute to coastal erosion in one way or another. Increases in atmospheric and oceanic temperatures result in permafrost thaw and thermal erosion (Lunardini, 1996). The warmer the air temperature, the greater the SAT and the warmer the permafrost becomes. This warmth triggers active layer detachment and sediment runoff into the ocean (Streletskiy et al., 2015). Rising oceanic temperature and sea-level rise cause flooding and thermal erosion by waves, which undercuts ice-rich coastlines (Cunliffe et al., 2019). Warmer oceanic temperatures result in the depletion of sea ice, which acts as a protective buffer limiting the physical vulnerability of coastlines to waves (Barnhart et al., 2014). A reduction in sea ice correlates to increased storm surge events per year (Overeem et al., 2011). Storm surges bring warm saline water towards the coastline, which thaws permafrost upon contact and through wave abrasion (Cunliffe et al., 2019). During storm surge events, overland flooding and driftwood deposition are common (Kramer and Wohl, 2015). Overland flooding causes saline inundation, killing vegetation and encouraging thermal erosion, effectively destabilizing the coastline (Lapka, 2013; Terenzi et al., 2014). Driftwood deposited on low-lying beaches protects low-lying beaches against coastal erosion because it encourages beach accretion (Kramer and Wohl, 2015). Conversely, driftwood accumulation damages the bases of high bluffs, which are battered by the material during periods of high wave action (Doong et al., 2011). Permafrost thaw is a considerable contributor to coastal erosion (Cunliffe et al., 2019). An increase in ALT of the permafrost leads to an increase in mass wasting events in active layer detachments, retrogressive thaw slumping, and block failure. The faster the permafrost melts, the faster new permafrost is exposed to warm temperatures, and the faster the coastline erodes (Cunliffe et al., 2019).

Along the Yukon North Slope and the outer periphery of the Mackenzie Delta, rapid coastal erosion is troubling. In some communities, control measures have been used to slow the erosion since the 1970s; however, lessening the impact of the damage is extremely expensive (Shaw et al., 1998; CBC News, 2019). Between the 1950s and 1970s, the shoreline of the Yukon North Slope eroded at a mean rate of 1.3 m/yr. Between the 1970s and 1990s, the mean erosion rate fell to 0.5 m/year. Unfortunately, the erosional rate has since increased and has returned to 1.3 m/year, with localized rates as high as 8.9 m/year (Irrgang et al., 2018). On the southeastern shores of *Qikiqtaruk*, between Collinson Head and Pauline Cove, extremely rapid erosion has been documented (see fig. 10). In the summer of 2017, 14.5 m of coastline was lost, which is over six times the average erosional rate from 1952 to 2011 (Cunliffe et al., 2019). Overall, erosion on the North Slope impacts settlements, infrastructure, wildlife, and culturally significant areas (Radosavljevic et al., 2016; Irrgang et al., 2018; Irrgang et al., 2019).

Figure 10. *Rapid erosion of coastline near Pauline Cove, Qikiqtaruk, in July 2019.* © Katelyn O'Keefe, 2019.

3.3 Implications for Heritage

Climate change processes impact Inuvialuit heritage resources across the Inuvialuit Settlement Region (Friesen et al., 2012; Irrgang et al., 2019). Heritage resources are impacted by overland flooding, storm surges, permafrost thaw, and coastal erosion (Friesen et al., 2012). Historic structures in low-lying areas, like those on Simpson Point on *Qikiqtaruk*, or at Shingle Point, on the North Slope, are at risk of flooding. The immediate risk can be lessened by lifting the buildings or stabilizing them and moving them from their original locations. This has already been done for several buildings at Pauline Cove (Friesen et al., 2012; Yukon Government, 2019a). Unfortunately, relocation efforts are only feasible for historic structures and archaeological features, including the remains of Inuvialuit sod houses, cannot be relocated. Therefore, the risk of flooding cannot easily be lessened, and they will eventually be lost to erosion (Friesen, 2012, Irrgang et al., 2019). Presently, storm surge-induced episodic flooding is more problematic for low-lying heritage sites because it brings large amounts of saline water onto the land surface. Episodic flooding is problematic because, as previously mentioned, it inundates the area with salt, killing vegetation. The vegetation loss makes the coast less stable and more susceptible to erosion (Lapka, 2013). Heritage on high bluffs is most at risk of coastal erosion due to permafrost melt and wave action.

Researchers with the Arctic Cultural Heritage at Risk Project (Arctic CHAR) have created a model to predict the storm surge vulnerability of archaeological sites in the Mackenzie Delta (Friesen, 2015b). The model was tested by repeatedly ground-truthing a coastal stretch with known archaeological sites (O'Rourke, 2017). For the Yukon North Slope, Irrgang et al. (2019) used aerial photographs from 1950 to 2011 to create two scenarios that depict risk to heritage by coastal erosion. The first scenario (S1) is conservative, predicting a loss of 850 hectares of coast lost to coastal erosion by 2100. Under this scenario, 45 percent of known cultural features will be lost. The second scenario is less conservative, predicting a loss of 2660 hectares by 2100. According to this scenario, 61 percent of known cultural features along the Yukon North Slope will be lost to erosion (Irrgang et al., 2019). Warmer temperatures also cause organic deposits in archaeological sites to decay before being lost to erosion (Hollesen et al., 2016). Once thawed, the deposits are subject to microbial degradation, generating even more heat (Hollesen et al., 2016).

With countless archaeological sites at risk, efforts have been made to document and mitigate the heritage resources at greatest risk. The Arctic CHAR Project (2012-2017) identified high-risk sites in the lower east channel of the Mackenzie Delta. Upon identification, the selected sites were excavated, and their artifacts were preserved (Friesen, 2017). Archaeological sites are also being digitally recorded using terrestrial laser scanners (Dawson et al., 2009). Laser scanning is an effective tool to quickly document an archaeological site, such as an Inuvialuit sod house. In addition, digital models can be made for educational purposes (Dawson et al., 2009). In this research, a UAV was used to capture imagery of Simpson Point on *Qikiqtaruk*, the island's most heritage-rich area.

3.4 Chapter Summary

In this chapter, the physical geography of the ISR, from the Alaska-Yukon Border to the outer Mackenzie Delta, was described. There was a particular emphasis on *Qikiqtaruk*, the area of interest in this study. The following section discusses modern climate change in the region previously described, with documentation from academic researchers, the federal government, and the IPCC. The various processes described in this chapter are part of a complex system and are highly interrelated. The final section of this chapter summarized the impact of climate change on heritage sites on the Yukon North Slope, *Qikiqtaruk*, and the Mackenzie Delta, many of which are in coastal areas. The information presented in this chapter provides the reader with a geographic understanding of the area of interest in this study. In addition, knowledge of climate change processes in this region is beneficial when considering the significance of the sites mentioned in the following chapter.

4 CULTURAL BACKGROUND

This chapter provides the necessary cultural background for the research presented in this thesis. The study area for this research is Simpson Point, a spit adjacent to Pauline Cove on *Qikiqtaruk* (also known as Herschel Island), an island off the Yukon North Slope (see fig. 8 in section 3.1). The island is culturally significant due to a nearly continuous record of occupation spanning the last 800 years (Friesen, 2012). Not only was the island inhabited by the Inuvialuit and their ancestors, the Thule, but in the late 19th and early 20th centuries, Pauline Cove was used for large-scale whaling and trading activities. In addition, others were drawn to the area, including missionaries and, later, the Royal Canadian Mounted Police (RCMP). In 1987, *Herschel Island – Qikiqtaruk Territorial Park* was created to protect the unique cultural and physical landscape. The modern Inuvialuit, the descendants of the Inuvialuit and the Alaskan Iñupiat, continue to utilize *Qikiqtaruk* for traditional hunting and harvesting. As a result of the numerous pre-contact and post-contact activities on *Qikiqtaruk*, there are a plethora of invaluable heritage features, most of which are in the vicinity of Pauline Cove (Friesen, 2012).

This chapter is divided into four sections. The first section summarizes the culture history of the Yukon North Slope, from the earliest evidence of occupation to the Inuvialuit, emphasizing traditional Inuvialuit lifeways. See Figure 11 for a map of all documented heritage sites on the Yukon North Slope. Traditional Inuvialuit lifeways are an essential source of information when examining the Inuvialuit archaeological features on Simpson Point. The second section summarizes the historic period on *Qikiqtaruk*, including early exploration, the whaling period, the fur trade, missionaries, and the police. The third section of this chapter provides background regarding the tangible heritage of *Qikiqtaruk*, both archaeological and historic. The last section of this chapter outlines the heritage management practices of *Herschel*

Island – Qikiqtaruk Territorial Park, including information about the history of archaeological research, ongoing archaeological research, and the park resource plan and management actions.

4.1 The Culture History of the Yukon North Slope and *Qikiqtaruk*

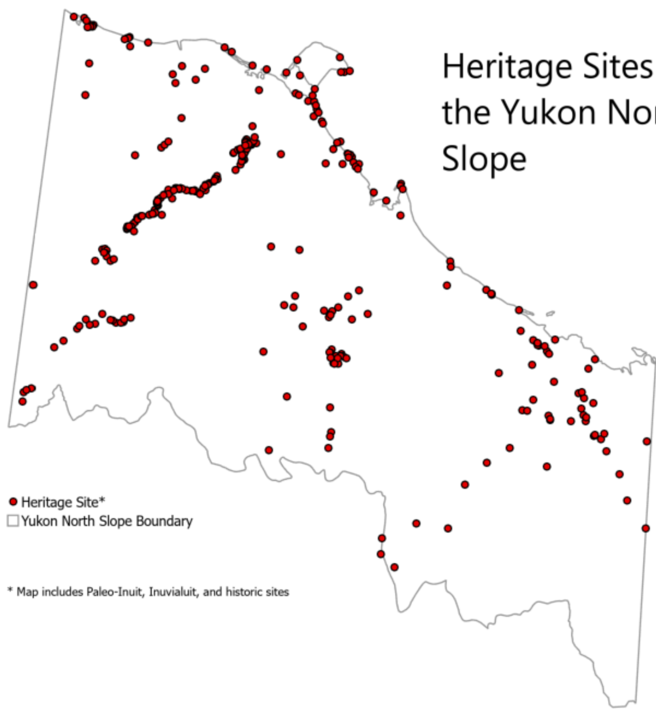


Figure 11. *Heritage sites on the Yukon North Slope, within the Inuvialuit Settlement Region.* © Katelyn O'Keefe, 2022.

4.1.1 The Paleo-Inuit and Thule

The Yukon North Slope is nestled between northwestern Alaska and the Mackenzie Delta, and due to extensive erosion, there is limited archaeological evidence from the Paleo-Inuit and Thule. The records in Alaska and the Mackenzie Delta can be used to infer the culture history of the Yukon North Slope (Friesen and O'Rourke, 2019). The North American Arctic has two cultural traditions, the Paleo-Inuit, and the Inuit, further divided into various phases (Friesen and O'Rourke, 2019). A phase is defined as a culture that is limited in space and time (Snow et al., 2019:17). A tradition is a well-defined, geographically extensive, and long-lasting unit. A string of related phases that develop over time forms a tradition (Friesen, 2015a; Snow et al., 2019:18). Lastly, a complex is a cultural unit defined as a grouping of related or associated traits and features (Snow et al., 2019:17). Figure 12, below, provides a simplified culture history of the Western Arctic (based on northwestern Alaska) and the Mackenzie Delta region (Friesen and O'Rourke, 2019:486).

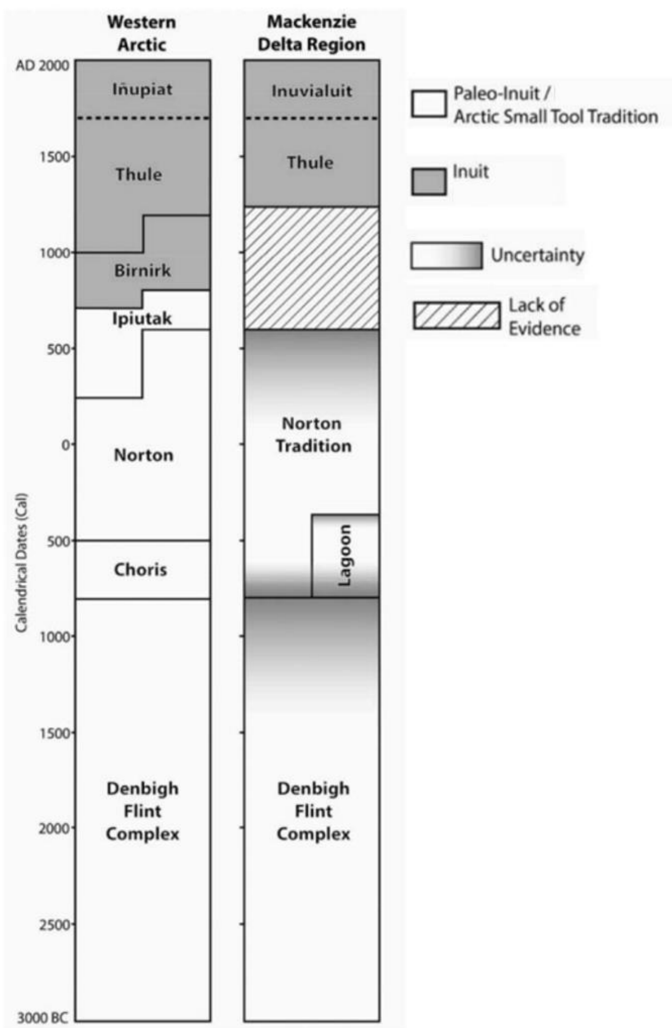


Figure 12. *Culture history of northwestern Alaska and the Mackenzie Delta, modified from Friesen and O'Rourke (2019:486).*

Paleo-Inuit in the Western Arctic consists of several phases, the earliest of which is the Denbigh Flint complex. Denbigh's initial origin is in Siberia, appearing in Alaska around 3000 BC. Denbigh people were the first in the Western Arctic to make a living on the outer coasts, something made possible by consuming marine mammals (Tremayne, 2015). Denbigh then developed into the Norton Tradition around 800BC and is split into three phases, Choris (800-500 BC), Norton 500 BC-AD 600), and Ipiutak (250-800AD). Choris sites are small and found in coastal and interior Northwest Alaska. They are known for the earliest ceramics in the region and their use of semi-subterranean dwellings (Friesen and O'Rourke, 2019). There are considerably more sites during the Norton phase, spread over a larger geographical area. An even greater focus is placed on coastal resources, and fish is incorporated into the diet during Norton (Dumond, 2016). Ipiutak, the final phase of the Norton tradition, is constrained to the interior and coastal areas of Northwestern Alaska and associated with distinctive burial art (Mason, 2016a).

Archaeological evidence of Paleo-Inuit on the Yukon North Slope is restricted to two sites, *Engigstciak*, within Ivvavik National Park, and the Trout Lake Site (Friesen and O'Rourke, 2019). *Engigstciak* is a rock outcrop located within the calving grounds of the Porcupine Caribou, 22 km inland from the Beaufort Sea coast and 35 km from Pauline Cove on *Qikiqtaruk*. The site is several days' travel by foot from the current coastline and has been interpreted as a seasonal hunting camp occupied only in the summer months by a marine-focused group (Friesen and O'Rourke, 2019). The Trout Lake Site is 45 km inland from the coast, along the Babbage River. Archaeological material suggests Denbigh, Choris, and Norton peoples occupied the site (Greer, 1991). To the east of the North Slope, there are several Paleo-Inuit sites in the eastern channels of the Mackenzie River Delta, including Cache Point, Sukunnuk, and Satkualuk. The fauna from these sites suggests that they were inland hunting camps at the time of occupation (Friesen and O'Rourke, 2019). The coastal location of these once inland camps suggests that Paleo-Inuit peoples were likely present throughout the adjacent Yukon North Slope, but that long-term coastal erosion has resulted in a dramatic loss of archaeological sites (Friesen and O'Rourke, 2019; Irrgang et al., 2019).

Following the Paleo-Inuit is the Inuit Tradition (also called Northern Maritime), ancestors of the modern Inuit (Friesen and O'Rourke, 2019). The first phase of Inuit tradition is Old Bering Sea, which developed in two phases, Birnirk (AD 700-1200) and Punuk (AD 800 – 1200). These phases differ from the Paleo-Inuit in that they incorporate large marine mammals (walrus, bowhead whale, etc.) into their diet, an indication of advancing hunting strategies (Mason 2016b). By approximately 1200 AD, the Thule culture developed from Birnirk and Punuk roots, spreading rapidly across the North American Arctic, eastward from Alaska to Greenland in a series of populations migrations (McGhee, 1976; McCullough, 1989; Morrison, 1999; Friesen and Arnold, 2008).

Thule culture is characterized by advanced hunting and transportation technology, including but not limited to slate knives, open socket toggling harpoons, soapstone containers, inflated harpoon line floats, kayaks, and umiaks (Whitridge, 1999; Jensen, 2016). Their subsistence was highly reliant on whales, and they moved across the landscape throughout the year by dog sled or kayak, following resources (Mathiassen, 1927). The Thule constructed elaborate winter settlements with easily distinguishable sod houses. These sod houses, constructed from locally sourced driftwood and sod, were semi-subterranean and cruciform in shape (see fig. 14, in section 4.1.2) (MacNeish, 1954; Yorga, 1980; Jensen, 2016). It is important to note that many of the distinctions between Thule in the Eastern and Western Arctic are attributed to differences in resource availability. There is a steady supply of driftwood in the Western Arctic, which was used for sod houses. In the Eastern Arctic, Thule houses are made from stone (Betts, 2008:58). Early Western Thule settlements consisted of one large rectangular house with smaller additional buildings., with sleeping platforms at the side or the rear. Later Thule settlements consist of larger multi-platform dwellings and larger sites, perhaps indicating a rise in the population (Friesen, 1999; Betts, 2008:48). In addition, the economic emphasis shifted from relying primarily on whale hunting to a more diverse economy that included fishing. The intensity of fish and beluga whale procurement also appears to increase. These changes have been interpreted as the markers of the Thule-Inuvialuit transition, which occurred sometime around 1400 AD (Arnold, 2016).

Thule archaeological sites on the Yukon North Slope, like the Paleo-Inuit archaeological sites previously discussed, are rare. The Washout Site is the best-known and earliest Thule-era site to the west of the Mackenzie River Delta (Friesen and Hunston, 1994). On Banks Island, the Nelson River Site is the only earlier Thule site east of Alaska (Friesen and Arnold, 2008). More information on Washout is given in section 3.3.1. Three additional sites on the Yukon North Slope have been weakly associated with Thule, Whitefish Station West (NfVc-1), Trail River, and Backhouse River (NjVn-5). Whitefish Station West was recorded by MacNeish in 1954 and described as the remnants of one to three Thule houses. MacNeish’s test pit contained several diagnostic Thule artifacts; however, when Morrison excavated the site in 1990, no additional artifacts attributed to Thule were found. Morrison (1990) suggests that the artifacts collected by MacNeish are from another locality and that they were accidentally combined with the NfVc-1 site description in his notes. The Trail River Site (NgVh-1) located 25 km inland, near the Trail River and at the foothills of the British Mountains, consists of several tent rings, house depressions, and hunting blinds. The assemblage was suggestive of Western Thule and was estimated to be from 1400AD; however, further daring indicates an occupation between 1570-1665AD (LeBlanc, 1986; Nagy, 1988:14). The Backhouse River Site (NjVn-5) is a single sod house dated to the 15th or 16th Century; however, an earlier component is believed to be present (Yukon Government, 2021). Lastly, at *Avadlek* Spit, also on *Qikiqtaruk*, there are numerous approximately 40 settlement features, some of which are from 1500AD, around the time of the Thule-Inuvialuit transition (Friesen, 2012).

Overall, minimal archaeological evidence of the Paleo-Inuit and Thule has been found along the Yukon North Slope. The earliest human occupations of the Yukon North Slope can be extrapolated using the chronologies of northeastern Alaska and the Mackenzie Delta regions. The Beaufort Sea coastline is exceptionally dynamic due to its composition. The Yukon North Slope is comprised of unlithified, ice-rich landforms, making the coast particularly susceptible to thermal erosion, and is being continuously re-shaped by storm events, permafrost melt, and sea-level rise (Solomon, 2005; Lantuit et al., 2012; Irrgang et al., 2019). Based on modern annual shoreline change and knowledge of post-glacial coastal transformation, it is estimated that the Beaufort Sea coastline would have been 100 km north of its current position 7000 years ago (Shaw et al.,1998). Since many of the earliest archaeological sites in the region were likely located within 100 km from the coast, it is not surprising that there is limited archaeological evidence of the Paleo-Inuit and the Thule on the Yukon North Slope due to extensive coastal erosion (Friesen and O'Rourke, 2019).

4.1.2 The Inuvialuit

Inuvialuit in Inuvialuktun means “the real people” and describes the beneficiaries of the *Inuvialuit Final Agreement* (IFA) who live in the communities within the Inuvialuit Settlement Region (IRC, n.d.a). The Inuvialuit of the Mackenzie Delta and the Yukon North Slope are the descendants of the Thule. Modern Inuvialuit also descend from the Uummarmiut (Alaskan Iñupiat, also called the Nunataarmiut) from the Noatak River region of Alaska due to intermarriage and migration into the region in the 19th and 20th Century (Nagy, 1994:1; Nagy, 2012). In this document, the term Inuvialuit, rather than Mackenzie Inuit, is used to describe the Inuit occupying the Mackenzie Delta and Yukon North Slope Region before and at the time of contact with Europeans, since this is the name they use to self-identify. In historical texts, the Inuvialuit are also referred to as the Mackenzie Eskimo, and informally, as huskies (Whittaker, 1912; Stefansson, 1913; Arnold and Hart, 1992). The term "husky" and undoubtedly, "Eskimo" are pejorative and convey undesirable meaning. This section will briefly outline the traditional lifeways of the Inuvialuit, including pre-contact groups and demography, settlement pattern, economy, and religion. This information is based on oral history, ethnography, and archaeological records.

Pre-contact Groups

Traditionally, the Inuvialuit were split into eight contemporaneous but autonomous regional groups, making them the largest and most affluent pre-contact Inuit group in Canada. These groups represent distinct ethnic and socioeconomic entities with various degrees of interaction (Morrison, 2003a:13; Betts, 2009). While there was little collective sentiment, it is clear from oral history that they distinguished themselves from other Inuit and Dene (Nagy

1994:2-3). The Inuvialuit were the most territorial of all Canadian Inuit and crossing into another group's territory could result in severe penalties (McGhee, 1974:10-11; Arnold, 1988:92-93; Betts, 2009). From west to east, the pre-contact groups were the Qikiqtarungmiut, Kuukpangmiut, Kitigaaryungmiut, Imaryungmiut, Nuvugarmiut, Avvarmiut, and the Igluyuaryungmiut (see fig. 13, below). These names are derived from the names of their main winter villages. The regional group that is of most significant interest in this research is the Qikiqtarungmiut, which translates to "the people of the sea" or "small island peoples" (McGhee, 1974:10). Qikiqtarungmiut lived along the Yukon North Slope, from Shingle Point to Barter Island, Alaska, and *Qikiqtaruk* (Betts, 2008:49). Their main winter village was *Qikiqtaruk*, sometimes spelled Qikiqtaryuk, at Pauline Cove. As elder Emmanuel Felix of Tuktoyaktuk remembers, the Qikiqtarungmiut were also called the *Tuyurmiat* by their eastern neighbors, which means strangers. This term indicates that their neighbors perceived them as culturally different or isolated (Nagy, 1994:26; Morrison, 2003a:14; Betts, 2008:51). Both the Uummarmiut and other Inuvialuit groups avoided interaction with the Qikiqtarungmiut due to their apparent hostility. Similarly, the Qikiqtarungmiut are thought to have feared the other groups (McGhee, 1974:10-11).

The regional groups spoke different dialects of Inuvialuktun, a strong indicator of group affiliation alongside geographic location. The three distinct dialects of modern Inuvialuktun are Siglitun (also called Sallirmiutun), Uummarmiutun, and Kangiryuarmiutun (Nagy, 1994:1). Sometimes the pre-contact groups were described based on the language spoken. For example, the missionary Emile Petitot referred to the people he encountered as the Tchiglit (Siglit), but Tchglit would refer to multiple groups (Savoie, 1970:208; Morrison, 2003a:12). Generally, the linguistic groups are broad categorizations, and the regional group names offer higher specificity.

Uummarmiutun is spoken in the community of Aklavik (Nagy, 1994:1). The dialect spoken by the Qikiqtarungmiut was likely similar to Siglitun (Nagy, 2012). For this reason, the Inuvialuktun terminology used within this thesis is in Siglitun. See Table 12 in the appendix for a list of these words, with English meanings and Uummarmiutun translations.

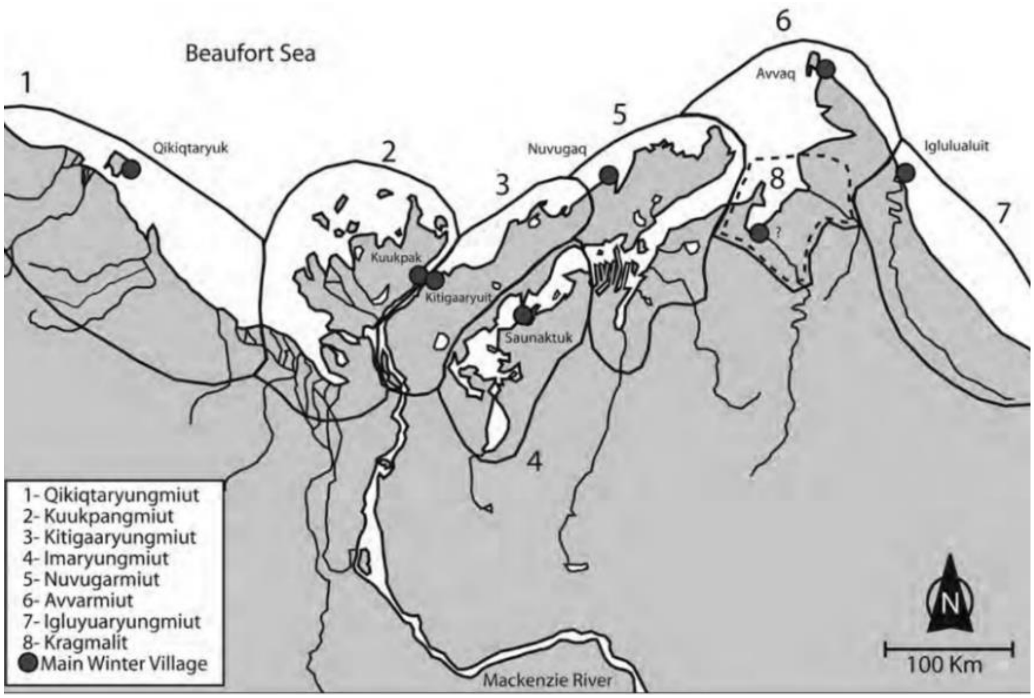


Figure 13. *The territory of pre-contact Inuvialuit groups (Betts, 2008:49).*

The pre-contact Inuvialuit population has been estimated based on the quantity of sod houses (winter houses) found at Inuvialuit archaeological sites. Sod houses serve as a better population proxy than summer dwellings since tents do not leave behind debris in the archaeological record, and tents were placed near the coast, meaning that any remnants would likely be lost to erosion (Friesen, 2004). Most main villages had between three and ten multi-family sod houses, though there were up to thirty in some instances. An estimate of the pre-contact population of the Inuvialuit is between 1000 to 2500 people (Usher, 1971:171; Morrison, 2003b:60; Nagy, 2012). Unfortunately, numerous epidemics struck the Inuvialuit population in the 19th and early 20th centuries, and the epidemics were felt hard in many Inuvialuit villages, including *Qikiqtaruk*. The population declined rapidly, and only 10 percent of the population survived (Jenness, 1964:14). It would take over a century for the Inuvialuit population to recover to pre-contact numbers (Nagy, 2012).

Settlement Pattern

The location of the main village within each group's respective territory is illustrated in Figure 13. The main villages share two key characteristics, a central location within the group's territory and proximity to a river channel or other water source (Betts, 2009). The villages contained up to 30 sod houses, though the average was between three to ten houses (Morrison, 1997). Father Emile Petitot incorrectly documented that the villages were only inhabited between October and March, after which the residents would leave the village, traveling elsewhere for seasonal resources (Savoie, 1970). Petitot was correct that in the spring, hunting and gathering activities occurred elsewhere within territorial boundaries; however, the winter villages would often be re-occupied in the summer to intercept migratory species like the beluga (McGhee, 1974:22-23; Arnold and Hart, 1992; Betts, 2009). Post-hunt, residents would disperse, searching for other resources like fish and caribou, living in satellite villages (Stefánsson, 1919:139; Friesen, 2004). The seasonal movement of pre-contact Inuvialuit was unique to each regional group since they pursued slightly different seasonal resources (Betts, 2009).

Three well-documented traditional structures exist in Inuvialuit culture, the *igluryuaq*, *qaluurvik* and *qatdjgit*. *Igluryuaq* (plural, *igluyuaruit*) is the Inuvialuktun word for the Inuvialuit sod house (IRC 2011:35). They were semi-subterranean and cruciform in shape, with several alcoves serving as sleeping platforms (Savoie 1970:164; Arnold and Hart, 1992). For an illustration, see Figure 14. *Igluyuaruit* were built in the late summer following the whaling season when the permafrost had melted, making it easier to excavate the pit (Friesen 2012). The houses were made from split driftwood, placed flat side inwards at an angle and the roots upwards, serving as a crown on which the moss or sod covering could rest. Beams supported the roof, with the flat sides down, running down the length of the structure (Whittaker, 1937; Friesen, 2004; Levy et al., 2004). An entrance passage served to trap heat and as a place to store (Morrison, 2003a:19; IRC, 2011:35). Inside the structure, the floor was lined with driftwood, and the structure was heated by an open fire or with a *qulliq* (stone lamp) that burned whale oil. Smoke generated from the *qulliq* was released through a *qingaq* (vent) on the roof. The structure had a window sealed using animal intestine or ice (Arnold and Hart, 1992).

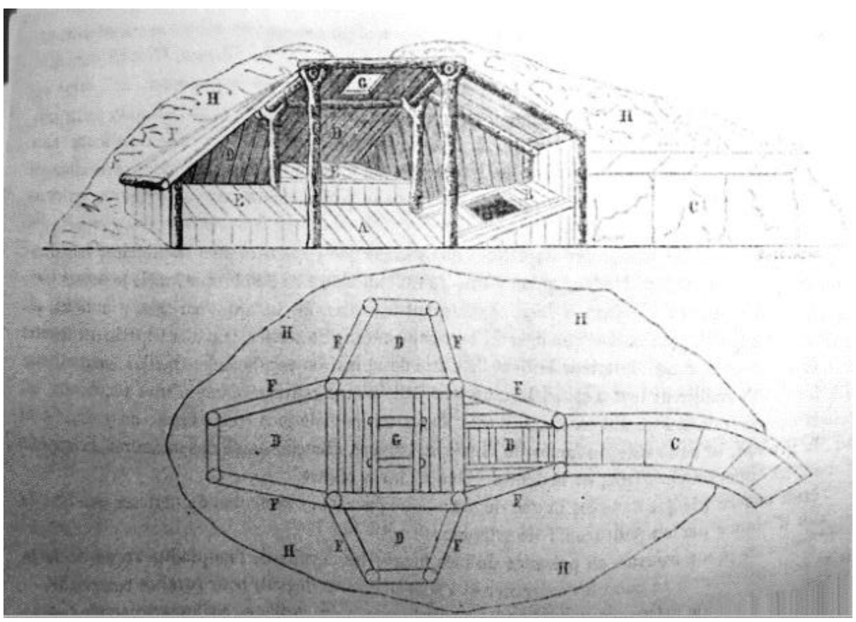


Figure 14*. Inuvialuit sod house (Savoie,1970:164).*

Measuring 3.7 m in diameter, *Igluryuaq* could house up to 25 people (Friesen, 2004). Archaeologists have found that Inuvialuit sod houses got larger over time (Arnold and Hart, 1992). In most ethnographic accounts, these structures are described as having been occupied only in the winter; however, oral history suggests that with regular maintenance, the interiors could be kept moisture-free for summertime occupation (Nagy, 1994:91).

In the spring, the Inuvialuit would travel searching for resources, living in conically shaped summer tents made of driftwood poles covered in caribou or seal skin (Morrison, 2003a:21). In the late 19th Century, a new summer dwelling was adopted from Alaska, called a *qaluurvik* (Morrison, 2003a:21). *Qaluurvik* were dome-shaped, made of willow, and covered with skins or moss. Ethnographic accounts from Stefánsson (1919) and Whittaker (1937) indicate that these summer dwellings would open into and share a central cooking area. At other times of the year, tents were assembled and occupied adjacent to the main winter villages. The summer tents were located along the bank of the river or water source, while the permanent sod houses were situated further back on higher ground (Friesen, 2004). The third structure, the *qatdjgit,* has been documented as part of major Inuvialuit villages. Measuring up to 20 m long, *qatdjgit* were built for ceremonial events, including drum dances. It was also a place for men to assemble and is sometimes called a council house (Morrison, 2003a:20; Friesen, 2004). Villages known to have these structures include Kittigaaryuit, Qikiqtaruk, and Nuvugaq (Morrison 2003a:20).

When the whaling industry on *Qikiqtaruk* (see section 4.2.2.) collapsed circa 1910, Inuvialuit families once again resorted to traditional trapping and hunting to sustain themselves (Lyons, 2009:69). The furs they collected would be sold in trading posts like Aklavik (GNWT, 1991:61). Their children were sent to residential school at Shingle Point and later to schools in Aklavik and Inuvik. For these reasons, much of the population moved into cabins and government-built homes for convenience (GNWT, 1991:62). These posts later became the communities of Aklavik, Tuktoyaktuk, Paulatuk, Sachs Harbor, and Ulukhaktok (formerly known as Holman) (GNWT, 1991:62-63). Increasing migration into community centers increased intermarriage amongst local Indigenous groups and non-Indigenous settlers (Lyons, 2009:70). Intermarriage with southern traders is evident in the Delta as some families like the Gruben's, Gordon's, and the Arey's continue to carry their names (Nagy 1994:37). Soon, Aklavik became the administrative and trading center of the Western Canadian Arctic (IRC, 2011:116). Tuktoyaktuk is the community in which most Kitigaaryungmiut migrated after the abandonment of Kitigaaryuit. The location of Paulatuk, Inuvik, Sachs Harbor, and Ulukhaktok were determined by Euro-North American settlers and the Northwest Territories Government (GNWT, 1991:63).

Economy and Socio-Political Organization

The traditional economy of the Inuvialuit was focused on natural resources, including beluga, fish, seals, and caribou (Betts, 2008). The Inuvialuit had the greatest reliance on the beluga of any Arctic society since its by-products were used for subsistence, light, heat, and as coverings for summer dwellings (Friesen, 2004). The socio-political organization of the Inuvialuit was intrinsically tied to natural resource procurement since the annual beluga hunt, and caribou hunt were labor-intensive and required the cooperation of multiple regional groups. These events caused the aggregation of non-politically unified people and the uprooting of an otherwise relatively sedentary society (Friesen, 2004). The only other event that would cause people from the various regional groups to congregate was the annual trade fairs. These fairs occurred on Barter Island between the Uummarmiut and the Qikiqtarungmiut and at the village of Kuukpak, which brought groups from the east and the west (Betts, 2008:51).

To the east of the Yukon North Slope, the Mackenzie Delta provided ideal hunting grounds for beluga, which enter the Mackenzie Delta each summer (Friesen and Arnold, 1995). The socio-political implications of the beluga hunt are somewhat different from those documented in the bowhead whale hunt undertaken by the Iñupiat. For the Iñupiat, the hunt, undertaken using large skin-covered boats called *umiaks*, is directly associated with socio-political status (Morrison, 1997). The Iñupiat leader of the bowhead whale hunt was the owner of an Umiak and was called an *Umialik*. Each party required hunting equipment and an umiak controlled by the *Umialik*, therefore ensuring that he received a more significant share of resources from the hunt. This system intrinsically linked the economy to the social status of the *Umialik*, enabling him to exert extensive social control (Friesen, 1999).

Conversely, the Inuvialuit did not have the same hierarchical social system. The leader of each beluga hunt was chosen on a hunt-by-hunt basis, so the head of the hunt had less authority and could not amass resources in the same way as the Iñupiat *Umialik* could (Nuligak, 1966). Sometimes the term *Umialik* is used in ethnographic texts regarding the Inuvialuit; however, this term and the term *ataniq* were used to refer to their heads of extended families and, therefore, of villages (Friesen, 1999). The Inuvialuit *Umialik* were not tied directly to the resources generated by the beluga hunt and could not themselves be the leader of a beluga hunt (Nuligak, 1966; Friesen, 1999).

The Inuvialuit used single-man kayaks for hunting the beluga since their speed and maneuverability were better in the shallows than Umiaks, while Umiaks were used for transportation purposes only (Friesen, 1999). In July, the hunt would begin when the belugas were observed close to the settlement. Between 25 and 100 male kayakers would enter the water, forming a driveline (Stefánsson, 1919:172; Whittaker, 1937:174). The hunters used their paddles to splash the water, pushing the beluga into shallow waters where they could be easily harpooned (Nuligak, 1966; Morrison, 1997; Friesen, 1999). Afterward, a blowpipe was used to inflate the carcass, preventing it from sinking (Krech, 1989:63). While the hunt was a communal effort, each beluga was the hunter's property, even if they returned with multiple. Ownership of belugas was reinforced using hunter-specific markings on harpoons (Friesen, 1999). Following the hunt, the women would process the meat and skins, storing excess meat in driftwood-lined cache pits (Friesen, 2004).

For the rest of the year, Inuvialuit groups relied on caribou, fish, and seals within their respective territories (Friesen, 1999). Fish was especially crucial because stocks are abundant throughout the Mackenzie Delta and along the North Slope (Morrison, 2000; Usher, 2002). Bowhead and caribou populations became stressed and declined significantly throughout the whaling period, so fish served as a dependable fallback resource (Morrison, 1997; Friesen, 2004). In the fall, the main food procurement event was the Caribou hunt (Stefánsson, 1919:139). Caribou was an essential aspect of the Inuvialuit economy for subsistence and skin (Morrison, 1997). The women used caribou skins to make warm winter clothing. The skins were finely cut using an *ulu*, an all-purpose knife (Mason, 1890). Winter clothing consisted of a pair of double-layered *qarlik* (pants) and *atigi* (parka), comprising of an inner layer with inward-facing fur and an outer parka, with the fur facing outwards (Morrison, 2003a:27). The men's ensemble was completed with boots, and both sexes wore mittens of various materials (Savoie, 1970:171-175). In the summer, both men and women wore a single layer, which was usually the previous winter's inner layer turned outwards. Men wore decorative lip ornaments near the corners of the mouth called *tuutak*, like the labrets worn in Alaska (Morrison, 2003a:27). Women were tattooed on their hands and their feet (Morrison 2003a:28).

There was a shift to a mixed economy in the early 20th Century. A mixed economy is an economy that includes traditional subsistence practices and wage-based employment (Usher 2002). Many Inuvialuit opted to move closer to trading posts, where they acquired employment and traded goods with missionaries, fur traders, ethnographers, and whalers (Stefánsson, 1919; Bockstoce, 2012; Friesen, 2004). They were particularly fond of Euro-North American material culture, adopting hunting gear, food, clothing, alcohol, and firearms. Other factors influencing the shift towards a wage economy and the move eastward into the Mackenzie Delta include epidemics, the establishment of missions with schools in the delta, and later, employment for the construction of the Distant Early Warning (DEW) (Usher, 2002; Alunik, 2003:163; Friesen, 2004). The establishment of Inuvik and oil exploration associated with the Mackenzie Valley Pipeline Project pushed the Inuvialuit into the wage economy (Leo-Paul et al., 2008; IRC, 2011:122). Soon, the Inuvialuit filled construction and operation positions, which paid more than they had ever made in the past. These positions presented their difficulties because they accentuated social inequity (IRC, 2011:116).

In response to rapid social change and environmental concerns, Inuvialuit pushed for an agreement with the Federal Government. The *Inuvialuit Final Agreement* (IFA) was signed in 1984. The IFA is a comprehensive land claims agreement between the Inuvialuit and the Federal Government, created to preserve Inuvialuit cultural identity and traditional lands while enabling Inuvialuit to meaningfully contribute to the northern and national economy (Keeping, 1984; IRC, 2020). The land settlement resulted in the designation of the ISR (see fig. 15).

Environmental concerns and concerns over the preservation of their traditional culture led to the creation of the Committee for Original Peoples Entitlement (COPE). This organization represented the interests of the Inuvialuit, kickstarting negotiations for a land claim agreement with the Federal Government (IRC, 2011:126,190). The Inuvialuit Regional Corporation (IRC) was created to ensure that beneficiaries (Inuvialuit people and businesses) retain control and receive financial compensation for development of their lands, control wildlife harvesting, protect the lands designated as part of the Inuvialuit Settlement Region (ISR) and enable Inuvialuit peoples to active participants in the national economy (Keeping, 1984; IRC, n.d.a).

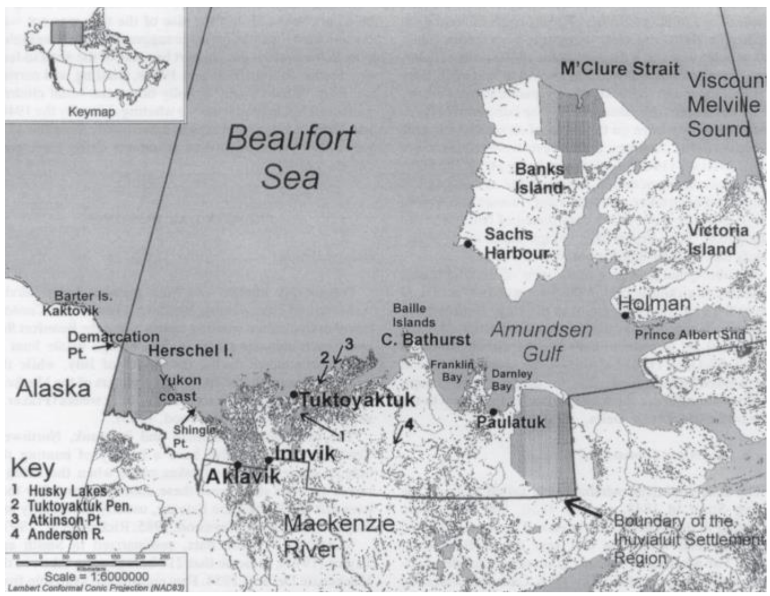


Figure 15. *Map of the Inuvialuit Settlement Region (Harwood and Smith, 2002:79).*

Additional goals of the IFA and the IRC are to preserve the social and cultural well-being of the Inuvialuit (IRC, n.d.a). Today, the Inuvialuit economy is a mixed, subsistence-based economy. Most Inuvialuit households in smaller communities still rely on natural resources to feed themselves, working wage positions only as needed. Inuvialuit families are connected by harvesting, trade, and sharing, just as their ancestors were in the past (Usher, 2002). The *Inuvialuit Final Agreement* has ensured that modern politics and business remain intertwined, much of which relates to natural resources (Wilson and Alcantara, 2012).

In summary, the Inuvialuit worldview centers around their coastal lifeways and resources found on or near the coast provided everything required for survival (IRC, 2011:29). Knowledge and respect for the land are key tenants of Inuvialuit culture (IRC, 2011:10). The traditional economy of the Inuvialuit was resource-based, with extreme importance placed on coastal resources and the caribou. Not only did these resources provide sustenance, but they provided materials for housing, light, travel, clothing, and tools (IRC, 2011:29-35). While regional groups were not socially or politically unified, they congregated for communal hunting activities, particularly the beluga hunt (Friesen, 1999). Each extended family resided in a winter village, a home base, and these winter villages are visible in the archaeological record. Like the Thule before them, these settlements are located on the coast, in proximity to valuable marine resources. Inuvialuit society was like that of the Thule, but with increased inequality (Whitridge, 1999). As mentioned in the demography section of this paper, the influx of Uummarmiut into the region resulted in changes to the Inuvialuit economy and a fusion of culture and traditions (Friesen, 2004). In the 20th Century, interaction with Euro-North Americans and other social factors led the Inuvialuit to adopt a mixed economy and enter the wage economy (IRC, 2011:116)). The signing of the IFA has ensured that the Inuvialuit are active participants in the national economy while protecting their traditional coastal lifeways and territory (Keeping, 1984).

Traditional Religious Practices

Traditional Inuvialuit religious practices are also tied to coastal lifeways. Respect for the land, animals, and natural resources is engrained in the Inuvialuit worldview (IRC, 2011:48). Traditionally, the Inuvialuit believed in *nappan*, which are a multitude of spirits. To appease *nappan*, the Inuvialuit abided by a set of taboos related to food and sleeping practices (IRC, 2011:48). An example is providing water to a whale after it had been killed, and not doing so would offend the animal, preventing them from killing whales in the future (IRC, 2011:48). Prayer was not part of the traditional belief system; however, offerings of food and water were given to the spirits (Nagy, 1994; Friesen, 2004; IRC, 2011). In addition, charms made of hide were often worn around the neck of hunters. These charms have been found in the archaeological record (IRC, 2011:48). Before the arrival of Christianity, the Inuvialuit had spiritual leaders called *angatkuq*, meaning shaman (Nagy, 1994:30). Shamans were individuals, men, or women, who interacted with the animal spirits. They could send away the *tuunriat* (evil spirits), save lives, and control the weather (IRC, 2011:48). To communicate with the animal spirits, they would enter a trance-like state, transforming themselves into animals to perform magic (Morrison, 2003a:24). Shamans were not prevalent after the turn of the 20th Century, and their existence became questioned by the younger generation (Nagy, 1994:30).

Ceremonies, including the drum dance, were performed in the *qatdjgit*, and used to enact legends and traditions (Friesen, 2004:229; IRC, 2011:50). These dances were part of social gatherings, often accompanying feasts and celebrations. At the changing of the seasons, the Inuvialuit would have a feast devoted to the sun in the summer, celebrate new foods in the fall, and celebrate renewal in the spring (Savoie, 1970: 207). They incorporated shamanic activity and were performed by both men and women under the supervision of the head of the village (Friesen, 2004; Morrison, 2003a: 25). The dancers, both men and women would dance themselves into an exhausted, frenzied state (Morrison, 2003a:25; Friesen, 2004).

The Inuvialuit believed that the spirits of the deceased could be brought back to life by gifting their name to children (Morrison, 2003a: 24). The mortuary customs of the Inuvialuit included burying the dead in their winter houses. If removing the deceased from the house, they must not be removed through the front door because this would taint the house and render it unusable (Savoie, 1970:207). Instead, they would dig a hole into the back of the structure. Afterward, the family would visit the dead at sunrise and sunset to mourn, dance, and bring objects for the spirit (Savoie, 1970:207-208).

Overall, the traditional religious beliefs of the Inuvialuit are intrinsically tied to coastal lifeways and resources. Many ceremonial events took place during gatherings for resource procurement, and these ceremonies took place in the *qatdjgit*, a structure present in coastal villages. As a result, religious practices played a role in all aspects of Inuvialuit life, including their settlement pattern.

Unfortunately, ethnographic accounts of Inuvialuit religious practices, except those from Father Emile Petitot, are dated to the turn of the 20th Century, likely after some level of Christian influence had taken hold (Friesen, 2004). Most of these accounts are from missionaries whose own religious beliefs may have jaded their documentation. Christianity began to influence the Inuvialuit around the turn of the 20th Century, and several missions were built along the Yukon North Slope and the Mackenzie Delta, including St. Patrick's Anglican Mission House on *Qikiqtaruk* (Iceton, 2012:172). More information on missionary activities on *Qikiqtaruk* can be found in section 4.2.3.

4.2 Euro-North American Contact and the Historic Period on *Qikiqtaruk*

4.2.1 Early Non-Indigenous Occupants

The first European to visit Inuvialuit territory was Alexander Mackenzie in 1789. He traveled downriver that now bears his name to the Arctic Ocean. The Dene guided Mackenzie, and he did not encounter any Inuvialuit on his travels. This was likely intentional since traditionally, the Inuvialuit and the Dene were adversaries (Morrison, 2003:58). Mackenzie did not visit *Qikiqtaruk*. Compared to other North American Indigenous peoples, Europeans made direct contact with the Inuvialuit quite late due to stories of aggression told by the Dene (Franklin and Richardson, 1828; Morrison, 2003b). *Klaboonacht*, meaning "white people" and "heavy eyebrows," was a term used by Inuvialuit to describe Europeans (Franklin and Richardson, 1828:174). The origin of this term is of interest because it was used first by the Eastern Canadian Inuit, therefore implying that the Inuvialuit learned about the arrival of Europeans from them (Morrison, 2003b:55). While there was no direct contact between Europeans and the Inuvialuit at this time, we can be confident that the Inuvialuit knew of their existence since an indirect, long-distance trade of Russian goods through Iñupiat intermediaries began in the 1780s. The second source of indirect trade was from the Hudson's Bay Company (HBC), which set up Fort Good Hope in 1826 (Morrison, 2003b:57).

The first European to learn about *Qikiqtaruk* was John Franklin, who named it Herschel Island after the Herschel Family when he saw the island standing from Kay Point on the mainland. Days later, in July 1826, he and his party landed on the island, likely at Lopez Point, and met the Qikiqtarungmiut (Burn and Jenness, 2012). Many of the European names used for the physical features on Herschel Island and the Yukon North Slope can be attributed to John Franklin and John Richardson. In 1837, Thomas Simpson and Peter Dease of the HBC mapped the coastline of northern Alaska and Yukon. They traveled through workboat passage and landed on *Avadlek* Spit. They noticed that there were many people on the island and that there were the remains of a bowhead whale on *Avadlek* (Burn and Jenness, 2012). Following the disappearance of the Franklin expedition, several ships were sent to the Western Arctic to look for Franklin and his crew. This included Lt. William Pullen of the British Royal Navy in 1849, whose crew camped at *Avadlek* Spit in an unoccupied sod house. In 1851, Captain Richard Collinson of the H.M.S. *Enterprise* was also sent to look for Franklin. His crew spent several days nearby and saw several Qikiqtarungmiut. When the ship encountered strong winds, it was blown back to Kay Point, where several Inuvialuit approached the ship in kayaks (Burn and Jenness, 2012).

In the summer of 1889, news broke that to the whaling ships in eastern Alaska, the waters off the Yukon coast were rich in bowhead whales and a suitable harbor at Pauline Cove on *Qikiqtaruk*. The news resulted in a frenzy to reach the cove the following year (Burn and Jenness, 2012). More information on whaling at Pauline Cove can be found in the following section. The U.S.S. *Thetis*, a naval vessel, met the first whaling ships that had been at *Qikiqtaruk* in August of 1889, and Lt. Cdr Charles Stockton ordered his men to chart Pauline Cove, which he named after his wife. His crew surveyed the island and the cove, publishing the first chart of the area in 1890 (Bockstoce, 2012).

Numerous scientists and ethnographers visited *Qikiqtaruk* to study the physical environment, vegetation and animal species, and the Inuvialuit themselves. Roald Amundsen, the Norwegian explorer, visited *Qikiqtaruk* in 1905, staying for several days after his ship became stuck in the ice. He observed the whalers' diet, clothing, and health (Burn and Jenness, 2012). In 1906, the Danish explorer Ejnar Mikkelsen and the American geologist Ernest Leffingwell reached Pauline Cove, where they were to join Vilhjalmur Stefánsson to explore the Arctic Ocean north of Alaska. Unfortunately, they did not arrive in time, and the original expedition did not go ahead. When Mikkelsen did arrive at Pauline Cove, he documented that the whalers and missionaries had, in his words, corrupted the Inuvialuit (Burn and Jenness, 2012). Stefánsson, in the meantime, reached Pauline Cove in August of 1906, and when they did not arrive, he spent the winter at Shingle Point, living with an Inuvialuit family. The following year, Stefánsson returned with American zoologist Dr. Rudolph Anderson for the Stefánsson-Anderson Expedition, an exploratory expedition sponsored by the American Museum of Natural History and the Geological Survey of Canada. In 1913, the duo would return to the Arctic for the Canadian Arctic Expedition (1913-1918), sponsored by the Canadian Government. Although not much time was spent on *Qikiqtaruk* during these expeditions, valuable information about the landscape and the Inuvialuit were documented (Stefánsson, 1919).

4.2.2 Whaling and the Fur Trade

In the 1880s, American whaling activity was prevalent to the west of *Qikiqtaruk*, off the Alaskan coast. Whaling stocks were being depleted, and soon, whalers were seeking new stocks to the east. In 1887, Uummarmiut traders informed a shore-based whaleman in Point Barrow that they had spotted many bowhead whales in Mackenzie Bay (Bockstoce, 2012). Joseph Tuckfield was sent with a year's supplies to investigate this claim the following year. Tuckfield returned with news that the whales were "thick as bees" and that he had located a suitable port on the southeastern end of *Qikiqtaruk* (Bockstoce, 2012). Seven whaling ships immediately headed east for Pauline Cove; however, only two of them, the *Orca* and *Thrasher*, remained and caught two whales each. The Pacific Steam Whaling Company (PSWC) of San Francisco outfitted a small vessel, the *Grampus*, and a tug, the *Mary D. Hume*. The *Hume* reached *Avadlek* Spit in August 1890, and the crew built a small storehouse. They had little success here and more their supplies and storehouse from *Avadlek* to Simpson Point, on foot, after their ship had become stuck in the ice. In 1891, both ships had an incredible harvest. The *Grampus* returned south in the fall of 1891, and the Hume in the fall of 1892 (Bockstoce, 2012).

Pauline Cove was about to get much busier since the PSWC had decided that the cove was an ideal place for ships to overwinter, giving them an early advantage the following summer (see fig. 16). The winter of 1892-93, 1893-94, 1894-95, and 1895-96 saw four, seven, fifteen, and thirteen overwintering ships at Pauline Cove, respectively (Bockstoce, 2012). Unfortunately, by 1896-97, the bowhead population had been severely reduced, and the remaining whales were found further east. The whaling industry slowed, and the number of ships to overwinter dwindled until 1907-08, when the whalebone market collapsed, and most of the fleet left the Beaufort Sea (Bockstoce, 2012). From 1890-97, 27 different ships had overwintered at Pauline Cove, however most of them only once or twice. At the same time, however, prices for furs were dramatically increasing, and some whalers re-branded themselves as fur traders. Pauline Cove quickly became the center of the fur trade (Bockstoce, 2012).

Figure 16. *Whaling Era photos of Pauline Cove. (A): The Whaling Fleet at Pauline Cove, 1985. (B): Qikiqtaruk residents around Community House, July 4th, 1896. Photos published in Yukon Government (2019b:2,16).*

At the height of the whaling period in 1894-95, Pauline Cove was home to 1000 to 1500 seasonal residents, when accounting for Euro-North American occupants (whalers, traders, etc.), Uummarmiut, Inuvialuit, and Gwich'in Dene (Bockstoce, 2012; Yukon Government, 2019b:3). At the time, Pauline Cove was the largest community in what is now called the Yukon (Yukon Government, 2019b:3). The whalers hired the Uummarmiut and Gwich'in to provide fresh caribou and other food for them, as they were thought to be better hunters than the Inuvialuit

(Morrison, 2003c:83). Additional Inuvialuit were drawn to Pauline Cove by the trade. The whaling period at Pauline Cove was the first time there was prolonged contact between the Inuvialuit and non-Indigenous occupants (Friesen, 1995:119).

The winter was long and anticlimactic, so the residents of Pauline Cove found numerous ways to keep themselves entertained. Winter and social sports such as skiing and tobogganing in the hills above the cove, soccer, and a baseball league with four teams. Outdoor sports could be hazardous due to rapidly changing weather conditions. In March of 1897, five men died during a baseball game when the weather changed, and temperatures fell to minus 30 degrees Celsius. The following morning, three whalemen and two Indigenous were found frozen to death (Bockstoce, 2012). Indoor activities were popular during poor weather, and a games room was set up in the Community House. Others would perform theatrical shows for entertainment. Beginning in 1894, the wives and families of the senior whalers overwintered. The wives put on elaborate social parties, including a fourth of July celebration, with games and contests (see fig. 16) (Bockstoce, 2012).

With a population so large, conflicts were inevitable. The PSWC forbade its whalers from trading whiskey, which had been problematic elsewhere. Regardless, homemade alcohol was made and traded by both the whalers and Indigenous residents, causing difficulties (Bockstoce, 2012). In addition, the relations between the Euro-North American occupants and the Inuvialuit residents may have faced some tension. Elder Joe Nasogaluak of Tuktoyaktuk recalls that "the whalers would take the women away from the Inuit men. They made children […] They would leave them and find another wife like they weren't married" (Nagy, 1994:36). This would have undoubtedly generated some confusion for the Inuvialuit, whose traditional territory had been overtaken by strangers (Morrison, 2003c:83). Reports in southern newspapers of debauchery on the island were commonplace; however, some of this activity was likely exaggerated since many whaling captains had little hesitation in bringing their families to the island (Bockstoce, 2012).

The Fur Trade

Much of the early trading activities were undertaken by whalers that acted as traders, supplying the Inuvialuit with manufactured goods at 20 to 30 percent of the coast that they would have paid at the HBC forts to the south. The whalers traded the items for fresh fish and game, preferring caribou. It is estimated that in Pauline Cove's busiest years, up to 2000 caribou were traded to the whalers (Bockstoce et al., 2012). A trade jargon, which was a mix of the different languages and dialects of the whalers and Indigenous population, was soon developed so that residents could communicate basic ideas (Stefánsson, 1909; Bockstoce et al., 2012). The convenient location of Pauline Cove and the lower prices caused many Inuvialuit to stop trading furs to the HBC posts down south. The situation was so dire for the HBC that John Firth told the whalers that the company would no longer provide mail service to Pauline Cove unless they stopped trading in furs. This curtailed the fur trade on *Qikiqtaruk*. However, the whalers still traded for meat (Bockstoce et al., 2012). Unfortunately for the HBC, the Inuvialuit, Uummarmiut, and Dene preferred to obtain other trade items from the whalers since their prices were much lower. The HBC prices were due to increased transportation costs associated with overland and downriver travel from southern Canada.

Between 1900 and 1929, the prices for fox fur began to rise significantly, slumping for only one year during WWII. A single fox fur was worth fifty dollars in 1929, five times its value in 1900 (Bockstoce et al., 2012). Many independent and Inuvialuit trappers soon set up trapping camps all along the coast, bringing their pelts to Pauline Cove in the summers. In 1915, the HBC finally established a post at Pauline Cove, which consisted of several buildings (Bockstoce et al., 2012; Yukon Government, 2019b). They soon found business to be poor due to the preference of the trappers to trade with H. Liebes and Company's Captain Pedersen. Pedersen was widely respected by all due to his honesty, high-quality trade goods, and exceptional prices. The HBC attempted to become competitive by reducing costs by using ocean freight; however, bad timing, severe ice, and questionable planning impeded their plans. Furthermore, their poor attitude towards customers, disorganized bureaucratic structure, and higher prices prevented their success (Bockstoce et al., 2012).

In 1923, Pedersen left H. Liebes and Company and formed the Northern Whaling and Trading Co., further preventing the HBC from establishing themselves at Pauline Cove and establishing a monopoly in the Western Canadian Arctic. In response, the HBC contacted the Canadian Government for protection, and in 1924, the Government enacted legislation preventing foreign vessels from participating in the coastal trade east of *Qikiqtaruk*. Pedersen immediately purchased a larger vessel to supply two smaller Canadian-flagged supply schooners and created Canalaska, a Canadian corporation (Bockstoce et al., 2012). Canalaska was remarkably successful until the early 1930s, when the great depression caused a drastic slump in fur prices. In 1938, he sold the Canalaska company to the HBC. The HBC decommissioned its Pauline Cove post around the same time since many of the Uummarmiut and Inuvialuit were moving eastwards towards the Mackenzie Delta. The HBC moved its operations to Shingle Point and Tuktoyaktuk. Post-WWII, there was a small boom in the fur trade, and the RCMP opened a small post for families at Pauline Cove; however, much of the trade was now happening in Aklavik, which had become the largest settlement in the Mackenzie Delta (Bockstoce et al., 2012).

4.2.3 Missionaries

Throughout the commercial whaling and fur trading period, missionaries continued to visit Pauline Cove. The first missionary to arrive was Reverend Isaac Stringer of the Anglican Church in 1893. He returned in 1894 and then in 1985 with his wife Sadie to establish a mission; however, numerous attempts to construct a church were hampered by a lack of supplies (Yukon Government, 2019b). The PSWC invited Stringer to use the Community House building as a residence, school, and church. The Stringers provided essential medical services for the community, and when epidemics spread quickly at Pauline Cove, Stringer conducted funerals for those who perished (Iceton, 2012). In 1896, Isaac Stringer's health began to decline, and in 1901, he and Sadie left the Arctic without converting any Inuvialuit. They had an immensely positive influence on the social environment of Pauline Cove during the whaling period, however, and returned several times for visits in later years (Iceton, 2012).

Charles Whittaker took over the role from Stringer upon his departure. Whittaker had spent the winter at Pauline Cove in 1895-96 and relocated to Fort McPherson. Whittaker's character proved to be unpopular and, at times, patronizing (Iceton, 2012). In 1905, Whittaker's daughter died at Pauline Cove, and he and his wife brought her body down to Fort McPherson to be buried next to her brother, who had died a couple of years earlier. Whittaker returned permanently to Fort McPherson shortly after. Until 1916, Pauline Cove was only periodically visited by missionaries; however, several Inuvialuit were baptized during Stringer's later visits. In 1915, the re-establishment of a mission at Pauline Cove was discussed. In 1916 the Anglican Church attempted to secure one of the former whaling buildings; however, these were occupied by the police (Iceton, 2012). A new mission house was constructed in 1916. William Fry and his wife Christina took the missionary role that year and in addition to their missionary activities, they taught day school for the Inuvialuit children until 1919, when the Fry's left Pauline Cove due to William Fry's failing health. They suggested to Stringer, who was by now the Bishop of Selkirk (later, Yukon), that missionary activities should be relocated to Shingle Point. The mission at Pauline Cove was not overly successful; however, it had a tremendous long-term influence on the Inuvialuit living along the Yukon North Slope. In 1917, Gareth Notik, James Atumiksana, and Thomas Umaok were the first Inuvialuit to be appointed and ordained as ministers. Thomas Umaok would eventually become the deacon of Pauline Cove in 1927. By the 1930s, missionary activities at Pauline Cove had ceased, and the St. Patrick's Mission was abandoned entirely (Iceton, 2012). However, missionary work continued elsewhere, and the Inuvialuit ministers were catechists, propagating information about Christianity throughout the Yukon North Slope (Iceton, 2012).

4.2.4 The Police

The NWMP, the precursor to the Royal North-West Mounted Police (RNWMP) and later, the Royal Canadian Mounted Police (RCMP), was established to enforce a Canadian presence and enforce Canadian law. In the northwesternmost corner of the country, their efforts also included extending government services, representing Canada's commercial interests, and transforming hunters into citizens of Canada (Neufeld, 2012). Repeated requests for the presence of law enforcement at Pauline Cove were made by Bishop Bombas, the Bishop of Selkirk (Yukon), and an inspector of the NWMP in the 1890s, as they felt that relations amongst the whalers and the Indigenous needed to be managed. The HBC also complained about the whalers, who it felt had not paid customs duties on their trade goods (Neufeld, 2012). Fortunately for the whalers, the Canadian Government had little interest in dispatching police to Pauline Cove in the 1890s, primarily because they were already pre-occupied with policing the Klondike. Anti-

British sentiment following the unsatisfactory settlement of the Alaska Boundary Dispute in 1903 led to a strong surge of nationalism, and Canada quickly responded by dispatching the NWMP to Pauline Cove. The intent was to enforce Canadian sovereignty (Neufeld, 2012).

In the summer of 1903, the NWMP arrived at Pauline Cove, and the following year, a permanent detachment was founded to monitor whaling and trading activity. In 1909, the first special constable (Inuit constable) was hired. The cooperation of the Inuvialuit, including as special constables, was crucial to policing the North Slope since they shared knowledge and skills with the police (Neufeld, 2012). Up to this point, the NWMP acted almost exclusively as a federal presence rather than a force of change. This was about to change, and the Pauline Cove detachment became the subdistrict headquarters for the Western Arctic (1910-1931) and the staging area for patrols along the Yukon North Slope and the Mackenzie Delta (Yukon Government 2019b). Gradually, the assertion of Canadian law and government services resulted in cultural and social changes. The police became eager to establish order and demonstrate the meaning of the law to the Inuit in Northern Canada (Neufeld, 2012). The most significant effort to exert dominion over the North occurred in 1923 when two Inuit men were brought to Pauline Cove to be tried for murder. The intent was to demonstrate the meaning of British law to the Inuit; however, the guilty verdict had already been decided, and the two men were hung in the Bonehouse at Pauline Cove. In short, the trial was an elaborate display of control, meant to send a strong message to the Inuit. However, the intended lesson was misunderstood due to language barriers and cultural differences (Neufeld, 2012; Komar, 2020).

Following the decline of the whaling industry, the police focused their efforts on regulating the fur trade and establishing national sovereignty. The soaring prices of fox pelts in the early 20th Century lured American traders into the region by ship until regulations were tightened to prevent ship-borne trade (Neufeld, 2012). When the fur trade collapsed in the 1930s, the RCMP post at Pauline Cove was no longer viable. In 1933, the detachment at Pauline Cove closed, and personnel was moved to Aklavik. In addition to the Aklavik detachment, the RCMP patrolled the waters of the Western Canadian Arctic by vessel, *St. Roch (*Neufeld, 2012*)*. Post-war, many Inuvialuit families living on Barter Island in Northeastern Alaska decided to move back to be with their relatives in Canada when the Government introduced financial assistance and old-age pension programs. In 1948, *St. Roch* was conveniently overwintering at Pauline Cove.

The decision was made to reopen the previously abandoned detachment to monitor the movement of people and trapping activities in the area (Neufeld, 2012). However, a post-war jump in fur prices was incredibly short-lived, and the RCMP found itself in new roles. Low fur prices meant that fur trading companies were unwilling to credit Inuvialuit trappers already in debt. The Inuvialuit coming eastward from Alaska were not permitted to register for trap lines in the region. Aklavik was at maximum capacity, and there was no room for additional students in the schools (Neufeld, 2012). Together, these factors compounded and led to intense hardship for many Inuvialuit along the North Slope. The RCMP was tasked with providing relief supplies to the elderly and the sick and providing an annual report on the condition of the Inuvialuit (Neufeld, 2012). The RCMP protested the behavior of the trading companies; however, the companies felt that it was the Government's responsibility to provide relief. In 1950, the RCMP opened a trading store at Pauline Cove, distributing much-needed rations in exchange for furs. That first year, the store saw 85 Inuvialuit, including 37 children. In the few years that followed, poor hunting conditions meant that many depended on the store for their well-being (Neufeld, 2012). In the mid-1950s, jobs constructing the DEW Line, and the development of Inuvik drew many Inuvialuit into the Mackenzie Delta. The North Slope lost most of its residents, and the responsibilities of the Pauline Cove detachment were limited to the sled dog breeding program and DEW line patrol. The RCMP detachment was closed permanently in 1964 (Neufeld, 2012).

4.3 Tangible Heritage on *Qikiqtaruk*

In this section, the historic structures, and the Inuvialuit archaeological features on *Qikiqtaruk*, with an emphasis on those at Simpson Point, are summarized. These heritage features are the tangible (physical) manifestation of the history previously discussed in sections 4.1 and 4.2. Tangible heritage can be defined as the physical traces of past human activities, namely heritage sites. Conversely, intangible heritage is a concept beyond the physical, including cultural practices such as traditional knowledge, oral history, and cultural expression (Ahmad, 2006). Tangible and intangible heritage cannot be treated as distinct entities since the meaning of tangible heritage is interpreted using intangible heritage, such as oral history. In this section, the tangible heritage of *Qikiqtaruk* is discussed. The archaeological sites on Simpson Point and elsewhere on the island can be interpreted using Thule and Inuvialuit lifeways discussed in section 3.1. Much of the tangible heritage on *Qikiqtaruk* is located on Simpson Point. There are, however, archaeological features at *Avadlek* Spit, Lopez Point, Osbourne Point, and before erosion, N.E. of Pauline Cove towards Collison Head, at the Washout Site (Friesen, 2012). In this section, the archaeological features in the vicinity of Pauline Cove are discussed primarily, with brief summaries of the Washout Site and archaeological features at *Avadlek* Spit. Following the summary of archaeological features, the historic buildings on Simpson Point are described. Figure 17 is a map of the heritage features on Simpson Point.

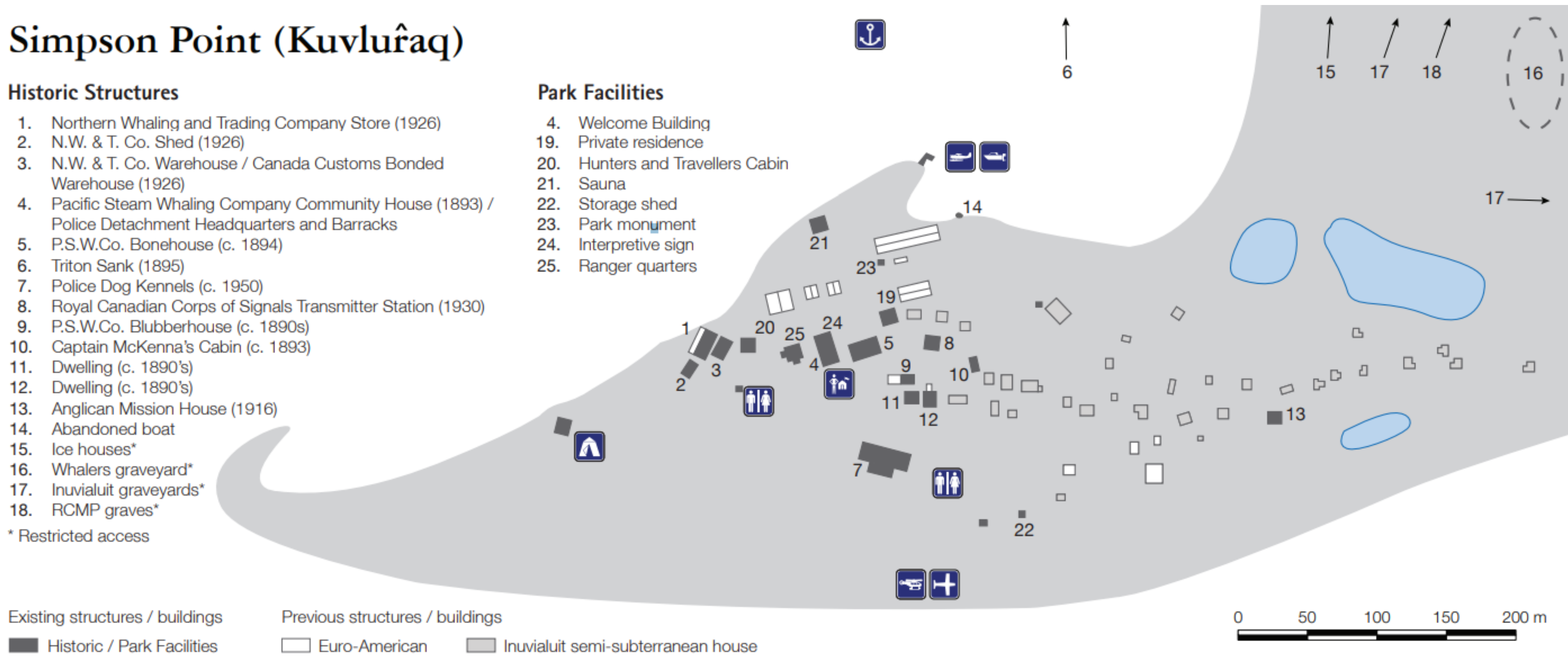


Figure 17. *Map of the heritage features on Simpson Point. Modified from original published in Yukon Government (2019a:vii).*

4.3.1 Archaeological features

On Simpson Point, there are at least twenty Inuvialuit sod house features, approximately half of which have been previously excavated (Friesen, 1995). Most of these sod houses are located between the whaling settlement and St. Patrick's Anglican Mission House, an area that has been informally called society row (see fig. 17). There are several pre-contact or proto-contact period sod houses beyond this point, in the direction of the Washout Site (Friesen, 1995:139). Due to their semi-subterranean architecture, vegetation growth, driftwood deposition, and flooding, it can be challenging to identify them from aerial imagery or on foot. Some of the structures are larger and more raised than others, making the former easier to identify (see fig. 18). Several of the historic buildings on Simpson Point were built on top of the oldest sod houses, and it was common practice to salvage driftwood from abandoned sod houses, either to construct a new house or to use the driftwood for fire (Yukon Government, 2019a). In addition, coastal erosion, particularly between Collison Head and the Mission House, has damaged several sod houses along the beach (Friesen, 2012). Therefore, the quantity of sod house features built at Simpson Point is almost certainly higher than what is recorded at present.

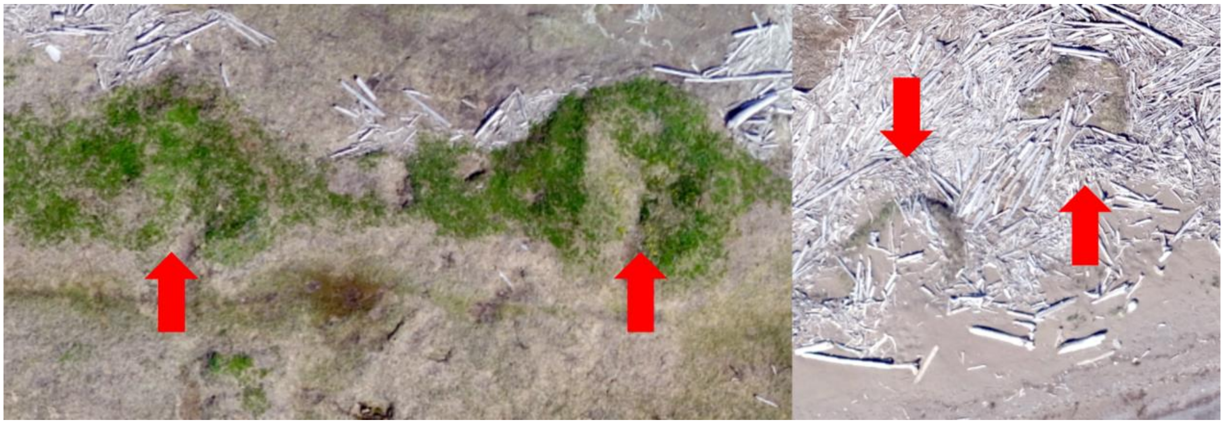


Figure 18. *Aerial imagery of Inuvialuit sod house features on Simpson Point.* © Katelyn O'Keefe, 2022.

At the time of Friesen's Qikiqtaruk Archaeology Project, there were at least fifteen sod houses from the pre-contact or proto-contact period, two sod houses from the early historic period, three sod houses that have multiple components, and twenty-four structures that are from the commercial whaling period or whose age could not be determined without excavation (Friesen, 1995:139). More details about previous excavations of sod houses on Simpson Point can be found in section 4.4.2.

Approximately 750 m to the northeast of the historic settlement at Simpson Point was the Washout Site, a large Thule settlement. Washout is the oldest known settlement on *Qikiqtaruk* and was the first settlement of the Qikiqtarungmiut. The site, comprised of nine sod houses, was occupied for nearly 400 years, from 1200-1600 AD (Friesen, 2012). The dwellings were large, with one dwelling measuring 4 x 3 m (Yorga, 1980:47-50; Friesen, 2012). It is likely that the Washout Site was far more extensive than what has been recorded and that there were significantly more dwellings originally; however, by the time of the first excavations in 1954, the coastline had receded considerably. Evident from its namesake, the Washout Site has been completely eroded. Figure 19, below, is an estimate of the site location relative to the historic settlement and 1944, 1970, and the modern (2017) coastlines.

On the southwestern end of the island, at the tip of *Avadlek* Spit, there are numerous early Inuvialuit sod houses. In total, over forty heritage features have been mapped. Excavations have revealed that the site's occupants relied almost entirely on birds and fish rather than seals, the typical dietary focus (Friesen, 2012). The shape of the spit continues to change drastically, and due to its low elevation, it is at risk of flooding and storm surge damage.

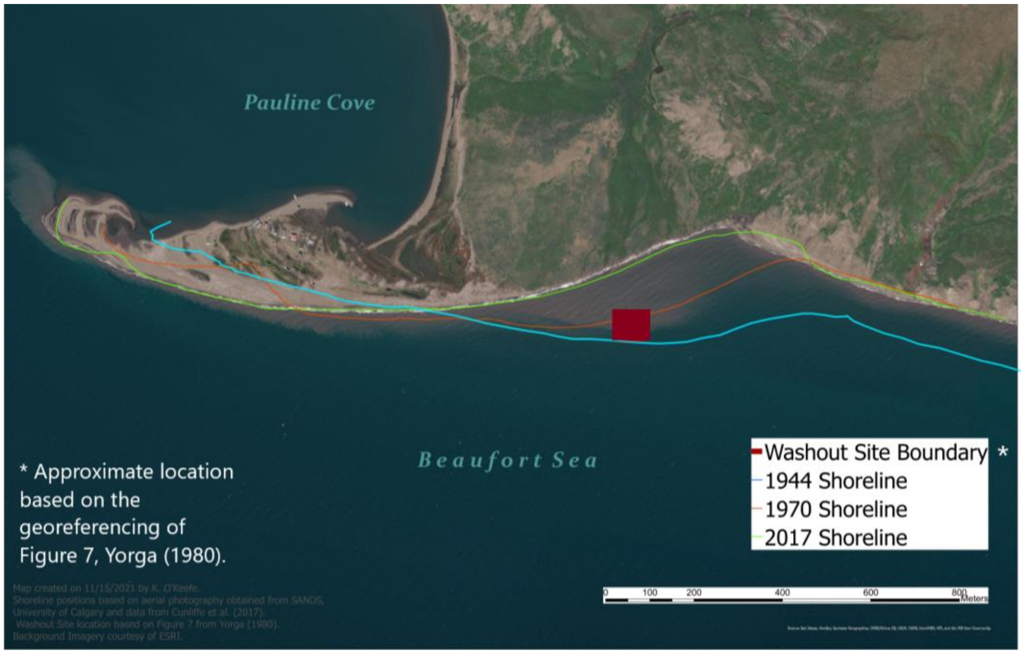


Figure 19. *Approximate location of the Washout Site, with shorelines from 1944, 1970, and 2017*. © Katelyn O'Keefe, 2022.

4.3.2 Historic Structures at Simpson Point

The Community House was built in 1893 by the PSWC. It is the oldest standing frame building in the Yukon (National Trust for Canada, n.d.). It is a large building, measuring 9.3 x 17.7 m (see fig. 20). Materials and some prefabricated components were shipped with the whaling crew. The building served many purposes and had a recreation room, storage, an office, and living accommodations for officers (Yukon Government, 2019b). This building played an integral part in the social activities at Pauline Cove. In 1896, the Reverend Isaac Stringer began using the building as a residence and as a place to teach school and hold church services on behalf of the Anglican Church. The Church would continue to use the building until 1906 (Yukon Government, 2019b). In 1911, the building and all other PSWC assets were purchased by the NWMP. The building was used as the detachment headquarters for the Western Canadian Arctic from 1910-1931 and again seasonally from 1948-1964. The building is currently used as a park office, visitor center, and museum (Yukon Government, 2019b). The building is in relatively good repair, with alterations done throughout its lifetime. The building is culturally significant because it is evidence of the resources and materials brought long distances by the whaling industry. The fine materials used in the construction of the building compared to other buildings in the settlement indicate the social inequity and segregation of social life between the whaling officers and the ordinary worker (Yukon Government, 2019b).

Figure 20. *The Community House building (right). Photo from Inuvialuit Cultural Centre Digital Library (n.d.).*

The Bonehouse was constructed in the 1890s by the PSWC as a warehouse. Later, two additions were built, one on each side of the main building. These additions were constructed from local driftwood and reused materials since materials were scarce (Yukon Government, 2019a). The building was used to store baleen, and the RCMP used it for storage and dog kennels. The building is associated with the first trial in the Arctic, which resulted in hanging the two Inuit men from a tie beam. The beam was removed and replaced by the RCMP in 1963 (Yukon Government, 2019b). This building is significant as evidence of the whaling industry and early issues in the concepts of justice in the Canadian North. Today, the central part of the building is used to store artifacts, while the sides are used for storage. The building is in reasonable condition.

The Blubber House was constructed in the mid-1890s for industrial purposes. The interior is utilitarian, with exposed framing, minimal windows, and air vents on the walls. Later, the RCMP used the building to prepare dog feed (Yukon Government, 2019a, b). This building is currently used for storage and is in reasonable condition.

The Northern Whaling and Trading Company Buildings were built in 1926. Three buildings were built: a warehouse and store, a shed, and a customs warehouse. Material left over from the construction of the store building and parts of a ship cabin were used for the shed. The third building is the Customs Warehouse Building, operated by the Northern Whaling and Trading Co. and supervised by the Department of National Revenue, the Canadian Customs Agency. These buildings are essential to the historic integrity of the settlement, due to their economic history and involvement in the fur trade. Unfortunately, a section of the store building was damaged by beach erosion and ice, and the westernmost portion of the building was removed following its collapse. In addition, the custom's warehouse building was damaged by fire in 1979, resulting in extensive damage and the destruction of an adjacent building, the Newport House (Yukon Government, 2019b). The building was soon repaired. Due to their position on unstable ground, coastal erosion, and landfast ice damage, the decision was made to relocate the customs warehouse, the shed, and the store 10 m inland (east). The buildings were kept in the same relative position and placed on blocks. These buildings are currently used as park storage (Yukon Government, 2019b).

The Royal Canadian Corps of Signals Transmitter Station is often called "The Signal House," this prefabricated building was shipped in components and assembled at Pauline Cove in 1930 as part of a communication system that connected the Yukon and Northwest Territories to the rest of Canada. After the departure of the Corps, the building was used by the RCMP for housing. The building has been refurbished in recent years and is currently used as accommodation for Park staff and researchers from ongoing research projects (Yukon Government, 2019b).

The RCMP Dog Kennels and Dog Run was created by joining two older buildings together in the 1940s. Adjacent to the dog kennel is a fenced-off dog run constructed from wire mesh and driftwood fence posts. From the 1940s to the 1960s, the RCMP used the building for its dog breeding program. The building has been stabilized, and the roof was repaired in 2019. The fencing of the dog run has partially collapsed, though the posts remain. This building and the dog run are not actively used (Yukon Government, 2019b).

The ***Captain James Mckenna Cabin*** was built by Captain James McKenna of the PSWC as a personal residence in 1893. Like other structures, the materials involved in this building were reused from materials leftover from the construction of the Community House. The interior was refinished several times as the occupants changed. The building is in good condition and used to store park equipment (Yukon Government, 2019a).

The ***St. Patrick's Anglican Mission House*** is a large two-story building built in 1916 when the Church could not secure one of the whaling buildings (Iceton, 2012). Initially, the Church planned to build a school and a mission; however, scarce resources meant that only one building was feasible. The building's size reflects the anticipated success of the mission. That success was short-lived since many Inuvialuit moved eastward along the Yukon coast towards the Mackenzie Delta (Iceton, 2012). In response, the Anglican Church moved its mission to Shingle Point on the Yukon mainland in 1919. After 1919, St. Patrick's hosted itinerant missionaries, and by the 1930s, St. Patrick's Mission was abandoned. The building has not been used since and is in poor condition. Cables have been used to brace the building to stabilize it and nesting boxes have been installed for Black Guillemots (Yukon Government, 2019b:8, Olynyk, 2012:205).

Figure 21. *St. Patrick's Anglican Mission House, July 2019.* © Katelyn O'Keefe, 2019.

Buildings 11 and 12 are smaller buildings built in the 1890s and used as accommodation. Building 11 and 12 were continuously modified, including several additions. Building 11 is of poor quality compared to the main building and was made of materials scavenged from other buildings. This building is presently undergoing extensive conservation work (Yukon Government, 2019b). Building 12 is much more decorative than Building 11, with gothic stylistic elements. As evidenced by the continuous modifications and cosmetic changes, Buildings 11 and 12 appear to have been nearly continuously occupied by different families. Neither building is currently being used (Yukon Government, 2019b).

Former buildings and structures are visible in historic photographs, including numerous buildings constructed by the HBC and the PSWC. The HBC built a warehouse, store, house, sop, doghouse, storehouse, coal house, and outhouse around 1915 (Yukon Government, 2019b). By 1938, the HBC dismantled several buildings at Pauline Cove and used the material for buildings at the HBC post at Tuktoyaktuk in the 1940s (Iceton, 2012; Yukon Government, 2019b). The PSWC's Newport House, built between 1890 and 1893, was next to the Custom's Warehouse. It was purchased by the RCMP in 1911 and was used for storage until it burned to the ground in 1973. Another PSWC building called the Pioneer House (later, "the woodshed") was built at *Avadlek* Spit and later moved to Pauline Cove. This building was dismantled after 1911, and the material was used to build RCMP patrol cabins along the Yukon coast. Finally, records indicate the existence of a blacksmith shop at Pauline Cove; however, no structure has been identified with this purpose at present (Yukon Government, 2019b). Several remnants of building foundations can be seen in the DSM of Simpson Point (see fig. 22, below). In addition to the structures built on Simpson Point, there were five icehouses built between 1891 and 1893 and three graveyards within the vicinity of Pauline Cove. Only one icehouse remains standing (Bockstoce, 2012). The three graveyards include the whaler's graveyard, two RCMP graves, and the Inuvialuit graveyard (Yukon Government, 2019b).

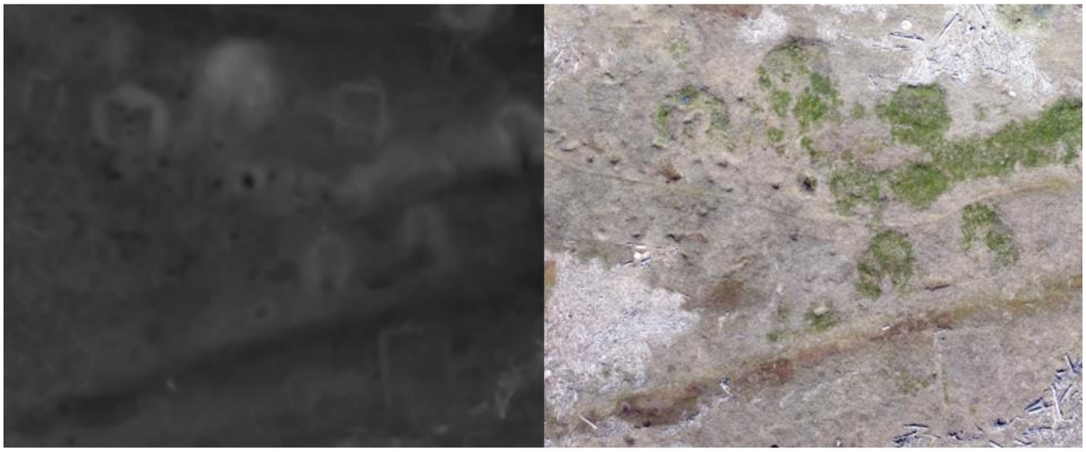


Figure 22. *Building foundations visible in the DSM at the boundary between Study Area 1 and 2.* © Katelyn O'Keefe, 2022.

4.4 Cultural Significance of Heritage on *Qikiqtaruk*

Thus far, this chapter has focused on the human history of *Qikiqtaruk*, including centuries of Inuvialuit settlement and Euro-North American endeavors in the vicinity of Pauline Cove. In addition, the heritage features, comprising of historic structures and archaeological Inuvialuit sod houses, have been described. While the significance of *Qikiqtaruk's* heritage features may be self-evident, this section emphasizes and elaborates upon their importance and addresses the following questions:

1. *Why should the heritage features within Herschel Island – Qikiqtaruk Territorial Park be preserved?*
2. *Why should we care about these heritage features?*

4.4.1 Reasons to Protect Qikiqtaruk's Heritage Features

The most straightforward answer to these questions is that the heritage features on Simpson Point and elsewhere on *Qikiqtaruk* are exceptionally unique. Before *Qikiqtaruk* was an island, the Thule settled 800 m east-northeast of Pauline Cove at the Washout Site. While it has since been destroyed by coastal erosion, the Washout Site was the best known and the earliest

Thule site west of the Mackenzie Delta (Friesen and Arnold, 2008). Archaeological evidence and oral history yield evidence that the Inuvialuit have continuously occupied the island since they developed from Thule. The Inuvialuit at Pauline Cove witnessed the arrival of explorers, whalers, fur traders, missionaries, and the RCMP. They participated in the commotion of the whaling and fur trading periods. The sod houses on Simpson Point were built before, during, and after contact with Euro-North Americans. Their contents reflect the influence of Euro-North American culture and the wage economy on the Inuvialuit (Friesen, 1995; Friesen, 2013). Further evidence of the dramatic cultural transition during the late 19th and early 20th centuries has been documented by elders (Nagy, 1994).

Overall, the archaeological remains and historic buildings at Pauline Cove are unique because they represent a plethora of different activities and the interaction of the Inuvialuit, Iñupiat , Dene, and Euro-North American settlers. With increasingly rapid erosion in the Mackenzie Delta and along the Yukon North Slope, the protection of archaeological sites, especially those as culturally significant as those on *Qikiqtaruk*, is extremely important.

Another argument for preserving the heritage within the vicinity of Pauline Cove and elsewhere on the island is the association with the whaling industry, maritime affairs, and Canadian sovereignty. As mentioned in section 4.2.2, whaling activities at Pauline Cove were prolific, albeit somewhat short-lived. At the peak of the whaling period at Pauline Cove, it is estimated that nearly 1000 people overwintered (Yukon Government, 2019b). The whalers constructed many buildings on Simpson Point, including the Community House, the oldest standing wooden frame building in the Yukon (Yukon Government, 2019b). These buildings are reminders of the hardship of northern life. Many of the whalers married into Inuvialuit families, with descendants in the villages of Aklavik, Inuvik, and Tuktoyaktuk carrying their surnames

(Nagy 1994:37). The whalers doubled as traders, providing reasonably priced goods to the Inuvialuit, to the dismay of the HBC. In response to complaints from the HBC, restrictions were placed on American traders within Canadian territory, and concerned by the outcome of the Alaska Boundary Dispute; the Canadian Government began to exert its authority over *Qikiqtaruk*. The arrival of the RCMP on the island and the patrolling of Canadian waters was the first time Canada acted to exert sovereignty in the Western Arctic (Neufeld, 2012). Overall, the activities undertaken by the whalers and the RCMP, and the built heritage associated with these activities, serve to document the history of maritime affairs and sovereignty in the Western Canadian Arctic.

Lastly, the heritage features and cultural landscape of *Qikiqtaruk* are invaluable to the Inuvialuit. Traditional Inuvialuit lifeways were and continue to be intrinsically linked to the coastal landscape in which *Qikiqtaruk* is a part. A cultural landscape is defined as a place that an Indigenous group values due to long-term social, economic, cultural, and spiritual relationships that the group has with the land. Indigenous lifeways are embedded in the land itself (Parks Canada, n.d.; GWNT, 2007). The island has been important for hunting and gathering activities for the Inuvialuit since time immemorial (Nagy, 1994; Yukon Government, 2019a). In accordance with the IFA, Inuvialuit have the exclusive right to hunt and harvest on the island. The island continues to be used for traditional activities, including subsistence hunting (Staples, 20112:217,219). Since the mid-1990s, there has been a summertime Elder and youth program, where Inuvialuit Elders teach youth the “old ways”, including fishing, hunting, food preservation and preparation and camping skills. In addition, these elders often tell traditional stories about the land, passing these stories down to the youth (MacRae and Nielsen, 2012:213-214). The youth then interact with park visitors, and Elders educate these visitors about Inuvialuit culture and subsistence hunting. This program is invaluable because it connects Inuvialuit youth with their culture and with the land, while promoting their involvement in protecting the natural and cultural resources of *Qikiqtaruk* (MacRae and Nielsen, 2012:214).

4.5 Heritage Management in *Herschel Island – Qikiqtaruk Territorial Park*

Herschel Island – Qikiqtaruk Territorial Park is a legacy of the IFA, between the Federal Government and the Inuvialuit (Keeping, 1984). The IFA recognizes that the Yukon North Slope and Qikiqtaruk are special places that require protection and long-term management (Staples, 2012:217). *Herschel Island – Qikiqtaruk Territorial Park* was established in July of 1987 and was the first Yukon Park created as part of a land claims agreement (Yukon Government 2019a: iii). The following section summarizes the *Herschel Island – Qikiqtaruk Territorial Park Management Plan* and the goals pertaining to heritage preservation. Subsection 4.5.2 addresses the following question: How can the heritage features be documented and protected? In addition, efforts made to protect and document the heritage on the island are discussed. The final subsection details the history of archaeological research within the park. Overall, this section outlines the management of heritage resources within the park and provides details about the efforts being made to protect and document the heritage features.

4.5.1 The Herschel Island – Qikiqtaruk Territorial Park Management Plan

The park is co-managed by the Inuvialuit and the Yukon Government. In 1991, the first park management plan was put into place following the collaboration of Yukon Parks and the Wildlife Management Advisory Council (North Slope), which consists of Inuvialuit, Yukon Government, and Government of Canada representatives (Yukon Government, 2019a:1). The plan has been revised twice, in 2006 and 2019. The plan outlines the park's vision and provides guidelines and goals for the management of the park. The plan contains goals organized into four categories, one of which is heritage and culture. The second category of goal which is of interest is visitor use, as this pertains to heritage conservation and knowledge sharing. As previously mentioned, many of the heritage sites are within the Simpson Point – Pauline Cove area. There is a designated special feature heritage zone for Simpson Point (fig. 23, below). Activities such as traditional Inuvialuit hunting and harvesting, natural and historic appreciation, interpretation, heritage conservation, education services, and scientific research can be conducted within the heritage zone (Yukon Government, 2019a:14-15).

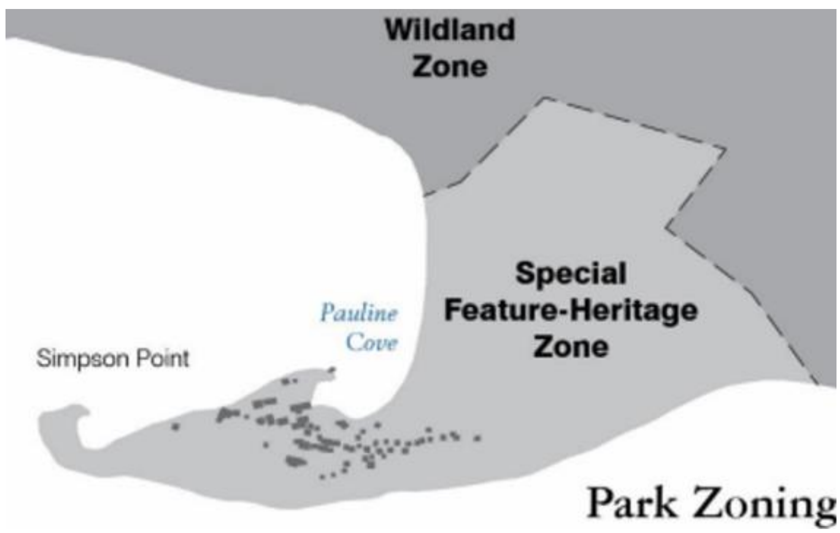


Figure 23. *Map of the special feature - heritage zone within Herschel Island – Qikiqtaruk Territorial Park (Yukon Government, 2019a:14).*

There are two broad goals set out by the management plan that pertain to heritage and culture. Goal #4, in summary, is to maintain *Qikiqtaruk* as a place of knowledge sharing and cultural connection, that is, the sharing of intangible heritage and cultural practices to future generations of Inuvialuit, by Inuvialuit (Yukon Government, 2019a:19-20). Full details on this goal can be found in the park management plan. Goal #5 of the management plan is more specific to the tangible heritage features within the park, stating that the historic, archaeological, and palaeontological values of *Herschel Island – Qikiqtaruk Territorial Park* are to be conserved and interpreted (Yukon Government, 2019a:20-21). Table 1 outlines the management actions for goal #5, as per the 2019 park management plan.

Management Goal #5	
The historic, archaeological, and palaeontological values of Herschel Island – Qikiqtaruk Territorial Park are conserved and interpreted.	
Management Actions	
5.1	Build public appreciation for the heritage values of the historic settlement and the Inuvialuit through interpretation, education, and outreach.
5.2	Manage and conserve the park's heritage resources according to the Standards and Guidelines for the Conservation of Historic Places in Canada (2010, second edition), which will provide guidance on the maintenance, use, and development of the individual built and archaeological resources, and the site as a whole.
5.3	Document historic, archaeological, and palaeontological resources to ensure that the information is not lost.
5.4	Continue researching, monitoring, and documenting historic and heritage resources to ensure their heritage values are maintained.
5.5	Conduct a risk assessment of the park's heritage resources and their vulnerability to and risks from climate change and other stressors by identifying implications to the cultural integrity and implementing adaptation and mitigation strategies.
5.6	Pursue designation of the historic settlement area as a Yukon Historic Site under the Historic Resources Act.
5.7	Maintain status on the tentative list for World Heritage Site, with Ivvavik and Vuntut National Park.
5.8	Develop and implement a policy for the community-based management of burial sites in the park in collaboration with Yukon Tourism and Culture's Cultural Services Branch and the community of Aklavik, and in consultation with the Inuvialuit Cultural Resource Centre and the RCMP; Goal #5: The historic, archaeological, and palaeontological values of *Herschel Island – Qikiqtaruk Territorial Park* are conserved and interpreted.
5.9	Set priorities and implement the *Qikiqtaruk* / Herschel Island Interpretation Strategy to promote the historic, archaeological, and palaeontological values of the park.

Table 1. *Goal #5 of the Herschel Island – Qikiqtaruk Territorial Park Management Plan (Yukon Government, 2019a:20-21)*

The research presented within this thesis strives to further many of these management actions. Goal #9, under visitation, applies to heritage protection as well. This goal is to sustain and protect heritage, wilderness, and ecological values for future generations and ensure all users' safety (Yukon Government, 2019a:23). Key management actions that are part of this goal include the development of a set of best practices and protocols for visitors to minimize impacts of the park's environment and heritage and the completion of risk assessments of park assets towards the development of a risk management plan (Yukon Government, 2019a:23).

4.5.2 Heritage Protection and Documentation Efforts on Qikiqtaruk

In addressing the question, *How can the heritage features be documented and protected?*, it is essential to acknowledge that erosion, overland flooding, and permafrost melt significantly impact cultural sites in the Western Canadian Arctic. On the Yukon North Slope, research indicates that nearly all coastal sites are at-risk (Irrgang et al., 2019). On *Qikiqtaruk*, low-elevation landforms rich in archaeological features, including Simpson Point, are particularly susceptible to climate change. Several strategies are being used to limit the damage to the historic buildings on Simpson Point, including raising the buildings and relocating them further inland (Yukon Government 2019b). While these strategies prevent further damage in the short-term long-term, these may not be enough. Additionally, the physical displacement of the heritage structures alters the cultural context and commemorative integrity of the site itself. Parks Canada has coined the term commemorative integrity to describe the health and wholeness of a heritage site (Kell, 2013:280).

Unfortunately, the strategies used to limit damage to the historic buildings cannot protect the Inuvialuit sod house features at Pauline Cove. By nature of their design, they cannot be raised or moved like the historic buildings around them. Therefore, there is only one course of action to excavate and record them before erosion. Excavations may be recorded using traditional archaeological techniques and digital capture technologies, such as TLS, to record the structures digitally.

4.5.3 History of Heritage Research in Herschel Island – Qikiqtaruk Territorial Park

Most archaeological work on *Qikiqtaruk* was undertaken between the 1950s and 1990s by various archaeologists representing various institutions (Yukon Government, 2019a:34). Most of this work has centered on the Inuvialuit sod house features at Pauline Cove; however, excavations of other sod houses have been completed at the Washout Site, northeast of the Pauline Cove settlement, and at *Avadlek* Spit (Friesen, 2012). Archaeologist Richard MacNeish conducted the earliest excavations in 1954 at the Washout Site (MacNeish, 1954; MacNeish, 1956a). Initially, six eroding houses were documented and excavated. In the late 1970s, three more sod houses were exposed by erosion and excavated by Brian Yorga from the University of Toronto and Jeffrey Hunston of the Yukon Heritage Branch (Friesen, 2012).

At Pauline Cove, two sod houses were excavated by John Bockstoce in 1973. Unfortunately, a fire destroyed the artifacts, which were being stored on site (Friesen, 1995:137). A later structure of unknown age was excavated by Jeffrey Hunston between 1985-1987. Max Friesen, a Ph-D student at the University of Toronto, conducted extensive excavation as part of the Qikiqtaruk Archaeology Project in the early 1990s. This project was funded as part of the Northern Oil and Gas Action Program (NOGAP) archaeology program, coordinated by the Federal, Yukon, and Northwest Territories governments (Friesen, 1995:98). Friesen and colleagues (including Dr. Peter Dawson, the academic supervisor of this research) conducted an extensive survey of Simpson Point and excavated seven sod houses. Friesen's research helped determine the occupational sequence of Pauline Cove since the excavated sod houses represented the late pre-contact (1000-1800 AD), proto-contact (1800-1889 AD), and early contact (historic) periods (1889-1910) (Friesen, 1995:96, 137). Figure 24, below, is a map of the excavated sod houses on Simpson Point as of 2019. Figure 25 is a photograph of an excavation undertaken in the 1990s by Max Friesen.

In 1991, Nancy Saxberg, a master's student from the University of Toronto, excavated a refuse pit adjacent to St. Patrick's Anglican Mission House (Saxberg, 1993). From 1989 to 1993, Murielle Nagy conducted the Herschel Island and Yukon North Slope Inuvialuit Oral History Project, part of the Inuvialuit Social Development Program. The project documented Inuvialuit land use and knowledge of the Yukon North Slope. Interviews with elders included traditional subsistence, trade, sod house dwellings, social life, and involvement with St. Patrick's Anglican Mission (Nagy, 1994). While this project was not archaeological in nature, the Herschel Island and Yukon North Slope Inuvialuit Oral History Project provided valuable details about life on *Qikiqtaruk* from the perspective of the Inuvialuit.

Collaborations between the Yukon Government and the University of Calgary began in 2018. These collaborations have addressed the need to document the heritage features on *Qikiqtaruk*. Thus far, these collaborations have resulted in the digital recording (using TLS) of the historic buildings on Simpson Point (see section 6.1.3 for more information), the creation of a digital heritage archive (https://herschel.preserve.ucalgary.ca), and the change detection research that is the subject of this thesis. The final component of this research is to use the procedures developed in this research towards creating a heritage monitoring strategy for Simpson Point. The framework of this monitoring strategy is discussed in Chapter 7. When combined, the change detection analysis and the monitoring strategy aim to address goals 4, 5, and 6 of the *Herschel Island – Qikiqtaruk Territorial Park Management Plan.* By detecting and monitoring

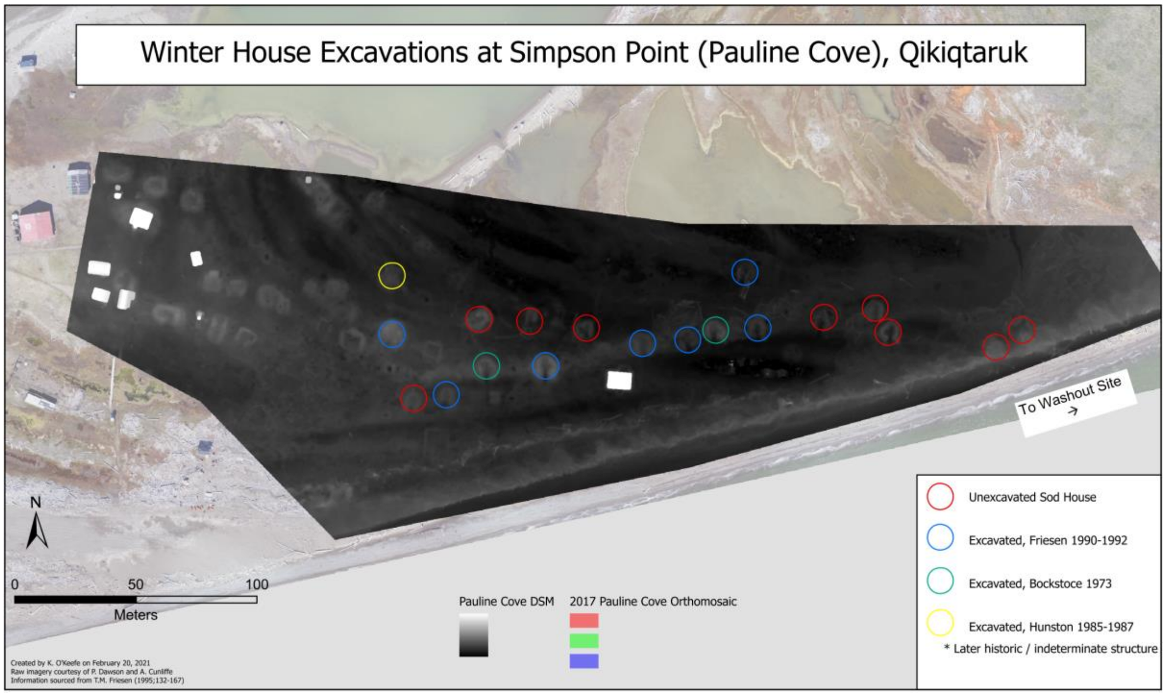


Figure 24. *Map of excavated sod houses on Simpson Point.* © Katelyn O’Keefe, 2022.

Figure 25. *Excavation of a sod house at Simpson Point, circa 1990. Photo courtesy of Dr. Peter Dawson (n.d.).*

changes to the Inuvialuit archaeological features, decisions can be made towards their preservation. The long-term preservation of these features contributes to maintaining the cultural connection between Inuvialuit and the island.

Elsewhere on *Qikiqtaruk*, minor archaeological work has been conducted. In the southwestern portion of the island is *Avadlek* Spit, a 5 km long spit that stretches into Workboat Passage. The site on *Avadlek*, NjVj-1, is a small site from the late Western Thule period. Max Friesen and colleagues excavated two sod houses on the spit in 1991. Apart from the archaeological sites in the vicinity of Pauline Cove (Simpson Point and Washout) and *Avadlek*, there is a known proto-historic settlement as Osborn Point; however, very little is known about the site (Friesen, 1995:220; Friesen, 2012).

4.6 Chapter Summary

This chapter provided the cultural background required for this research. In this chapter, the cultural chronology of the Yukon North Slope from the Paleo-Inuit, to the Inuvialuit. The traditional lifeways of the Inuvialuit, including pre-contact language, regional groups, settlement pattern, economy, and religion, were also discussed. Section 4.2 was a summary of Euro-North American activity and settlement on *Qikiqtaruk*, from early exploration, the whaling period, missionary activity, and the arrival of the police. Next, the heritage features on *Qikiqtaruk* were described, emphasizing those in the vicinity of Pauline Cove. The final section outlined the co-management of the park and the heritage management strategy for *Herschel Island – Qikiqtaruk Territorial Park*, as per the park management plan. In addition, a summary of archaeological research on *Qikiqtaruk* was provided. The information provided in this chapter is crucial to the reader since knowledge of the cultural background and the physical heritage features is applied throughout this research. The next chapter outlines the specifics of the data collection, data preparation and change detection analysis methods undertaken in this study.

5 METHODS

This chapter outlines the methods used in this research. The first section describes the data collection processes for the 2017 and 2019 data collection, including information about the UAVs, the flight plan, the camera parameters, and the photos collected. The following section details the data processing procedures used in this research, including processing in Pix4Dmapper© and the data preparation procedures in Autodesk Recap© and CloudCompare©. The last section of this chapter describes the workflow of both change detection analysis methods used, C2C and VIA. The C2C method was completed first since the resulting change maps enable the analyst to simultaneously visualize all change within the study area and identify areas with notable change. Figure 26, below, depicts the overall workflow for the methods used in this research. Streamlined instructional procedures for data processing, data preparation, and change detection method components of this chapter have been appended to this thesis.

5.1 Data Collection and Acquisition

The photogrammetric data used in this research comes from two sources. Another research group collected the 2017 UAV data, and the raw data was acquired, processed, and repurposed by the author for the change detection analysis component of this research. The 2019 data was collected for this research by the author, the author's supervisor, and a Yukon Government archaeologist. The author processed the 2019 UAV data. Both datasets were collected following Transport Canada's aviation regulation's part IX – remotely piloted aircraft systems (Transport Canada, 2021). Sections 5.1.1 and 5.1.2 describe the acquisition process for the UAV photogrammetry used in this study.

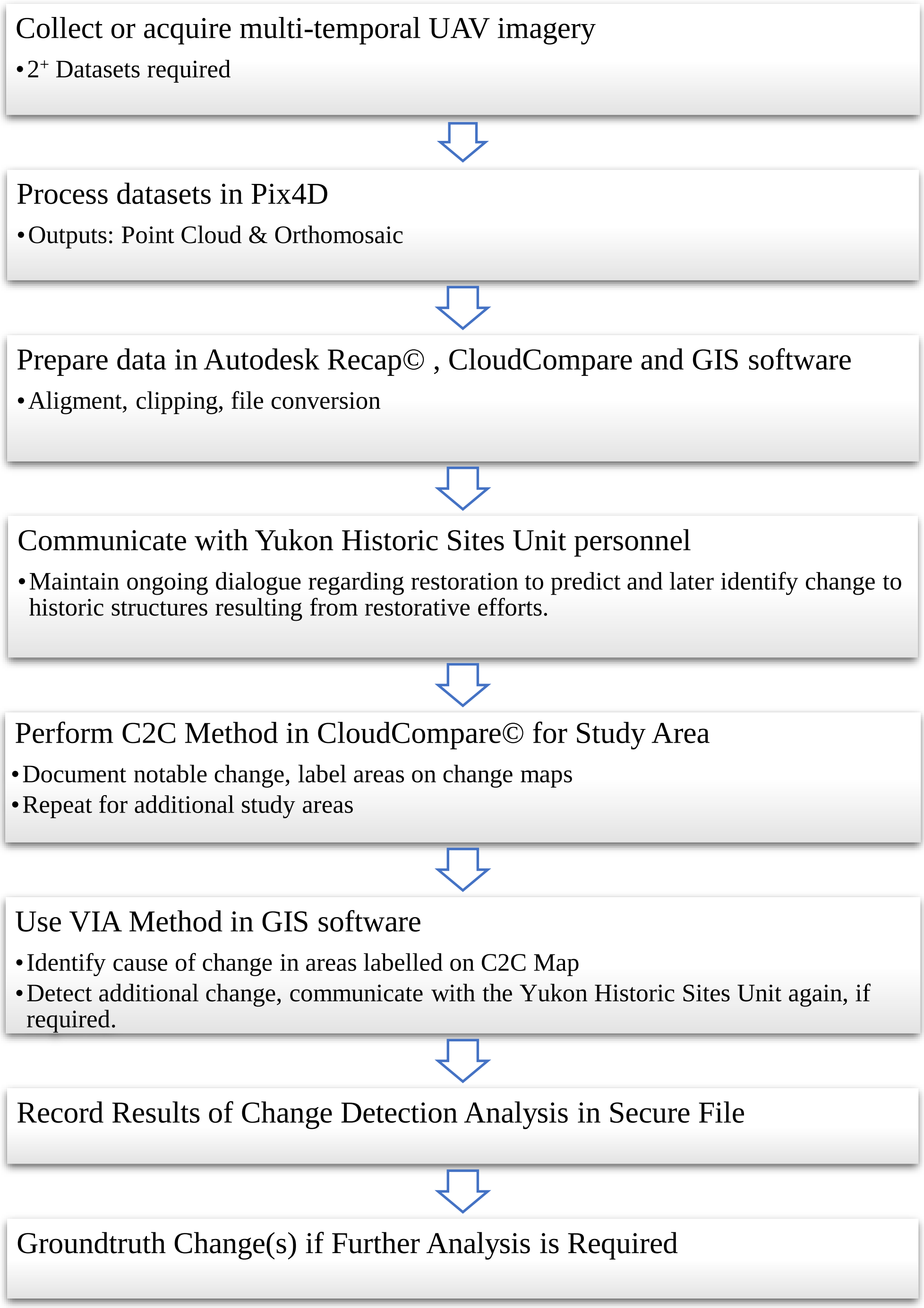


Figure 26. *Overview of method workflow used in this research. © Katelyn O'Keefe, 2022.*

5.1.1 2017 UAV Data

The raw data from 2017 was collected by Andrew M. Cunliffe, William F. Palmer, Jeffrey Kerby, and Isla H. Myers-Smith of Team SHRUB, a tundra ecology research group. While the data collected was not initially intended for heritage research, the extent of the UAV data captured the entirety of Simpson Point and Pauline Cove, where the heritage features are located. As mentioned in the introduction, the repurposing of data is beneficial. Found data is cost-efficient and environmentally friendly since it reduces the impact of repetitive data collection by decreasing travel and decreasing the physical impact of research activities on sensitive landscapes. Most importantly, sharing previously collected data fosters interdisciplinary opportunities and produces new research questions. For example, the change detection analysis performed in this research would not have been feasible without access to Team SHRUB's 2017 dataset due to pandemic-related travel restrictions.

The 2017 UAV imagery is of a stretch of coastline in the Island's southeast, including Simpson Point. Team SHRUB conducted seven surveys using two UAVs to capture a burst of rapid erosion along the permafrost coastline (Cunliffe et al., 2019). A summary of these seven surveys can is provided in Table 2 below. Cunliffe et al. (2019) provide a complete overview of the data collection methods used in their research. Their research was funded by the Natural Environmental Research Council (grant no. NE/M016323/1), the Natural Geographic Society (grant no. CP-061R-17), and the NERC Geophysical Equipment Society (grant no. GEF:1063 and GEF:1069) (A. Cunliffe, pers. comm. 2021).

The 2017 surveys by Team SHRUB captured imagery of the historic buildings and archaeological features on Simpson Point. The July 6, 2017, survey had the most suitable spatial extent compared to the 2019 data collected by our research group. This survey was conducted at the beginning of July, coinciding with the 2019 data collection timeframe. These qualities made the July 6, 2017, survey the most suitable for comparison with the 2019 data. The author of this text processed the raw data from the July 6, 2017, survey and named it *Floodplain2017* to distinguish it from the 2019 dataset. For this survey, Cunliffe et al. (2019) used a Zeta Phantom FX-61 fixed-wing UAV equipped with a Sony RX-100ii camera (1" CMOS sensor with 20.2 megapixels) to capture imagery over an area of 1.993 km^2 at 120 m above the ground surface. The longitudinal and horizontal overlap was 56 percent and 69 percent, respectively. The research team acknowledges that higher overlap is desirable for creating orthomosaics; however, the overlap achieved was deemed sufficient due to time limitations and challenging weather conditions (Cunliffe et al., 2019:1516). The extent of *Floodplain2017* is shown in Figure 27. The researchers used 98 GCPs for this flight. These were geolocated using real-time kinematic (RTK) Leica GNSS equipment to an absolute accuracy of approximately 0.02m (Cunliffe et al. 2019:1516). Additionally, an onboard GNSS to geotag the imagery throughout the flight (A. Cunliffe, pers. comm. 2021). More information regarding the extent of this survey can be found in section 5.2.

Survey Date	**Time**	**UAV**	**Altitude (m)**	**Images**
6, Jul 2017	12:20	Zeta Phantom FX-61	120	1325
13, Jul 2017	8:30	Zeta Phantom FX-61	120	194
30, Jul 2017	18:00	DJI Phantom 4 Pro	31	383
2, Aug 2017	8:00	DJI Phantom 4 Pro	100	2040
5, Aug 2017	11:40	DJI Phantom 4 Pro	37	336
11, Aug 2017	17:00	Zeta Phantom FX-61	120	8994
15, Aug 2017	10:20	DJI Phantom 4 Pro	42	402

Table 2. *Details of Team SHRUB's 2017 UAV surveys. Cunliffe et al. (2019:1517).*

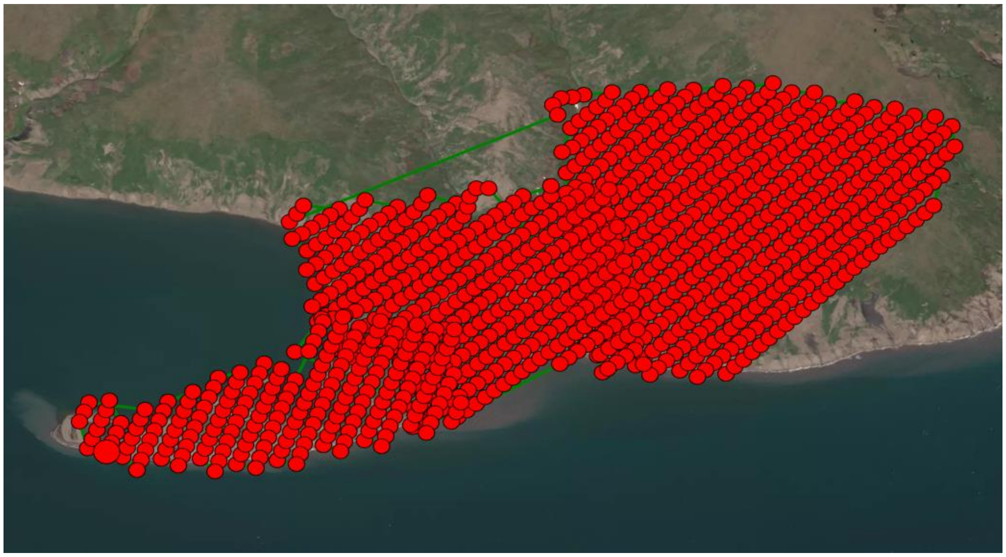


Figure 27. *Floodplain2017 UAV mission flight plan. Each red dot is the location of a geolocated image. Image generated using Pix4Dmapper©.*© Katelyn O'Keefe, 2022.

5.1.2 2019 UAV Data

The 2019 data collection was funded by the Cultural Services Branch, Government of Yukon, and Dr. Peter Dawson of the University of Calgary, as part of an ongoing research collaboration (see section 4.5.3). On July 7, 2019, the UAV survey of Simpson Point was conducted using a Parrot senseFly eBee X fixed-wing UAV equipped with a senseFly S.O.D.A. camera (1" CMOS sensor with 20.0 megapixels), and an onboard GNSS geotagged the imagery during the flight. No GCPs were used. The survey extent, shown in Figure 28, was planned, and executed using senseFly E-motion software. The mission was broken into two blocks, one extending from the rise of the bluffs in the east to the center of the spit and the other from the center of the spit to the spit's terminus. The drone was flown at 119 m above the ground for both blocks, and the image overlaps were set to 70 percent longitudinally and 80 percent horizontally. These parameters were selected because they captured the entire area while optimizing flight time. The flight took approximately 28 minutes to complete, and 338 geolocated images were taken over an area of 0.316 km^2 (see fig. 27). This survey was named "Pauline Cove 2019".

Table 3, below, is a summary of the camera parameters for Floodplain 2017 and Pauline Cove 2019.

Figure 28. *Flight plan for dataset Pauline Cove 2019. Each red dot is the location of a geolocated image. Image generated using Pix4Dmapper©..*© Katelyn O'Keefe, 2022.

Dataset	**Camera**	**Sensor**	**Sensor Size**	**Resolution (MP)**	**Nominal Focal Length (mm)**
Floodplain 2017	DSC-RX100ii	CMOS	1.0 inch	20.2	10.4
Pauline Cove 2019	senseFly S.O.D.A	CMOS	1.0 inch	20.0	10.6

Table 3. *Camera specifications for the cameras used for Floodplain 2017 and Pauline Cove 2019. Data from senseFly (n.d) and Imaging Resource (n.d.).*

5.2 Data Processing and Preparation

5.2.1 Data Processing

The datasets were processed using Pix4Dmapper© (V.4.5.6), a professional photogrammetry software suite for UAV mapping (Pix4D, 2021). Alternate software packages can be used, depending on the desired outputs. Pix4D was chosen for two reasons. The first was its superior digital reconstruction abilities, which yield precise, georeferenced maps and 3D models of large landscapes. The second reason is that the software is made specifically for drone-based mapping. Photogrammetric software uses imagery data and the metadata of that imagery, along with any geolocational information, to determine the spatial relationships of the imagery. Once the relationship between the images has been determined, various data outputs can be created, including orthomosaics, point clouds, and DSMs. This section outlines the processing workflow required to process the 2017 UAV and the 2019 UAV imagery. These steps are outlined in Figure 29.

First, a new project was created, and imagery was uploaded into the software. If the images are geolocated with an onboard GNSS, the proper coordinate system will be automatically detected and displayed under geolocation and orientation. There is also an option to include GCPs. For *Floodplain2017* and *PaulineCove2019*, the image coordinates produced from the respective onboard GNSSs were used to georeferenced the imagery, and the coordinate system for the images was set to WGS 1984 UTM 7N (EGM 96 Geoid). Cunliffe et al. (2019) describe the use of GCPs for the 2017 dataset; however, for consistency, the decision was made not to incorporate these during processing since GCPs were not part of the 2019 data collection strategy. The 2019 dataset was initially collected purely for visualization purposes, not for change detection analysis[3], and GCPs were not required. With the onset of the Covid-19 pandemic, the original research plan was no longer feasible, and this research became reliant on previously collected data. For this research presented in this thesis, the geotagged imagery files (text files with 3D image coordinates) for the 2017 and 2019 data were used to georeference the respective imagery. Rather than incorporating the GCPs from 2017 during the 2017 data processing and still having to align the 2019 dataset afterward, steps were taken to align the two datasets during data preparation without incorporating the GCPs.

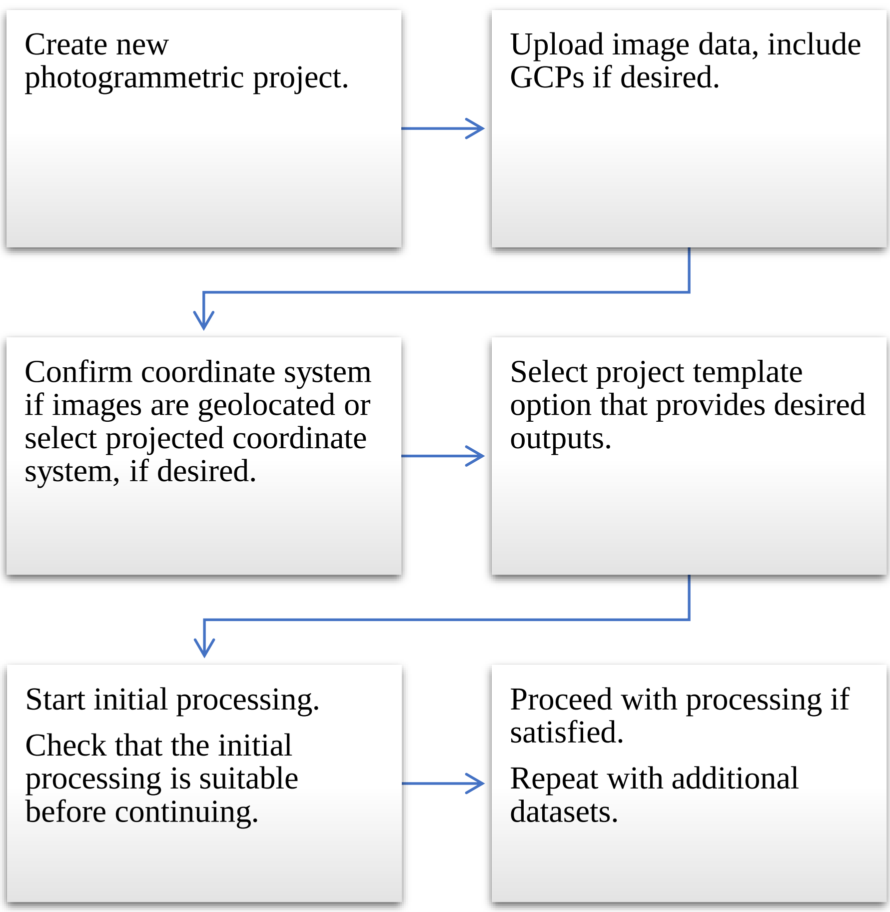


Figure 29. *Pix4D processing workflow for the UAV imagery.*

[3] The data was collected prior to the onset of the COVID-19 pandemic, which necessitated changes to the original scope of this research.

The software proceeds if acceptable image overlap is present in the uploaded imagery. Following these steps, the desired project template must be selected. The 3D Map template was chosen for this project because it produced the outputs needed for this research's change detection analysis component: an orthomosaic, a DSM, and a point cloud. Other options were specified before commencing, including merging all imagery into one file and the LAS file format for the point cloud. LAS is a 3D format created by the American Society for Photogrammetry and Remote Sensing, specifically designed for aerial remote sensing (Huber, 2011:78640A). Merging all imagery into one large file is crucial for creating seamless orthomosaics, DSMs, and point clouds. The next step is to begin the processing. The time required for the initial processing is minimal, and once this is complete, a quality report is generated, enabling the user to access the quality of the project outputs. Following satisfactory results, the program will complete the processing. The total processing time depends on the image format, the number of images uploaded, and the hardware used. Information about the minimum hardware requirements for Pix4Dmapper© can be found on Pix4D's website (pix4D.com).

5.2.2 Data Preparation

Post-processing, the decision was made to perform change detection analysis on two smaller study areas on Simpson Point. Two factors influenced the location and size of the study areas chosen. The first factor considered was the location and distribution of the heritage features on Simpson Point. The second factor was the need to reduce the size of the area under investigation due to error propagation that increased with distance from the alignment points used. Study Area 1 was selected due to its central position on the spit, where most historic buildings are located. Study Area 2 was chosen because numerous archaeological features, primarily the remains of Inuvialuit sod houses, are located within the area. The location of Study Area 1 and Study Area 2 relative to Simpson Point and Pauline Cove is depicted in Figure 30 below.

Before the point clouds could be clipped to the extent of the desired study areas, the data required preparation. The preparation included manipulating the datafile extension of the point cloud files, performing an initial alignment of the point clouds, performing cross-section analysis, and segmenting the full-extent clouds to the study areas before once again aligning the clouds. These steps are essential to prepare the study area point clouds for the C2C change detection method. In addition, the finalized study area point clouds are also required to clip the orthomosaics to the same extent, which is required for the VIA change detection method.

In Autodesk ReCap©, a software program used to manipulate 3D data, the limit box was used to clip the 2017 point cloud to match the approximate spatial extent of the 2019 point cloud. Once the desired results were achieved, the point clouds were converted into E57 format, suitable for CloudCompare©, the software chosen for the C2C change detection method. The E57 format is a general-purpose format capable of storing 3D data from any system providing 3D measurements (Huber, 2011:78640A).

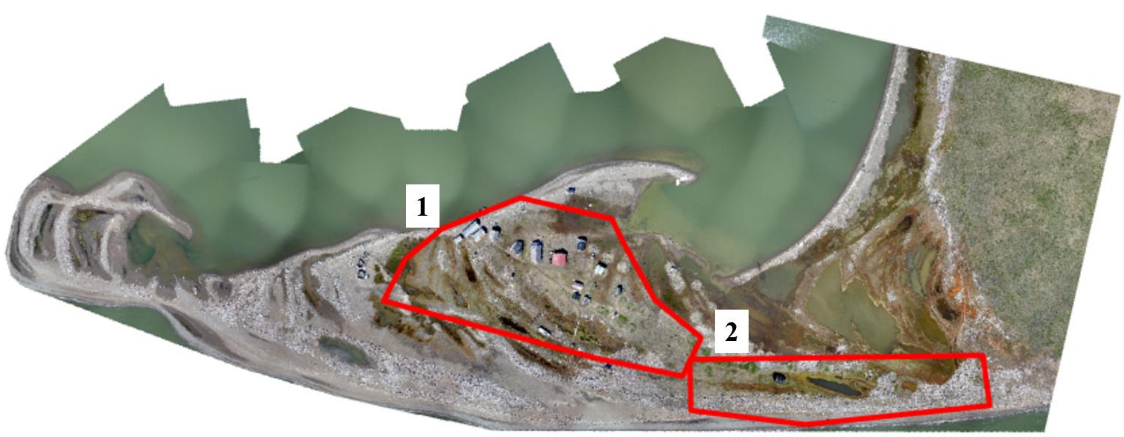


Figure 30. *Location of Study Area 1 and 2 on Simpson Point.* © Katelyn O'Keefe, 2022.

When imported into CloudCompare©, the 2017 and 2019 point clouds were of similar scale, and they were roughly aligned. Together, these are reasonable indications of properly processed and georeferenced clouds (D. Lichti, pers. comm. 2021). The data preparation steps in CloudCompare© are described below and outlined in Figure 31.

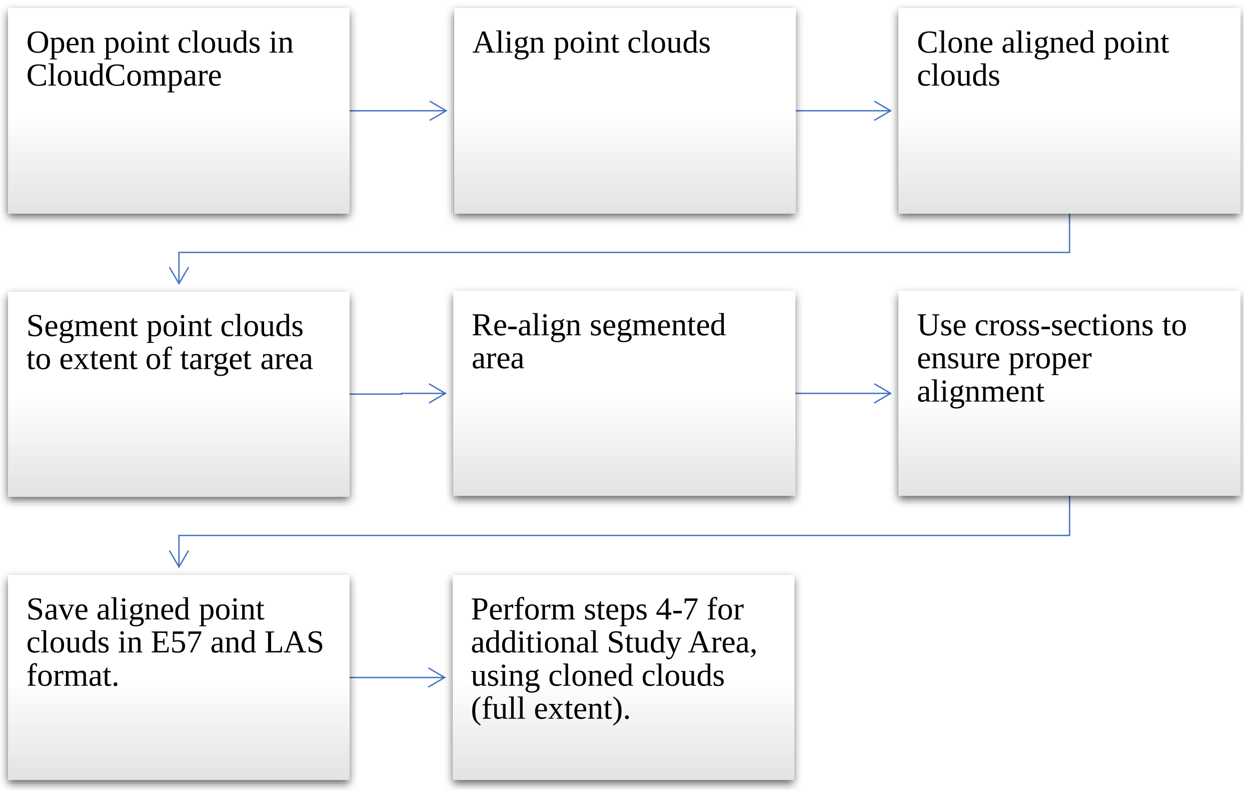


Figure 31. *Point cloud preparation workflow in CloudCompare©.* © Katelyn O'Keefe, 2022.

Because GCPs were not incorporated during processing, slight alignment was needed to prepare the point clouds before running the C2C distance computation tool. The Point-Pair Registration tool was used to align the point clouds. The 2017 point cloud was the reference cloud, and the 2019 cloud was the aligning cloud. It is common practice to use the older point cloud as the reference point cloud (Al-Rawabdeh et al., 2017; Hvidberg, 2019:77). The author carefully selected ten points for the alignment process. The location of these points is shown in

Figure 32. These points were the corners of buildings or other features known to be stable between 2017 and 2019, as confirmed through consultation with Yukon Historic Sites Unit personnel. The root mean square error (RMS) for this alignment was 0.091, and the scale was 0.991. Once the clouds were well aligned and an acceptable RMS value was obtained, the clone tool was used to duplicate the aligned full extent point clouds. Cloning the aligned clouds is critical because reverting to previous versions of a point cloud is challenging in CloudCompare©. Next, the segmentation tool was used to segment the edges of the aligned point clouds, which ensured that the spatial extent of both clouds was the same. Cross-section analysis was then used to confirm the alignment of the clouds. The cross-section tool was used lengthwise across the entirety of the clouds to check alignment. The location of one of the cross-sections is shown in Figure 33. As expected, the error increases with increased distance from the alignment points. Figure 34 is a cross-section segment depicting the two point clouds (the blue is 2017 and the green is 2019), and the error increases with distance from the historic structures, which appear as the scatters of points on the left of the figure. This error further justified the need to segment the point clouds into the smaller study areas described previously.

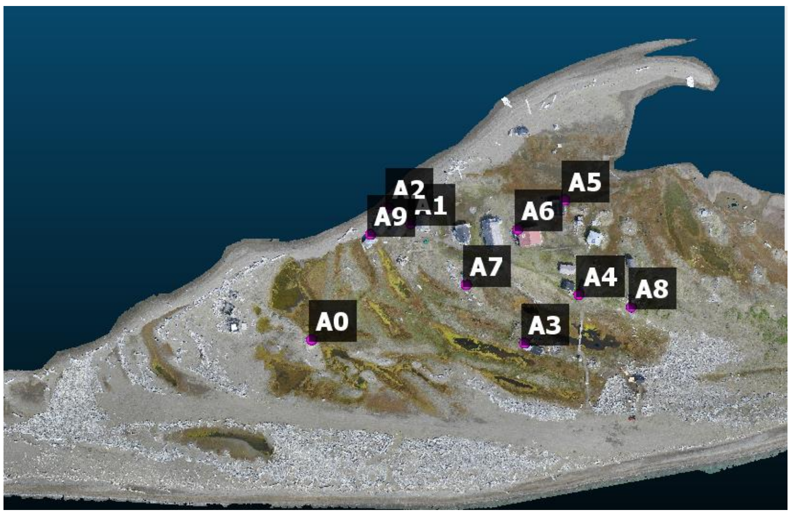


Figure 32. *Initial alignment points for the entirety of Simpson Point.* © Katelyn O'Keefe, 2022.

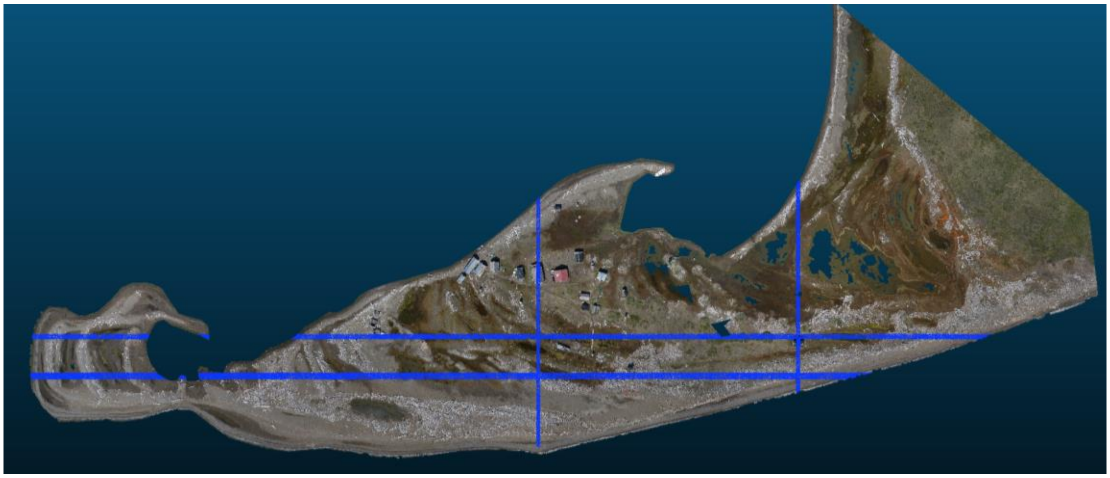


Figure 33. *Cross-section locations on the full extent point cloud.* © Katelyn O'Keefe, 2022.

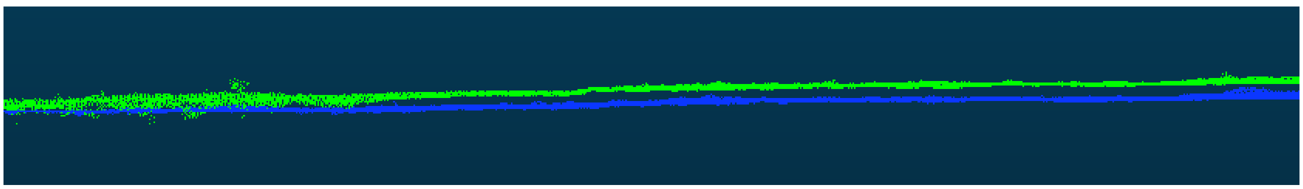


Figure 34. *Cross-section of 2017 (blue) and 2019 (green) point clouds, showing alignment error on the y axis with increased distance from the alignment points (historic structures). The historic structures appear as the scatter of points on the left. More error is present in the figure's right, corresponding with increased distance from alignment points.* © Katelyn O'Keefe, 2022.

The segmentation tool was used on the aligned point clouds to clip a smaller area, called Study Area 1. It is important to note that the segmented clouds will no longer be correctly aligned if one of the original alignment points is removed during the segmentation process. For this reason, the point clouds were re-aligned post-segmentation to ensure that the alignment would be corrected if any of the original alignment points were removed accidentally. The 2017 point cloud was used as the reference cloud again for consistency. The alignment points chosen for the re-alignment of Study Area 1 are shown in Figure 35. The RMS for the alignment of Study Area 1 was 0.078, and the scale was 0.999. Lastly, the segment tool was used again to clean any non-overlapping edges. Next, the Cross-section Analysis tool was used to check the alignment in the X and Y directions of Study Area 1. Figure 36 is a cross-section of the aligned

Study Area 1 point clouds through three historic buildings. No gap was detected in the cross-section, indicating proper alignment. The point clouds were saved as separate entities, *Study Area 1 2017*, and *Study Area 1 2019*. The spatial extent of the Study Area 1 2017 point cloud post-segmentation is shown in Figure 37.

Figure 35 *Alignment points for the Study Area 1 re-alignment. The cloud shown here is the reference cloud.* © Katelyn O'Keefe, 2022.

Figure 36*. Cross-section of the aligned Study 1 point clouds. No gaps between the point clouds can be seen, suggesting proper alignment.* © Katelyn O'Keefe, 2022.

Figure 37. *The aligned Study Area 1 point cloud. Shown here is the reference cloud.* © Katelyn O'Keefe, 2022.

The steps outlined above were repeated for Study Area 2, using the cloned full-extent point clouds. For Study Area 2, only one historic building (the Mission House) can be used for alignment. Large pieces of driftwood that had not moved between 2017 and 2019 were used as additional alignment points. Nine points in total were chosen (see fig. 38). The location of the alignment points was strategically selected for the best possible triangulation; however, the RMS value for the alignment of Study Area 2 was slightly higher than the RMS value of Study Area 1, where the alignment points were the corners of buildings. The RMS for the re-alignment of Study Area 2 was 0.221, and the scale was 0.999 (see fig. 39). The aligned point cloud for Study Area 2 can be seen in Figure 40.

Once satisfied with the results, the finalized Study Area 1 and Study Area 2 point clouds were saved as E57 and LAS files. The E57 file format was chosen because it is accepted by CloudCompare©, the software used for the C2C method. ArcGIS Pro© accepts the LAS format point clouds, and the software is needed to clip the orthomosaic imagery to the same extent as the point clouds.

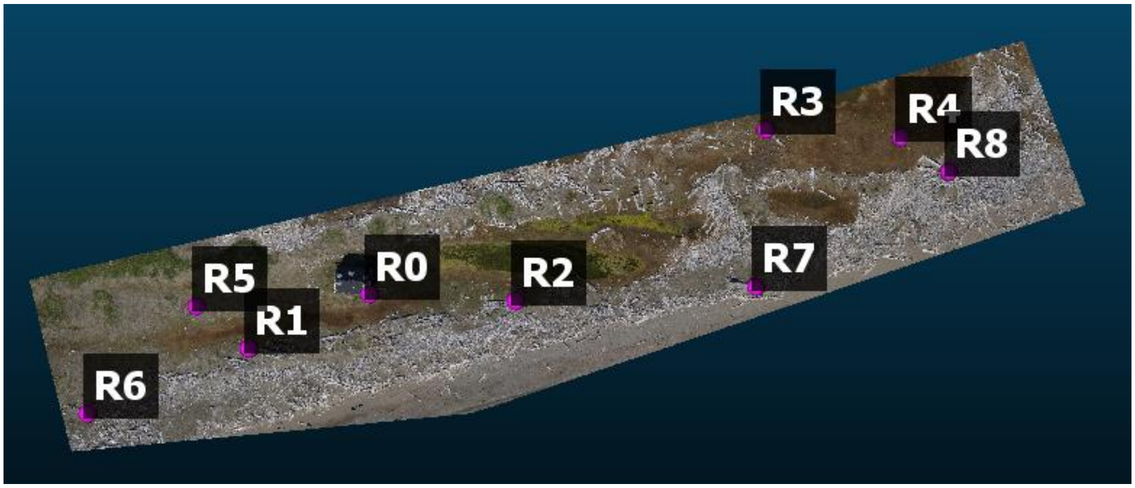


Figure 38. *The alignment points for Study Area 2 point cloud. Shown here is the reference cloud.* © Katelyn O'Keefe, 2022.

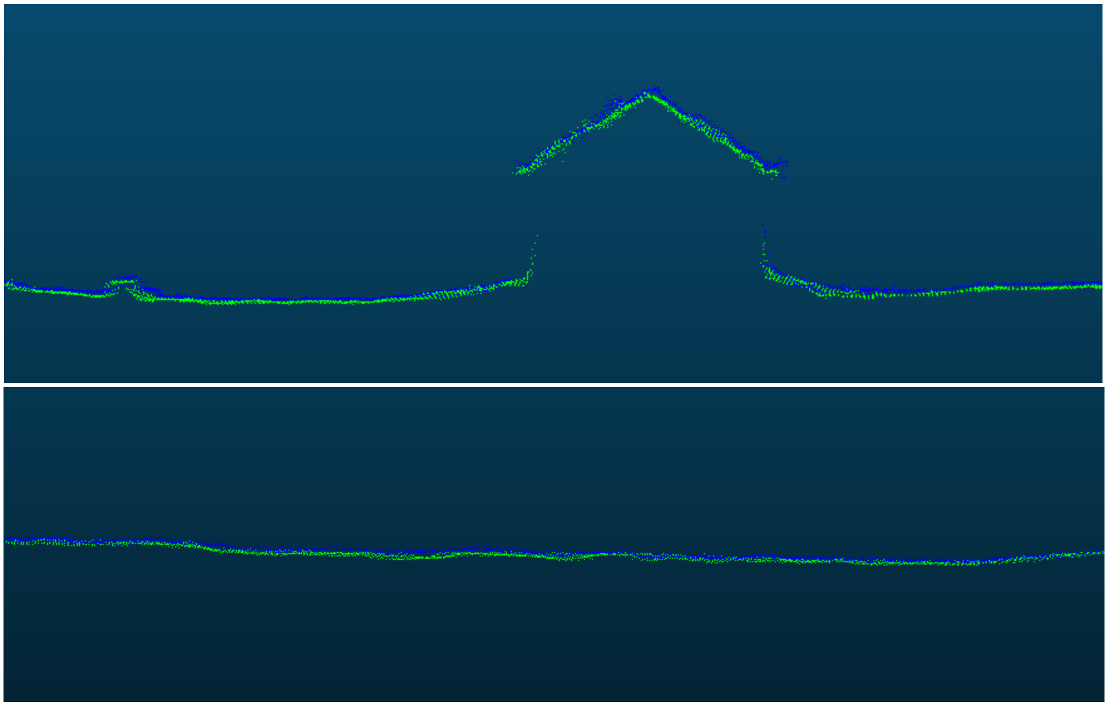


Figure 39*. Cross-sections of Study Area 2 after re-alignment.* © Katelyn O'Keefe, 2022.

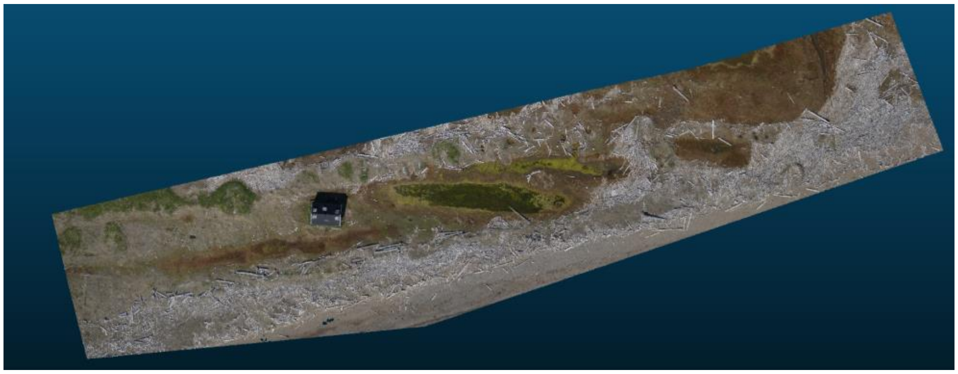


Figure 40. *Finalized Study Area 2 point cloud. Shown here is the reference cloud.* © Katelyn O'Keefe, 2022.

This section outlined the workflow for data processing in Pix4D and the required data preparation steps in Autodesk Recap© and CloudCompare©. Correctly prepared data is crucial to perform the change detection methods used in this research. The following section will use the data products prepared using the steps in this section. The finalized point clouds for Study Area 1 and Study Area 2 are essential for C2C and VIA since the cloud outlines are required to clip the orthomosaics.

5.3 Change Detection Analysis Workflow

As defined in section 2.2, change detection is a widely applicable technique that makes use of remote sensing data to identify differences in an object or landscape through observation at two or more moments in time (Singh, 1989:989; Mouat et al., 1993). The change detection methods used in this research are C2C and VIA. An explanation of these methods can be found in sections 2.2.1 and 2.2.2. These methods were specifically chosen for this research due to their compatibility, discussed at length in section 7.1. The C2C distance computation method was undertaken first to quantify the change and to identify critical areas of change before VIA. Once areas of notable change were identified in the two study areas, VIA was used to verify and identify the cause of the changes. In addition, VIA was completed for the entirety of the study areas, not just the areas with detected change, to record change that was not detected on the C2C change map. The following sections describe the workflow for C2C distance computation in CloudCompare© and the VIA done in ArcGIS Pro©.

5.3.1 C2C Workflow

Within CloudCompare©, the tool for cloud-to-cloud change detection is called Cloud-to-Cloud Distance. This tool functions by using nearest neighbor analysis to quantify the change between the points in the reference point cloud and a comparative point cloud (Girardeau-Montaut et al., 2005:1). The output from the cloud-to-cloud distance computation is a re-coloring of the comparative scan, with a scalar field indicating the amount of change detected between the two clouds (CloudCompare, 2015). A scalar field is a set of values, one for each point in the point cloud, displayed as colors corresponding to the magnitude of the change (CloudCompare, 2015). Further information on the C2C change detection method can be found in Chapter 2, section 2.2.2.

The C2C method workflow (summarized in fig. 41) begins once the point clouds for the study areas are correctly aligned, as described in section 5.2.2. The following steps will be performed twice, once for each study area. With the desired point clouds selected, click the Cloud-to-Cloud Distance tool. The tool will prompt the user to choose a reference cloud. The 2017 reference cloud was chosen for consistency, and so that the change reflected in the re-colored point cloud was the change that took place from 2017 to 2019. The default parameters were used for this calculation, and the maximum distance was not limited. The tool was run using the default algorithm, Hausdorff distance, since the cloud had a high density and was without large voids. As mentioned in section 2.2.2, Hausdorff distance is a form of nearest neighbor analysis used to calculate the maximum deviation between two or more 3D point models, in sizeable 3D point cloud datasets. Under approximate distances, the results were selected to be computed as absolute values in meters (m).

Once the options were chosen, the tool processed the data for approximately 5 minutes. Once finished, the properties of the re-colorized point cloud were edited to best display the results. The color ramp was edited, and the Blue>Green>Yellow>Red color ramp was selected. In addition, the values associated with each color were modified to best display the results in the scene. These steps were repeated for Study Area 2. See section 6.2.1 for the finalized re-colorized point cloud, also referred to as the C2C change map of Study Areas 1 and 2. The C2C method results are discussed in the following chapter, in section 6.2.

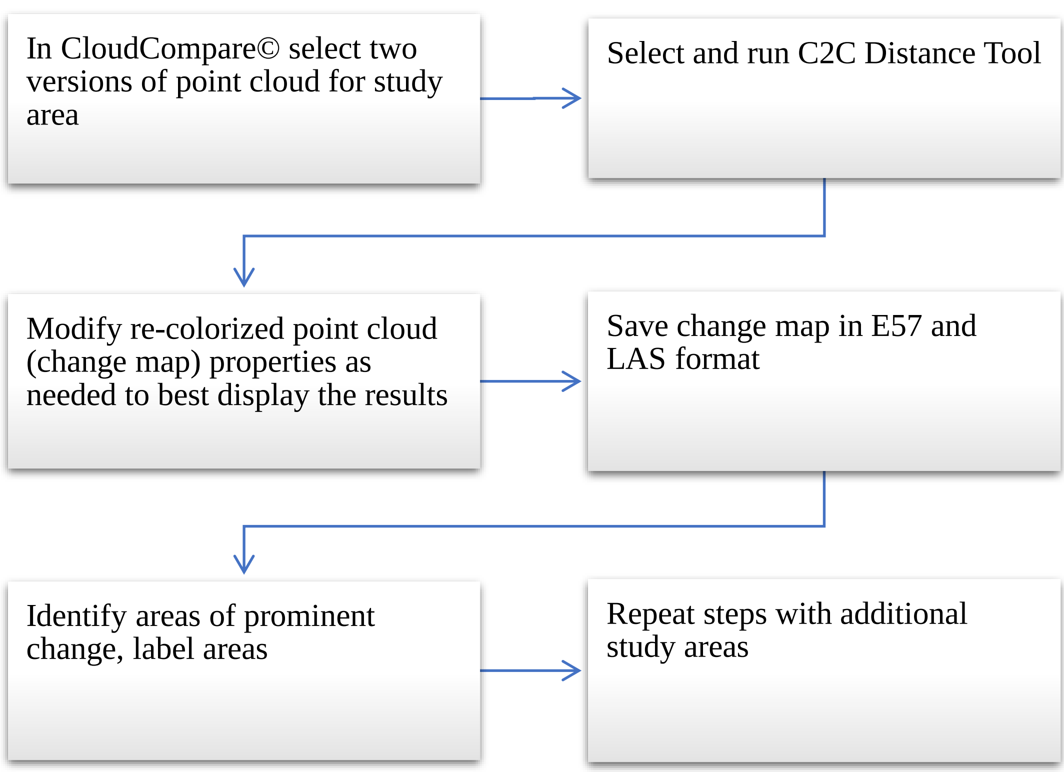


Figure 41. *Cloud-to-Cloud distance computation workflow in CloudCompare©.* © Katelyn O'Keefe, 2022.

5.3.2 VIA Workflow

VIA is a straightforward, manual method for identifying change between two or more imagery sets. VIA was used extensively before the 1970s on aerial imagery and historical photographs, as it did not require advanced computer techniques nor sizable data storage (Lu et al., 2004:2387). This process can be done using physical photographs or computer software to toggle the images back and forth. The author opted to use ArcGIS Pro©, by ESRI, to conduct the visual analysis change detection. There are many benefits to using a GIS for VIA, including the ability to toggle between datasets quickly, view raster data and 3D point data in one software, overlay a grid, and lastly, the zoom feature is advantageous when looking for change.

Figure 42 is a visualization of the workflow for the VIA method. It is essential that the spatial extent of the study area orthomosaics match the spatial extent of the study area point clouds, so their alignment was adjusted very slightly using the Auto Georeference tool in ArcGIS Pro. For consistency with the alignment process done in CloudCompare©, the 2017 data was used as the reference. The Auto Georeference tool functions similarly to the Point-pair Registration tool in CloudCompare© but without the need to manually select alignment points (ESRI, n.d.b). The LAS versions of the 2017 study area point clouds were then imported into the GIS. Because the point clouds from 2017 and 2019 had the same spatial extent, only one set of the Study Area 1 and 2 point clouds was needed to crop the 2017 and 2019 orthomosaics. The point clouds are visible in Figure 43 below, with 2017 orthomosaic also visible.

Two polygon feature classes were created using the outlines of the point clouds. These feature classes were used to clip the 2017 and 2019 orthomosaics to the extent of the study area point clouds. This process created four new orthomosaics, one for 2017 Study Area 1, one for 2019 Study Area 1, one for 2017 Study Area 2, and one for 2019 Study Area 2.

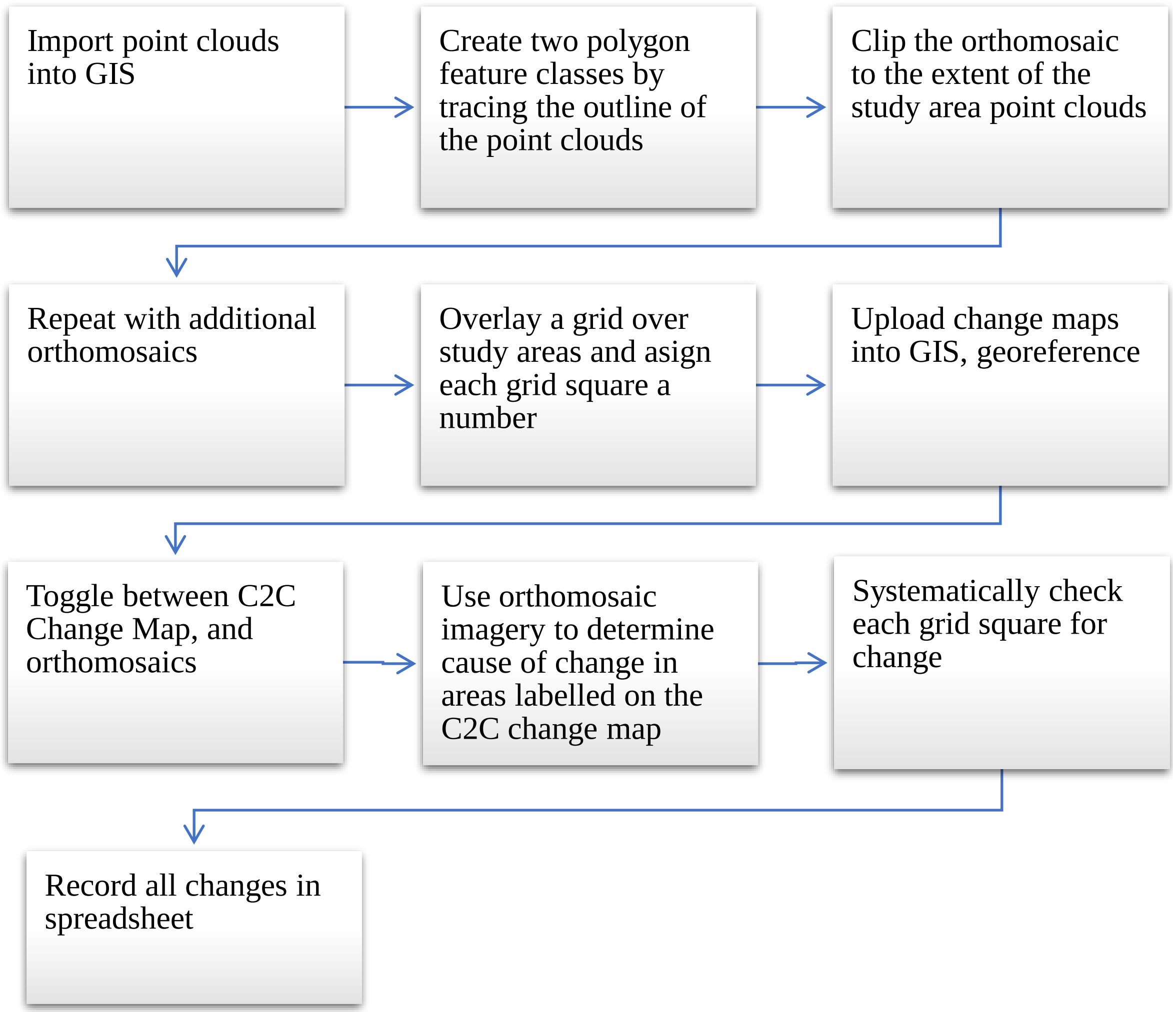


Figure 42. *VIA workflow.* © Katelyn O'Keefe, 2022.

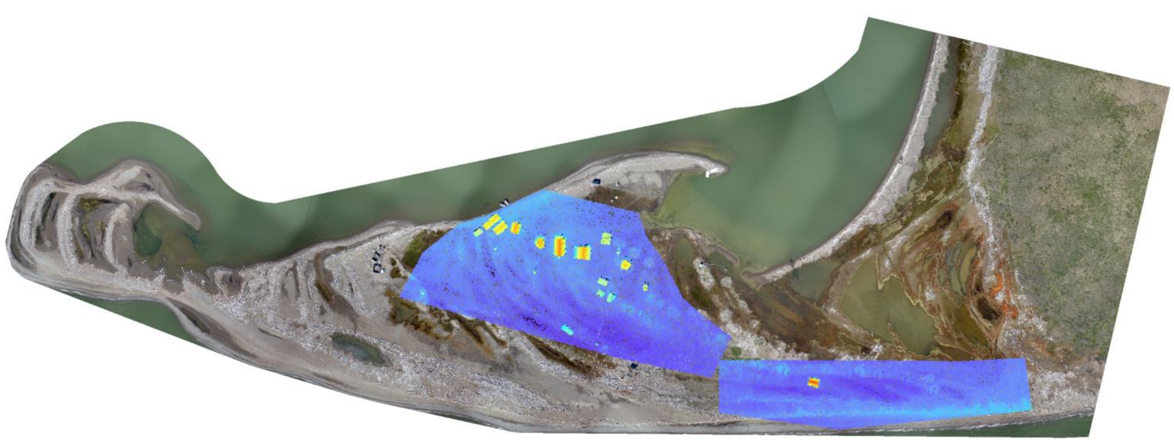


Figure 43. *The 2017 Study Area 1 (left) and 2017 Study Area 2 (right) point clouds overlay the 2017 orthomosaic in ArcGIS Pro©.* © Katelyn O'Keefe, 2022.

The orthomosaics were inspected visually. In the GIS, a 10 x10 m grid was overlaid on the Study Area Imagery at a rotational angle of 193.2 degrees. Since the study areas were uniquely shaped, aligning the rotation with both areas was impossible using a singular grid. This angle was chosen because it aligned well with Study Area 2. Screenshots of the gridded Study Area 1 and Study Area 2 orthomosaics were copied in a separate document, and each 10 x10 m grid square was numbered following a boustrophedon (ox-plow) track. Study Area 1 was divided into 345 squares, and Study Area 2 into 192 squares. For Study Area 1, it is essential to note that because of the direction of the imagery relative to the grid, and the decision to restrict the numbering of blocks to those with imagery, the numbers appear to "jump." For example, blocks 28 and 29 are not directly beside one another. The numbered grids for study areas 1 and 2 are shown below in Figure 44. In the GIS, the 2017 and 2019 orthomosaics and the C2C change map of Study Area 1 were selected and toggled on and off.

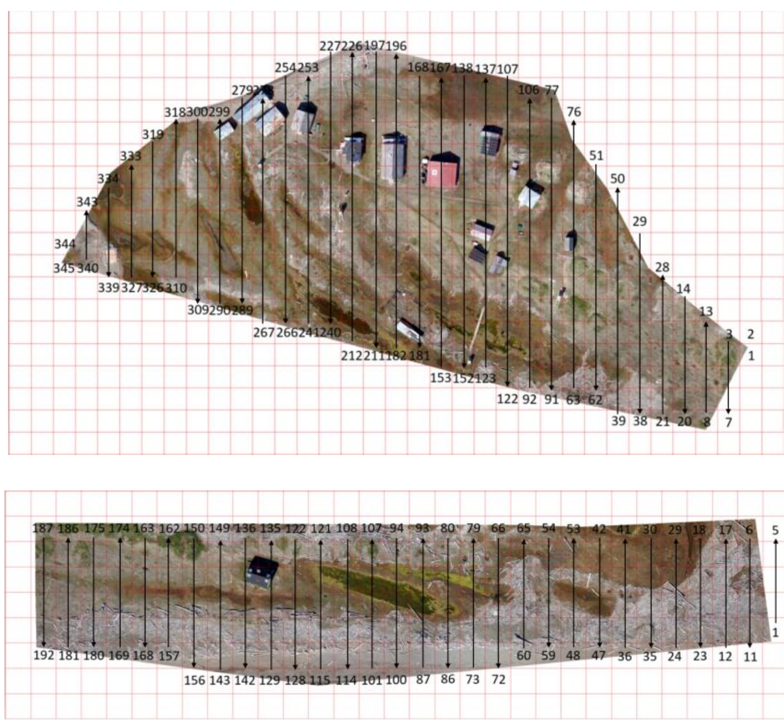


Figure 44. *Numbered grid on Study Area 1 (top) and 2 (bottom).* © Katelyn O'Keefe, 2022.

First, the most noticeable changes detected using C2C were inspected in the 2017 and 2019 orthomosaics. The cause of the change, if discernible, was recorded. This step was repeated for all noticeable changes labeled on the C2C change map. Then, the process was undertaken a second time, this time recording all noticeable changes in every 10 x 10 m square in Study Area 1. All differences between the 2017 and 2019 orthomosaic were recorded in a spreadsheet by square. For Study Area 2, the 2017 and 2019 orthomosaics and the C2C change map were selected and toggled back and forth in the GIS. The same steps described for Study Area 1 were followed for Study Area 2.

Following the completion of the change detection methods, the results of each method were documented, and the two methods were compared. The first round of VIA analyzed the areas of change noted in the C2C, and any changes found on the C2C map that were not noticed in the imagery were documented. Likewise, in the second round of VIA, where each 10 x 10 m square was analyzed for change independent of the C2C results, all changes not picked up by the C2C were documented. The change documented between the 2017 and 2019 datasets was recorded in a secure file. It is important to note that ground-truthing of results may still be required in some instances. For example, on-site observation may be required when the nature of a change cannot be determined through visual analysis or dialogue with the *Herschel Island – Qikiqtaruk Territorial Park* rangers or the Yukon Heritage Sites Unit personnel.

5.4 Chapter Summary

This chapter discussed the methods used to collect, process, and prepare the UAV data for change detection analysis. Figure 26 is an overview of the method workflow used in this research. The C2C method was undertaken first, using CloudCompare©. Figure 41 is a summary of the C2C workflow. The C2C method was performed first because the re-colorized point clouds (change maps) were used to identify areas of notable change for the following change detection method, VIA. Figure 42 shows the workflow for VIA. In ArcGIS Pro©, two rounds of VIA were completed. The first round targeted the areas of change labeled in the change maps for study areas 1 and 2, and the second round of VIA was systematically completed for each 10 x 10 m square in the study areas to document change that was either subtle on the C2C change map or detected by the C2C distance method. In the next chapter, the results of the Pix4D data processing and the change detection methods will be described.

6 RESULTS

This chapter is devoted to discussing the results of the UAV data processing and the results from the two change detection methods used in the methods chapter of this research. The change detection methods, C2C and VIA, were selected due to their compatibility. Section 6.1 of this chapter outlines the results of the UAV data processing. The following section, 6.2, summarizes the change detected using C2C. Section 6.3 utilizes the VIA results from the orthomosaic imagery to verify the changes detected by the C2C and explains the nature of the changes detected. Also in this section is a description of additional changes documented during the VIA process. Section 6.4 explains the possible causes of widespread patterns of change found in the change detection analysis, including increased standing water and vegetation.

6.1 Data Processing Results

The UAV data for this research was processed using Pix4Dmapper©. By selecting the 3D Map Template option, the post-processing outputs are 3D orthomosaics, 3D point clouds, and DSMs. With geotagged imagery, these outputs are automatically georeferenced. This section serves to outline the results of the Pix4D processing component of this research and provide visuals of the data outputs.

6.1.1 2017 Outputs

As mentioned in Chapter 5, the 2017 data shared by Dr. Andrew Cunliffe consisted of 1325 geolocated images. The initial processing step in Pix4D removes images that cannot be adequately calibrated, including images that share no recognizable features, such as images over the ocean. The shape of Simpson Point is long and narrow, meaning that there were numerous images captured of the Beaufort Sea and Pauline Cove. As a result, 231 images were automatically removed by the program, and the remaining 1094 images (82 percent) were calibrated and processed. As mentioned in section 5.2, the full extent orthomosaic and point cloud generated from the imagery was clipped to the extent of the 2019 imagery and then clipped again, to the extent of each respective study area (see fig. 45).

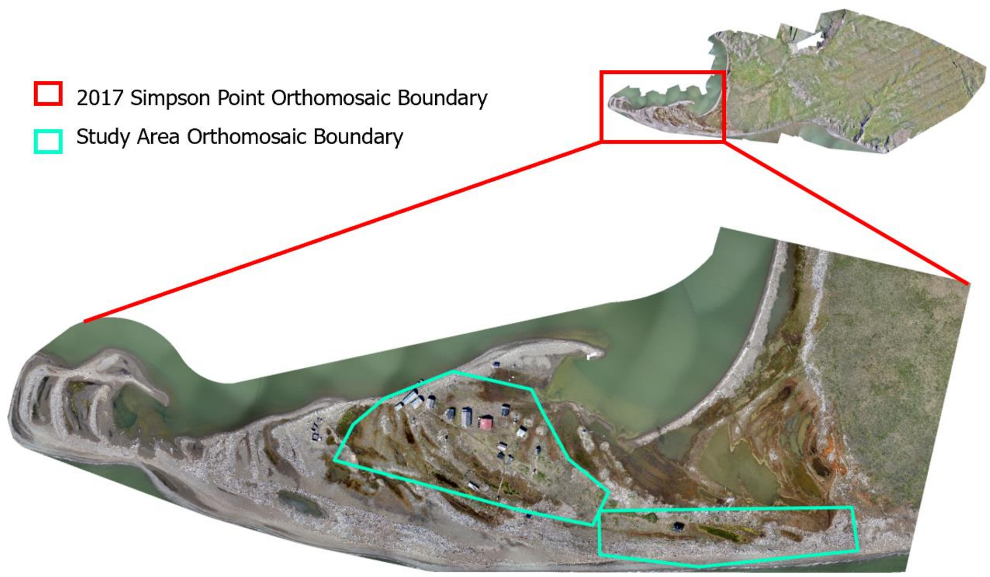


Figure 45. *Study area boundaries, shown on the clipped 2017 orthomosaic.* © Katelyn O’Keefe, 2022.

The dataset has 14,499.5 matches per calibrated image, and the orthomosaic has a resolution equivalent to the ground sampling distance (GSD) of 2.69 cm/pixel. The smaller the GSD value, the higher the spatial resolution of the imagery, meaning that more details can be seen (Pix4D, n.d.b). With sufficient image overlap and scaling, the relative accuracy of the datasets is one to three times the GSD (Pix4D, n.d.c). Therefore, the relative accuracy for the 2017 dataset is between 2.69cm and 8.07 cm. The point cloud has a total of 146,094,433 3D densified points and an average density of 176.3 points/m^3. Further details regarding the processing and output quality can be found in the quality report in the appendix.

6.1.2 2019 Outputs

The 2019 dataset covered a smaller area and consisted of 338 geolocated images, 277 or 82percent of which were calibrated during initial processing. The orthomosaic generated by Pix4Dmapper© is shown in Figure 46. The 2019 dataset has 17,713.9 matches per calibrated image, and the orthomosaic has a resolution equivalent to the ground sampling distance of 2.96 cm/pixel. Using the same calculation technique as the 2017 dataset, the relative accuracy for this dataset is between 2.96cm and 8.88cm. More information regarding the processing and output quality can be found in the quality reports in the appendix. Table 4 compares the post-processing results for the 2017 and 2019. Like the orthomosaic and point cloud of the 2017 data, the full extent orthomosaic and point cloud were clipped to the extent of study areas 1 and 2 (see fig. 46, 47 and 48).

Figure 46. *Orthomosaic generated from the dataset Pauline Cove 2019, with outlines of the Study Areas Image generated using Pix4Dmapper©..*© Katelyn O'Keefe, 2022.

Dataset Name	Observation Date	Images Captured	Images Calibrated	Area Covered (km^2)	Area Covered (Acres)	Avg. GSD (pixel/cm)
Floodplain 2017	06/07/2017	1325	1094	1.993	492.85	2.69
Pauline Cove 2019	07/07/2019	338	277	0.316	78.16	2.96

Table 4. *Post-processing results for Floodplain 2017 and Pauline Cove 2019 datasets.*

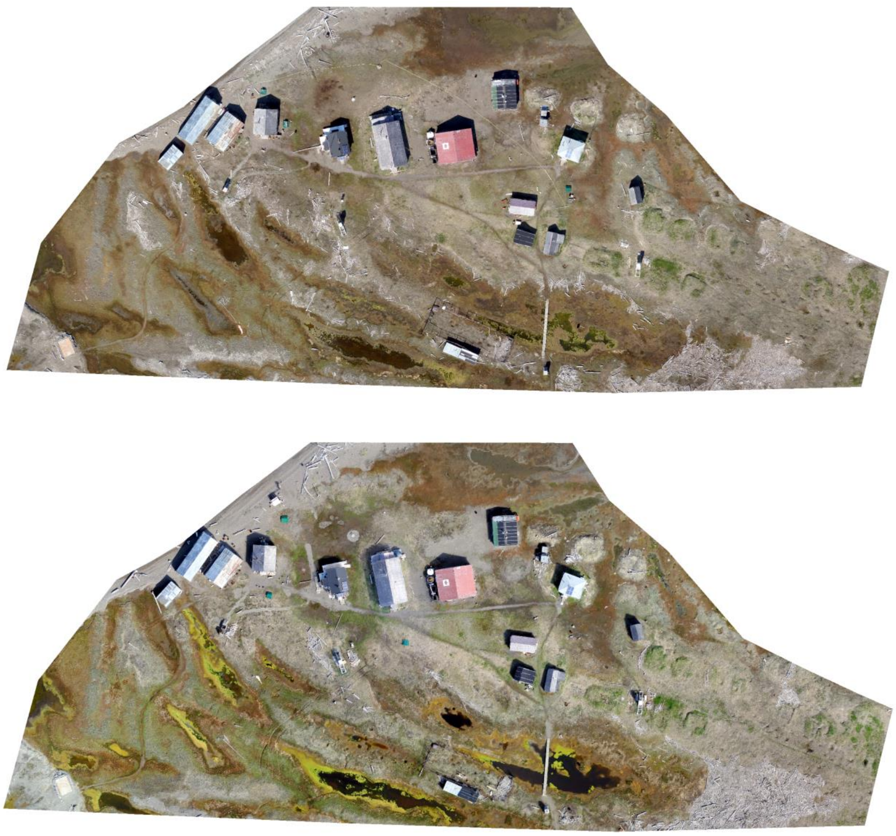


Figure 47. *Clipped orthomosaics of Study Area 1. The top image is from 2017, and the bottom is from 2019.* © Katelyn O'Keefe, 2022.

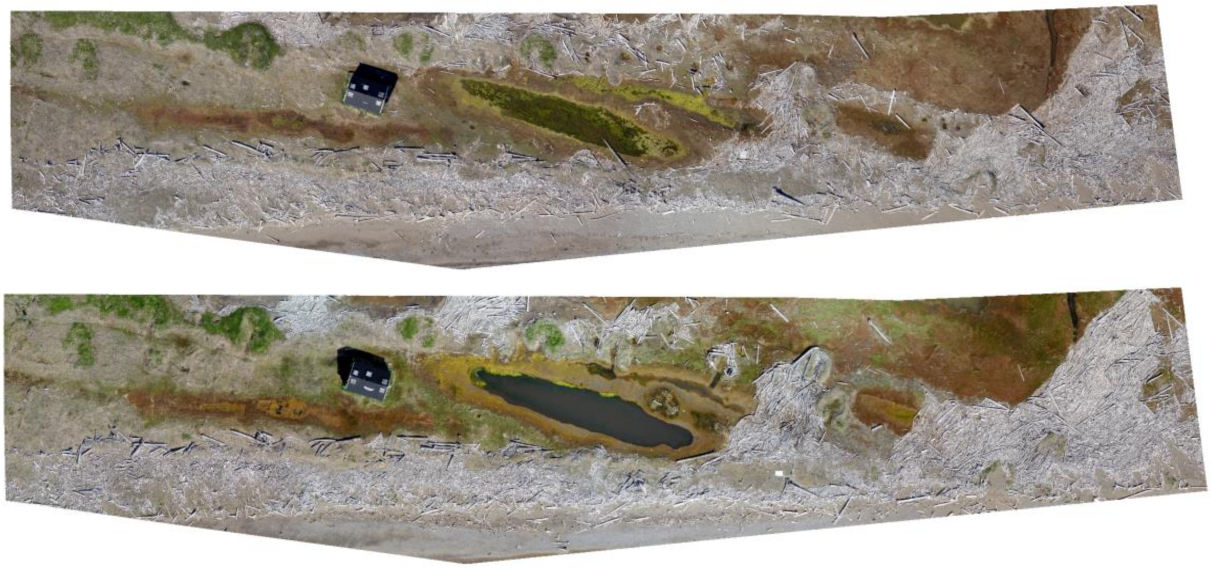


Figure 48. *Clipped orthomosaics of Study Area 2. The top image is from 2017; the bottom is from 2019.*© Katelyn O'Keefe, 2022.

6.1.3 Confirmation of Photogrammetric Models

In July 2018, a Z + F 5010X terrestrial laser scanner was used to create digital scans of several historic structures on Simpson Point. These scans were used to create accurate 3D digital models of the structures for the Digital Preserve website (https://herschel.preserve.ucalgary.ca/). Using the scanner and paper mounted targets, each structure was scanned from multiple locations. The scans were registered using Z + F Laser Control V.8.9 and exported into AutoDesk ReCap© V.6.1, for registration (Capture 2 Preserv, 2021). The scans for four buildings (the Blubber House, Bone House, Community House, and Captain Mckenna's Cabin), were then compiled into a singular LAS point cloud model using AutoDesk ReCap© V. 6.1 (P. Dawson, pers. comm. 2020). In total, 42 scans were included in the model. The data files and metadata for the 2018 TLS dataset is curated by the Capture 2 Preserv team and is available in the University of Calgary's digital data repository, PRISM Dataverse (Dawson et al. 2021a, 2021b, 2021c, 2021d).

TLS point clouds are highly accurate, permitting excellent true dimension measurements of historic buildings (Dawson et al., 2013:149). As such, measurements from the TLS model can be compared with measurements from the UAV models to confirm the accuracy of the UAV models. Ten measurements were taken from the 2018 TLS model, and the exact measurements were replicated for the 2017 and 2019 UAV orthomosaics. Figure 49, below, shows the TLS dataset with the buildings and labeled measurements. Table 5, below, lists the distances, in meters, for the ten measurements on all three models (2017 orthomosaic, 2019 orthomosaic and 2018 TLS).

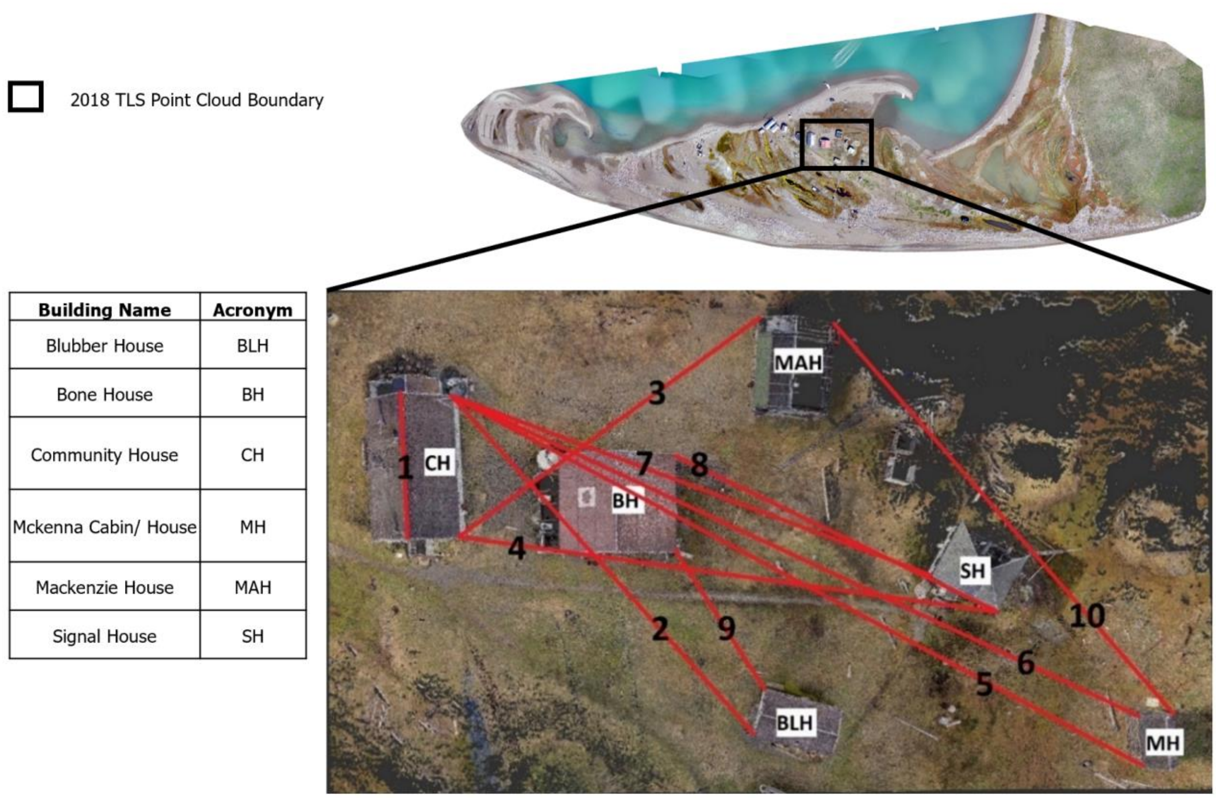


Figure 49. *Location of 2018 TLS survey on Simpson Point. Measurements 1-10 taken from the 2018 TLS data and the 2017 and 2019 orthomosaics, as shown on the TLS dataset.* © Katelyn O’Keefe, 2022.

Measurement	2017 Ortho (m)	2019 Ortho (m)	2018 TLS (m)	2017 - TLS (m)	2019 - TLS (m)
1	15.85	15.81	15.807	0.043	0.003
2	50.61	50.37	50.577	0.033	-0.207
3	41.64	41.58	41.452	0.188	0.128
4	60.06	60.08	60.022	0.038	0.058
5	87.13	87.11	87.226	-0.096	-0.116
6	35.39	35.42	35.405	-0.015	0.015
7	56.68	56.61	56.627	0.053	-0.017
8	20.12	20.21	20.237	-0.117	-0.027
9	28.33	28.22	28.242	0.088	-0.022
10	57.49	57.58	57.489	0.001	0.091
			Mean	0.02	-0.01
			Standard Dev	0.09	0.10

Table 5. *Comparison of measurements between orthomosaics and 2018 TLS Data.*

The TLS values for the ten measurements were considered as the true, real-life distances of these measurements. The values for the ten measurements taken from the TLS model were subtracted from the values for the same ten measurements on the 2017 orthomosaic model. The mean was calculated from the differences. This process was repeated using the 2019 orthomosaic and the TLS data. The mean difference for the 2017 orthomosaic was calculated to be 0.02 m with a standard deviation of 0.09 m, the latter of which is in good agreement with the expected relative accuracy of 8.07 cm or 0.08 m for this dataset (see section 6.1.1). The mean difference for the 2019 orthomosaic was calculated to be -0.01 m, with a standard deviation of 0.10 m, also in agreement with the expected relative accuracy of 8.88 cm or 0.089 m (see section 6.1.2). A two-sided t-test was then performed on the mean differences between the 2017 and 2019 models from the TLS data respectively, to assess the accuracy of the UAV measurements from 2017 and 2019. The alpha was set to 0.05 and as the standard deviations between the two samples are similar, equal variance was assumed. The p-value from the t-test was 0.46, which is greater than alpha. Therefore, there is not a statistically significant difference between the two means, meaning that both the 2017 and 2019 models produce similar results.

Minor discrepancies in the measurements may stem from inconsistencies accrued during the freehand measurement process, minor scaling errors in the Pix4D models, and errors due to difficulty determining the location of the building corner in the orthomosaics. This error results from rounded corners on buildings in the UAV models. To minimize the issue of rounded corners, measurements were taken at the expected location of the corner, based on the intersection of extended lines drawn over the building's walls in plan view. Another source of error that may contribute to the difference between the TLS data and Pix4D models is the difference in the data source. The measurements of the TLS data were taken from a 3D point cloud, and the point closest to the desired location was used. The orthomosaic measurements for the 2017 and 2019 models were taken from the corners of the building, based on the orthomosaic imagery.

Overall, the comparison with the TLS data serves to verify the accuracy of the 2017 and 2019 photogrammetric models, however, there are several caveats. Firstly, the TLS data is only available for a small area in the center of Simpson Point and cannot be used to compare measurements in the vicinity of Study Area 2. Additionally, the sample size of the measurements is limited, largely due to the relatively small area of TLS coverage. Lastly, this strategy can be used to statistically analyze planimetric precision, but height precision cannot be determined using TLS and aerial imagery.

6.2 C2C Results

C2C was the first of two change detection methods performed. For both study areas, the C2C Distance tool in CloudCompare© produced a re-colorized point cloud known as a scalar field, which depicts the magnitude and location of change within the scene (CloudCompare, 2015). For simplicity, the color ramp for the re-colorized point clouds was kept constant for the two study areas. In the re-colorized point clouds, dark blue represents areas with less than 0.10 m of change, light blue indicates approximately 0.10 m in change, green indicates areas with 0.25-0.50 m of change, yellow indicates approximately 1.00 m of change, orange indicates 1.50m of change and red coloring indicates an extreme change of approximately 2.00 m. Figure 50 is the scalar field produced for Study Area 1, reflecting the change between the reference (2017) point cloud and the 2019 point cloud. The maximum distance, or change in a point location, for Study Area 1, was 2.448 m. Figure 51 is the scalar field produced for Study Area 2, reflecting the change between the reference (2017) point cloud and the 2019 point cloud. The maximum change detected in Study Area 2 was 2.155 m. In both maps, the distances are relative and are measured in meters. Areas of significant change have been labeled alphabetically on each map. Several of the changes detected by the C2C distance method are in the vicinity of the various heritage structures on Simpson Point. For further information on the location of the buildings or the buildings themselves, see section 3.3. Once areas of change were identified on the change map, the second method, VIA, was used to determine the nature of the changes. This section describes the C2C results for the two study areas.

6.2.1 C2C Change Maps

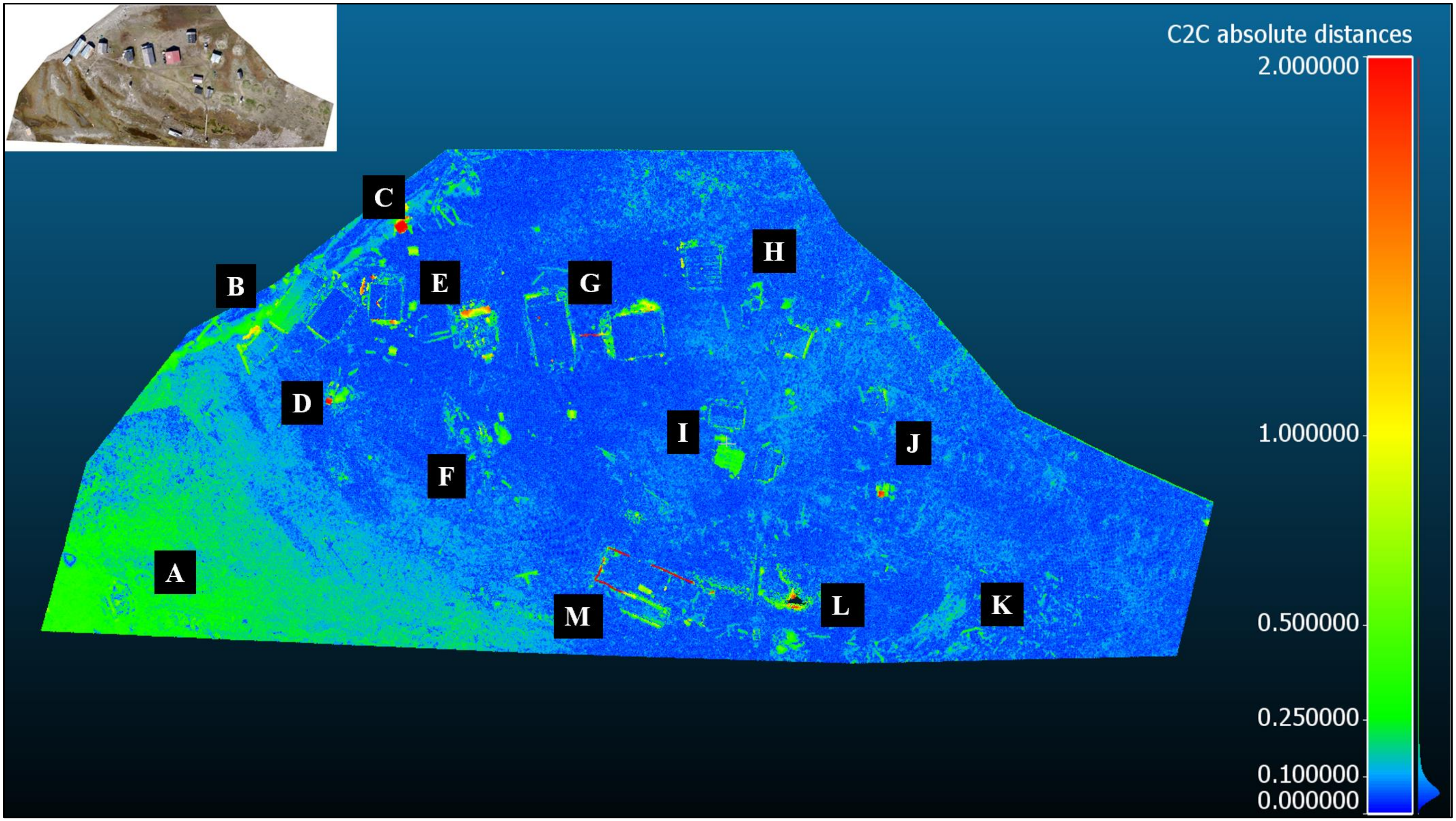


Figure 50*. C2C results for Study Area 1. Areas with significant change have been labeled alphabetically from A-M.* © Katelyn O'Keefe, 2022.

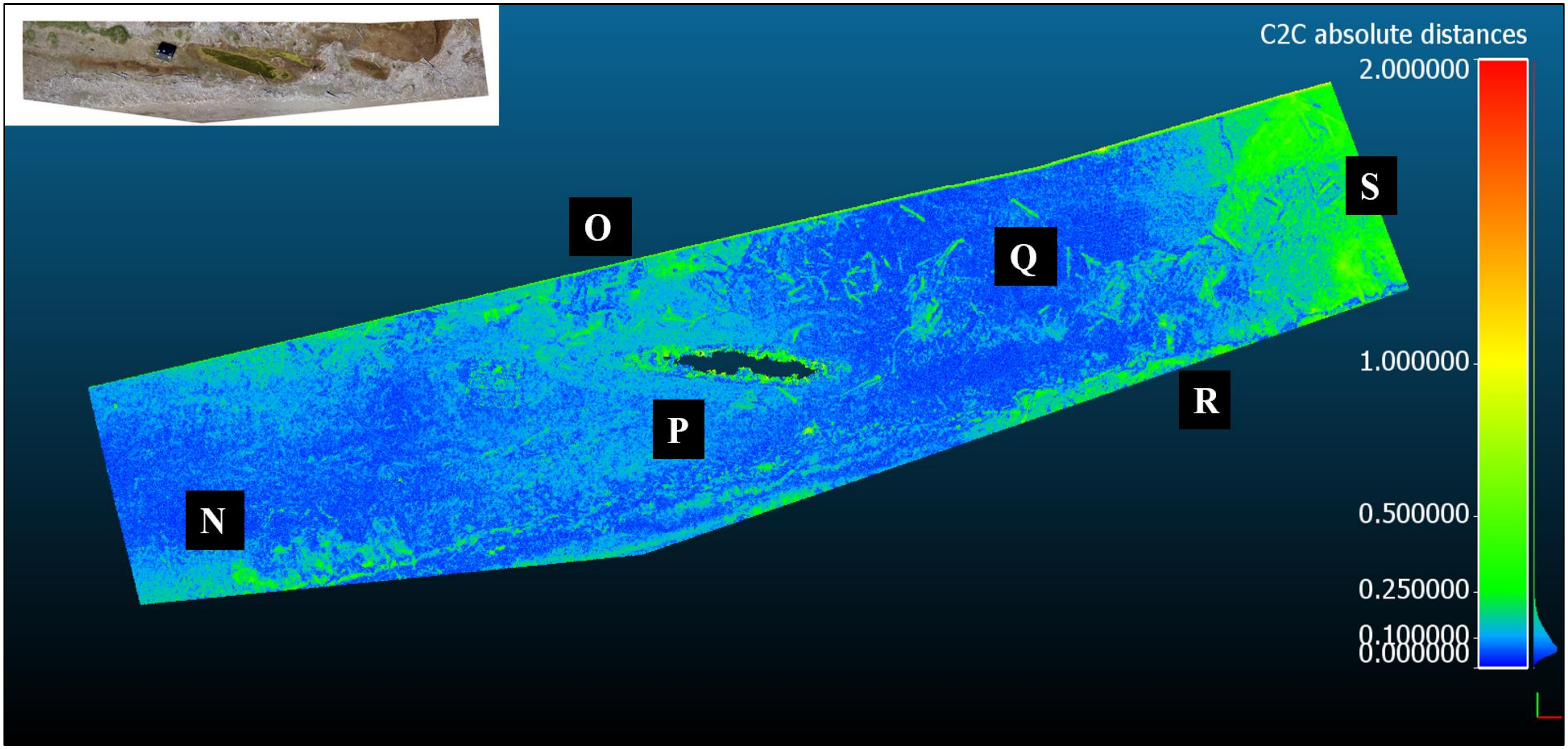


Figure 51. *C2C results for Study Area 2. Areas of significant change are labeled N-S.* © Katelyn O'Keefe, 2022.

6.2.2 Interpretation of Results

In Study Area 1, thirteen specific change areas were identified on the re-colored point cloud (change map). These have been labeled alphabetically. In Study Area 2, six specific change areas were identified and labeled alphabetically on that map. There are nineteen areas of change labeled from A-S between the two study areas. This subsection describes the pattern, shape, and magnitude of the change detected in these labeled areas. In certain instances, the pattern, shape, and magnitude provide some insight into the cause of the change; however, VIA is much more helpful for determining the nature of the change found. The changes described in this section have been verified and explained using VIA in section 6.3.1.

<u>Study Area 1</u>

"A" on the map identifies a large area of green-coded change located to the SW of the historic settlement. The change encompasses the bottom one-third of the study area, gradually becoming more intense towards the bottom left. Elsewhere, the green coloration becomes speckled in appearance. The cause of this change cannot be determined by the shape or patterning of the documented change; however, it is widespread on the landscape.

"B" on the map identifies change adjacent to two historic buildings, the Northern Whaling and Trading Company storehouse and shed buildings. Much of the change is green-coded, with some yellow-orange coded change north and northwest of the shed building, linear yellow change east of the shed building and yellow- orange at the rear (southwest), along the perimeter of the storehouse building. In addition, there are four yellow-coded patches of change north of the storehouse building, near the beach. These are located inland of a large log that was installed by Yukon Historic Sites Unit personnel as a makeshift breakwater in 2018, but this breakwater is beyond the extent of the clipped orthomosaics and point clouds. The green-coded change in area “B” is speckled inland and denser along the beach. Several linear green outlines along the beach and one behind the shed building. These linear outlines are sizeable and likely represent a repositioning of driftwood due to wave action. Lastly, there is a green-coded change on the rear portion of the warehouse building. As for the area of yellow-orange change adjacent to the shed building, this change is not in a discernable pattern and requires confirmation using visual inspection.

"C" on the map is a medium square of bright, red-coded change, surrounded by green and yellow-coded change, all along the beach. Running parallel to the beach is a collection of green linear features, and to the NE, some additional green-coded linear features are perpendicular to the beach. There is a small green and yellow-coded change in the southwest of this area, and a square yellow-coded change south of center. The yellow coded and red-coded squares are likely manufactured structures since that shape is uncommon in nature. The nature of the green-coded change surrounding the red-coded square certainly requires further investigation. The elongated, green-coded features near the beach can likely be attributed to driftwood movement due to wave action.

"D" on the map indicates an area of dense, green, and yellow-coded change, with a square of red-coded change. The red coded change indicates the maximum change within the scene, change over 2.00m. The outline of the green and yellow-coded change is irregular; however, there is some faint linear change, the majority of which is to the north, east and southeast of the red square. There is some subtle semi-linear light blue change to the northwest of the red square. The red-coded change is tightly constrained to a small square, likely indicating the addition or removal of a manufactured item or structure.

"E" is for the change around the Hunter and Traveller's Cabin and the Ranger's quarters building. There is a green-coded change along the perimeter of both buildings. In addition, there is a yellow, orange, and red-coded change in isolated areas. Three linear features are coded yellow-orange and red on the northwest side of the Hunter and Traveller's Cabin. On the roof of this building, there is a small, red-coded area. In front of the building, there is a dense area of green-coded change and a smaller area of red-coded change that is roughly square. Further south of this building, there are patches of green-coded change. Between the Hunter and Traveller's Cabin and the Ranger's quarters, there are several areas of green-coded change, including two that are linear. There is green coded change around the perimeter of the Ranger's quarters and on the roof; however, this change is sporadic. There is rectangular orange and red-coded change along the north side of the building and a minimal area of orange coded change on the front of the Ranger's quarters.

"F" is for the green-coded change south of the Ranger's quarters, and the change appears blocky and forms a semi-linear shape running from northwest to southeast.

"G" is for the change in the vicinity of the PSWC Community House (left) and the Bonehouse. The Community House has two small circular areas of red-coded change on its roof and green-coded change along its perimeter. Behind the Community House, two green-coded linear shapes are likely driftwood based on their shape and size. There is a linear area of red-coded change between the Community House and the Bonehouse (right of center). There is a green-coded change on the north and west sides of the Bonehouse, and there is an area of yellow change northeast of the building. The cause of these changes, like those around the other historic buildings, cannot be deduced without visual inspection.

"H" on the map denotes a change to the Mackenzie House and the Signal House. The Mackenzie House has small amounts of green and yellow-coded change along its perimeter and some linear green change on the roof. There is a green-coded change to the southeast of the Mackenzie House that forms three semi-circles. Even further east, there is a green-coded change behind the Signal House and along its north, east, and south sides.

"I" on the map encapsulates the change around three buildings, the Blubber House, Building 11, and Building 12. For the Blubber House and Building 12, there is a faint, green-coded change around their perimeter. For Building 11, however, there is much more extensive bright, green-coded change associated with approximately 0.50m of change.

"J" on the map is used to indicate change along the periphery of Captain McKenna's Cabin and dense, green-coded change to the south. There is a square of red-coded change at the center of the dense green change. The outline is like the ones described in "C" and "D," and the change is likely due to adding or removing a small building, such as a park outhouse.

"K" on the map indicates change located in the southwest portion of the study area and refers to the linear, green-coded change that runs diagonally from northeast to southwest. Based on the linear shapes, this is likely a change in driftwood position or accumulation due to inland flooding or ice push.

"L" is used to label the green-coded change found along the perimeter of the large water body. There is a clearly outlined green-coded change on the north and south side of the water body and along the walkway. On the north side, there is some yellow and red-coded change in a confined area; however, there appears to be data missing in the point cloud at the center of this change. This red-coded change may be due to missing points in the point cloud. In addition, there is a green-coded change that is linear but sporadic to the southeast of the water body and east of the outhouse.

"M" is used to label the linear change in the vicinity of the RCMP Dog Kennel building and yard. There is green-coded change along the perimeter of the kennel building and red-coded change that is linear along the yard's perimeter.

Study Area 2

"N" on the map refers to the change detected in the southwest of the study area, along the beach. In this rectangle, there is light blue and green-coded change. The green-coded change is mainly parallel to the beach, and some of this change is linear, parallel to the beach.

"O" on the map draws attention to the green-coded change along the northwestern half of Study Area 2, in the vicinity of several sod house features. The change is green-coded and patchy in appearance; however, some linear outlines within these patches suggest driftwood movement.

"P" on the map corresponds to the change detected around the water body. There is a green-coded change around the perimeter of the water body, which is then surrounded by light blue-coded change.

"Q" on the map corresponds to the sporadic, green-coded change found between the water body and the dense green-coded change. The change detected in this area appears in clusters, and within these clusters, there are linear forms. In addition, the clusters appear to form a rough line, set back from the beach, and the shape suggests driftwood shifting between 2017 and 2019.

"R" on the map corresponds to the bright, green-coded change along the edge of the study area, which is the beach. The change is thin and parallel to the beach. It is important to remember that the edge of the study area is slightly set back from the waterline to account for potential differences in water level between the 2017 and 2019 imagery (see methods chapter for more information).

"S" on the map corresponds to the large area dense, green-coded change in the northeast. On the western edge of the large area of dense, green-coded change, the change becomes more diffuse, and there are linear outlines, indicating that at least some of this change may be due to the relocation or accumulation of driftwood.

Apart from the change labeled alphabetically in this study area, there is light blue-coded change, mainly to the west and the southwest of the body of water at the center, around the St. Patrick's Anglican Mission House and along the beach. Like the more subtle change noted in Study Area 1, this change will undoubtedly require VIA to describe and determine the nature of the change.

The 19 areas of change in study areas 1 and 2 identify the most noticeable changes, as per the C2C change map. While most of the change falls within these areas, there is more subtle change elsewhere, as indicated by speckled dark blue, light blue, and sporadic green colorations found throughout the scene. These more subtle changes have also been analyzed using VIA.

6.3 VIA Results

VIA is the manual inspection of multi-temporal data for change (Lu et al., 2004: 2381). This method was employed following the other change detection method used in this research, C2C. The C2C results provide the analyst with an idea of where the change is occurring and how much change is occurring; however, these results provide minimal insight into the nature of the change. Determining the nature of the change is the strong suit of VIA. Also important is the use of VIA to discern whether the change detected by the C2C is from real change rather than from registration or alignment errors. If change is visually detected in areas A-S, this proves that the change is genuine and not simply the result of errors (Dawson et al., 2022). This section has three subsections. In the first section, the results of the C2C change map for areas A-S are compared with the results of the VIA. The second subsection summarizes the change detected using VIA that was either very subtle on the C2C change map or was entirely undetected. Lastly, the third subsection summarizes the widespread patterns of change in the two study areas based on the results of the VIA. It also identifies the contributing factors behind these changes.

6.3.1 Verification of C2C Results

The orthomosaics from 2017 and 2019 were compared, as described in the VIA section of the methods. The change documented throughout the VIA process was documented in a table for each 10x10m square. In this section, the results of the VIA are not described in this fashion; instead, the emphasis is on areas A-S, where the C2C indicated the greatest change. The nature of the change found is identified for each alphabetically labeled area, using the orthomosaics.

Study Area 1

The widespread change noticed in "A" results from vegetation increase in 2019 compared to 2017 (see fig. 52). This vegetation is more widespread and is "greener" in appearance. Additionally, there is more standing water in the low-lying areas in 2019 compared to 2017. The change in vegetation and standing water does not appear to increase to the southwest, as expected from the C2C results. While cross-sections of the point cloud were tested post-alignment, some of this green-coded change may be due to a subtle alignment error in this area since the distance between the alignment points and this corner is quite substantial.

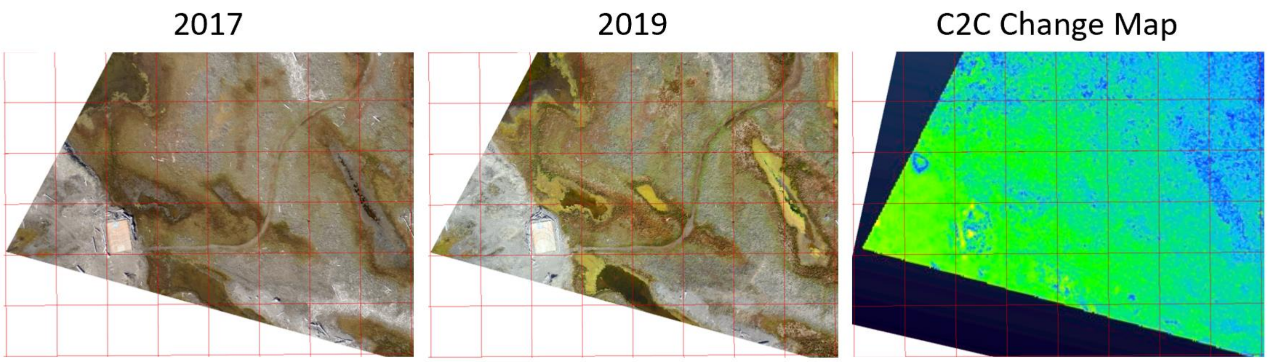


Figure 52. *Area "A" C2C and VIA comparison.* © Katelyn O'Keefe, 2022.

Much of the change labeled "B" was challenging to identify in the orthomosaic imagery (see fig. 53). Upon close inspection, there is sand accumulating inland in the 2019 imagery. The sand has been pushed and piled on the coastal side of the Northern Whaling and Trading Company storehouse and shed and is particularly noticeable north of the shed. Tidal and storm surge events are known to deposit and remove sand around these buildings yearly (G. Balzer, pers. comm. 2021).

In addition, several pieces of driftwood have moved between 2017 and 2019, which accounts for the linear green-coded linear shapes detected by the C2C, and the four yellow-coded shapes north of the storehouse. Another change that can be seen is the increase in vegetation to the southwest of the shed building. Lastly, the green-coded change detected on the southwestern half of the warehouse building was not noticeable using VIA. This change corresponds to the leveling of the building in 2017 and 2018. As previously mentioned in section 6.2.2, a large log was used as a makeshift breakwater (located beyond the north boundary of the study area) at the northwest corner of the storehouse building (G. Balzer and B. Riley, pers. comm. 2021). This breakwater may have contributed to change in sand and driftwood deposition adjacent to the storehouse building.

Figure 53. *Area "B" C2C and VIA comparison.* © Katelyn O'Keefe, 2022.

The changes labeled as "C" were identified as sand accumulation further inland from the beach and the movement of driftwood (see fig. 54). The red-coded square results from the appearance of a small structure in the 2019 imagery. In addition, a picnic table has been moved between 2017 and 2019, which accounts for the two yellow and green-coded rectangles located to the south and southwest of the red-coded square in the C2C map. Much of the green coded change is due to driftwood movement, and the natural removal of small driftwood fragments that were present in 2017, parallel to the beach. In 2017, there was a yellow hose running from west to east, that is no longer present in the 2019 imagery. Interestingly, the absence of this hose was not detected by the C2C method.

Figure 54. *Area "C" C2C and VIA comparison.* © Katelyn O'Keefe, 2022.

The red-coded, square-shaped change labeled as "D" was found to be the result of the outhouse being disassembled for cleaning in 2019, whereas the removable top of the structure was stacked on the base in 2017 (see fig. 55). The green-coded change to the northeast of the red square is the base of the outhouse structure, and the change reflects the absence of the upper part of the facility. The irregular green-coded change to the north, east and southeast of the red square is due to the rearrangement of driftwood and the stacking of large stack of wood piled beside the facility in 2019. The three linear green changes to the northeast are due to large pieces of driftwood being moved. Lastly, the faint light blue change to the northwest of the outhouse structure was caused by the disappearance of two large pieces of driftwood that were present in 2017. This change is interesting because one would expect this change to be more prominent on the change map than it is.

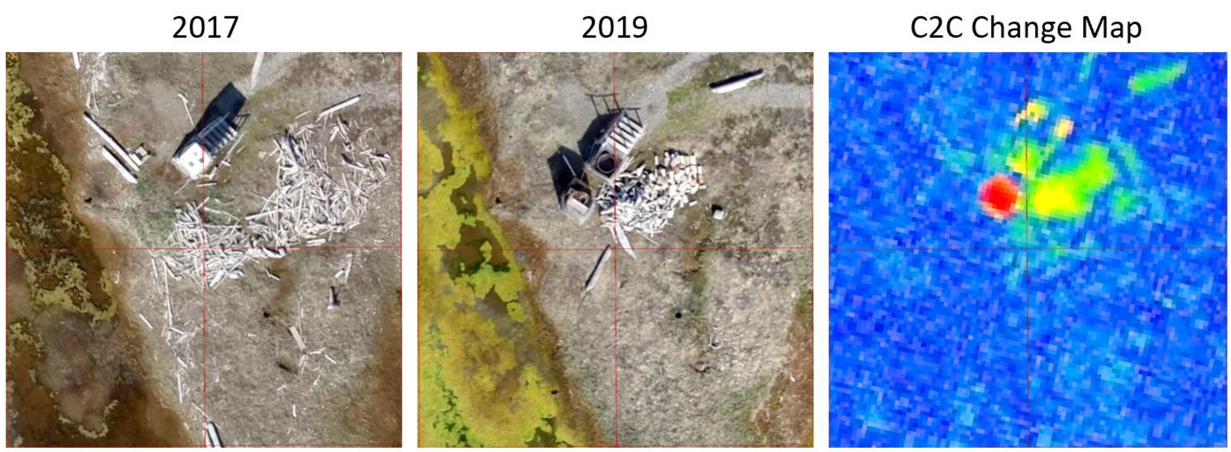


Figure 55. *Area "D" C2C and VIA comparison.* © Katelyn O'Keefe, 2022.

There are numerous changes in the area labeled "E"; however, much of the change results from activities performed by the park rangers (see fig. 56). Around the Hunter and Traveller's Cabin, several items have been moved or displaced along the perimeter between 2017 and 2019. At the front of the Hunter and Traveller's Cabin (south), there is significantly more wood stacked there in 2019, which accounts for the green and red-coded change on the change map. A new feature on the roof is identified in the C2C as the small red circle. On the eastern side of the

Hunter and Traveller’s Cabin, there is less vegetation in 2019 than in 2017, and the picnic table to the east of in 2017 has been moved to the south by 2019. The movement of the picnic table is depicted on the change map by two green and yellow coded rectangles in the 2017 and 2019 position. A few items and fragments of driftwood have moved to the east of the cabin between 2017 and 2019. Further east, on the west side of the Ranger’s quarters, a new sand pathway and deck have been built. The deck on the north side of this building has also changed, with a large item resting on the deck and a new set of stairs added between 2017 and 2019. This explains the yellow, orange, and red-coded change visible on the C2C map. On the south side of the Ranger’s quarters, additional deck pieces have also been added by 2019. Lastly, to the north of the Ranger’s quarters, sand has been deposited around a park monument (located just beyond the extent of fig. 56) and five low-lying areas, either by staff or overland flooding. Interestingly, the sand deposition was not captured on the C2C change map.

Figure 56. *Area "E" C2C and VIA comparison.* © Katelyn O’Keefe, 2022.

The change labeled "F" was associated with the outhouse and the driftwood around it (see fig. 57). While the outhouse itself has not moved, there is significantly more wood stacked beside it, and a rectangular wooden item can be seen north of the stack in 2019. In addition, the driftwood to the west of the facility moved between 2017 and 2019, which accounts for the sporadic green-coded change detected.

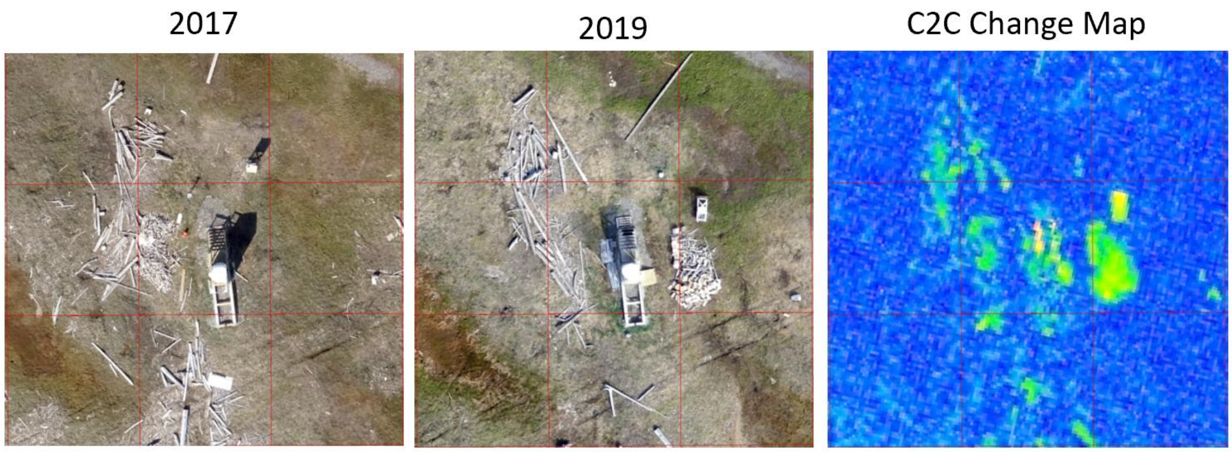


Figure 57. *Area "F" C2C and VIA comparison.* © Katelyn O’Keefe, 2022.

The changes labeled "G" found around the Community House and the Bonehouse were minimal using VIA (see fig. 58). The changes documented using around the perimeter of the Community House are a decrease in wood stacked at the rear of the building and a tank being moved slightly. These changes account for the yellow-coded change on the C2C map at the rear of the Community House. Another change noticed around the perimeter of the Community House is an increase in vegetation in 2019 compared to 2017. In the 2019 imagery, a new wire runs between the Community House and the Bonehouse; this wire accounts for the red-coded linear change on the C2C map. On the west side of the Bonehouse, the containers have shifted slightly between 2017 and 2019. The large green and yellow-coded change detected on the north side of the Bonehouse is very challenging to visually identify due to a large shadow obscuring the area. In 2017, the shadow is minimal, and the ground can be seen. In 2019, there appears to be a large driftwood fragment in western corner, however, the ground cannot be seen further east along the north perimeter. As a result, it is likely that this change on the C2C map is due to an error in the C2C which is hypothesized to be due to a reduction in 3D points in this area in 2019 vs. 2017, due to the shadow.

Figure 58. *Area "G" C2C and VIA comparison.* © Katelyn O'Keefe, 2022.

The changes labeled "H" include changes around the Mackenzie House and the Signal House (see fig. 59). There is extra vegetation on the north, west, and east sides of the Mackenzie House in 2019 vs. 2017. Secondly, the manufactured materials between the two buildings have shifted between 2017 and 2019. There is more standing water to the east of the Mackenzie House, and there is more vegetation on the sod house features in 2019. Lastly, there is more vegetation around the Signal House in 2019 than in 2017, accounting for the yellow-coded change.

The change associated with "I" is within the vicinity of the Blubber House, Building 11, and Building 12 (see fig. 60). A few items were removed or moved to the east of the Blubber House. There is slightly more vegetation around all three buildings. A table or box north of Building 11 is visible in 2017 but not in 2019. There are materials in front of Building 11 in 2019 that were not there in 2017. The roof of Building 11 has been modified by the 2019 imagery, something confirmed with the Yukon Historic Sites Unit. Otherwise, no widespread change is apparent in the VIA for Building 11, which is interesting considering the magnitude and size of the change detected in the C2C map. Communication with the Yukon Historic Sites Unit revealed that Building 11 was raised 0.45m in the summer of 2017 after the 2017 data was collected (G. Balzer and B. Riley, pers. comm. 2021). This information is invaluable because it confirms the accuracy of the C2C results.

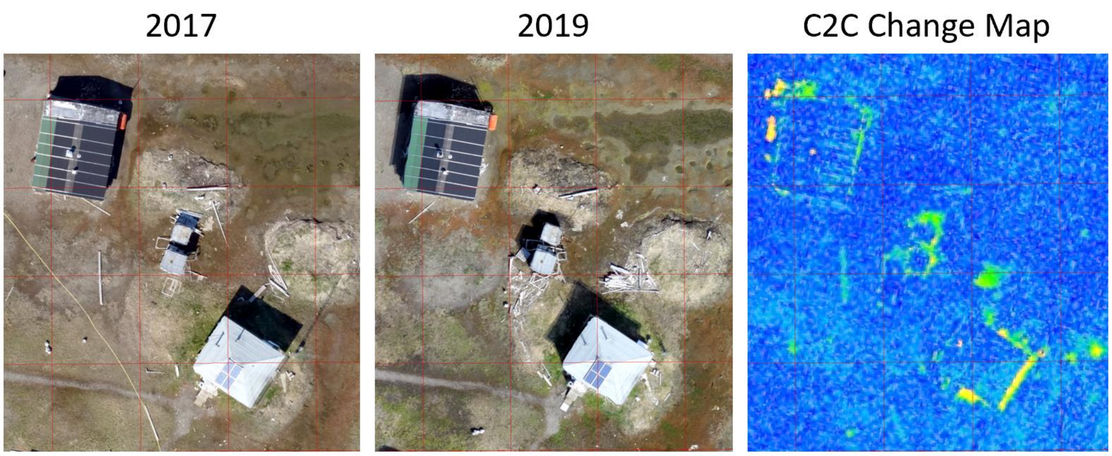


Figure 59. *Area "H" C2C and VIA comparison.* © Katelyn O'Keefe, 2022.

The VIA results for the change associated with "J" on the C2C map include the movement of driftwood around Captain McKenna's Cabin and an increase in vegetation around the cabin (see fig. 61). The green and yellow coded change on the north and east sides of Mackenna's Cabin are difficult to determine, since the shadow in 2017 and 2019 are in different locations. One clear difference, however, is the difference in the appearance of the roofline in 2019. In the 2019 imagery, the roofline and the northeast corner of the building are less crisp than they are in the 2017 imagery, and this may have contributed to the change detected by the C2C. The driftwood related change is captured by the linear green- coded change in the change map, however, the deposition of several driftwood logs to the south of Mackenna's Cabin in 2019 is not depicted as prominently as one would expect. To the south, the outhouse had much more material around it in 2019; however, the outhouse structure itself has only shifted slightly, according to the imagery. A lack of visible change is interesting since there is a square of red-coded change where the facility is located. An elevation change or an otherwise challenging change to detect with aerial imagery may be responsible.

Figure 60. *Area "I" C2C and VIA comparison.* © Katelyn O'Keefe, 2022.

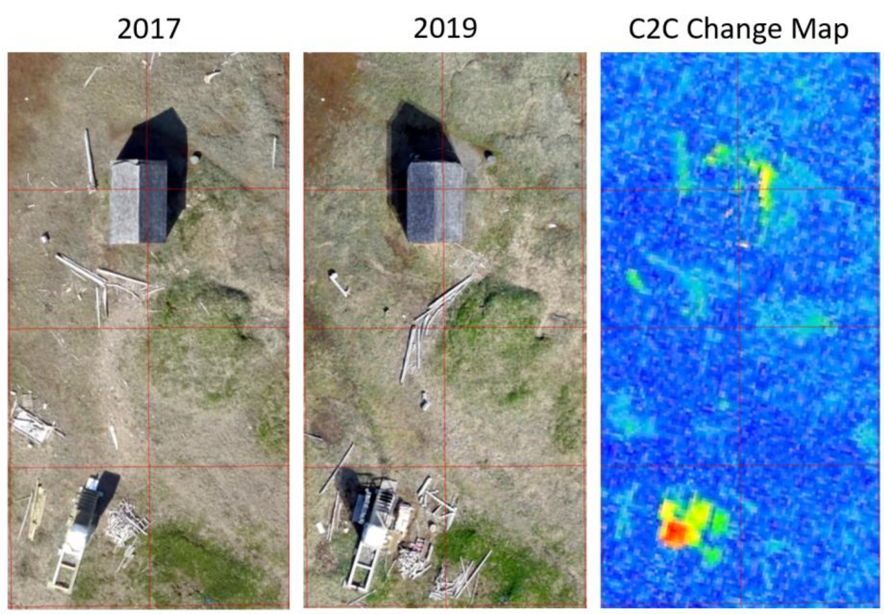


Figure 61. *Area "J" C2C and VIA comparison.* © Katelyn O'Keefe, 2022.

For the area labeled as "K," there is significantly more driftwood in this area in 2019 than there was in 2017 (see fig. 62). In addition, the driftwood fragments are larger in 2019 than they were in 2017.

The change labeled "L" includes the water body, the bridge, and the outhouse to the south of the bridge (see fig. 63). There is significantly more standing water in the water body and more vegetation around the perimeter of the water body in 2019. These changes relate to the green, yellow, orange, and red-coded changes seen in the C2C map. In addition, the bottom of the waterbody is no longer visible in 2019, suggesting that the water has gotten deeper. Interestingly, the C2C map appears to have a void in the center of the water body, and this void was not present in either the 2017 or 2019 point cloud. The void is due to the reflection of light off the water body. Lastly, there is more driftwood in the pile east of the bathroom in 2017 than in 2019, which accounts for the green-coded change.

The change labeled "M" is in the vicinity of the RCMP Dog Kennel and the dog run enclosure, as well as the western portion of the water body described in "L" (see fig. 64). The roof of the dog kennel building appears to have been modified between 2017 and 2019, which explains the yellow-code change detected in the C2C. One of the most noticeable changes in this study area is the red-coded linear change seen around the perimeter of the RCMP dog run enclosure. It is challenging to determine the nature of the change using the imagery; however, upon close inspection, several horizontal fence posts that make up the fence have been displaced or in the case of those along the northeastern side, have been partially covered with algae. These posts provide support for the fence, likely causing the fence to shift, tilt and disintegrate along most of its length. This shift is not the result of restoration efforts, and its deterioration has occurred naturally (G. Balzer, pers. comm. 2021). Another noticeable change in the imagery is the increase in standing water in the water body. The water body does not appear to have expanded horizontally; however, it appears that the depth has increased. The change on the C2C map is not as drastic as expected, supporting the findings of the VIA.

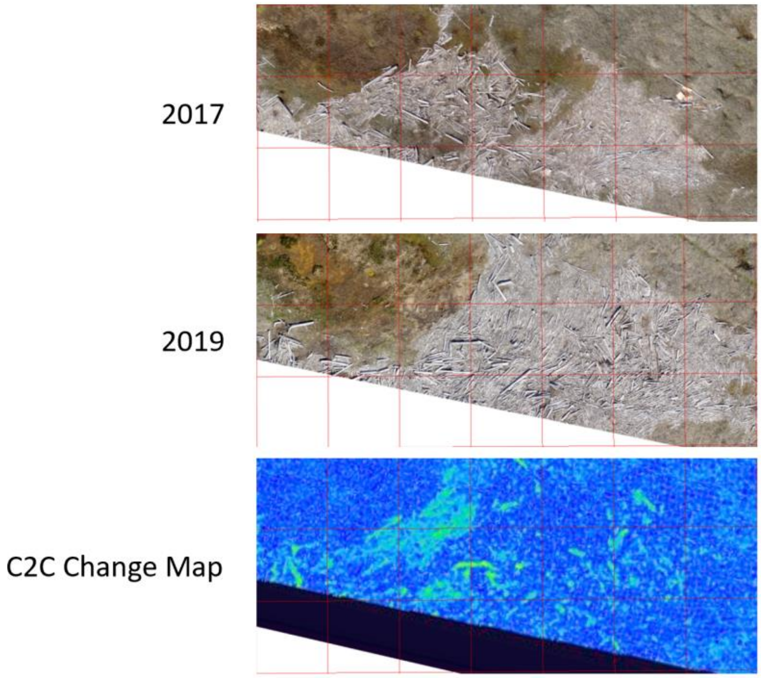


Figure 62. *Area "K" C2C and VIA comparison.* © Katelyn O’Keefe, 2022.

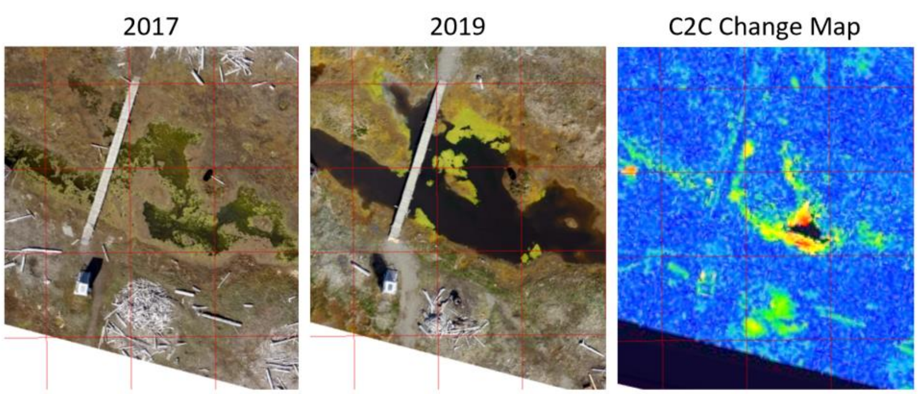


Figure 63. *Area "L" C2C and VIA comparison.* © Katelyn O’Keefe, 2022.

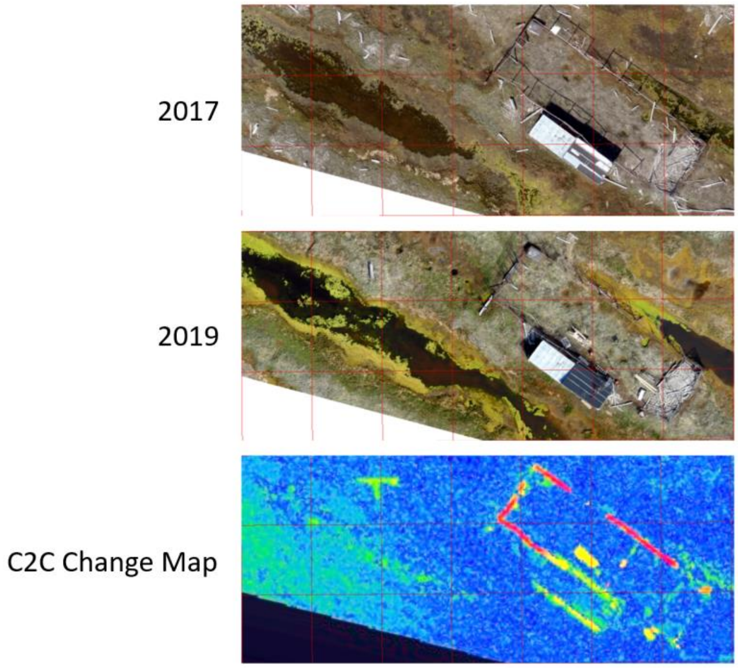


Figure 64. *Area "M" C2C and VIA comparison.* © Katelyn O'Keefe, 2022.

Study Area 2

The change labeled in "N" can be attributed to driftwood and sediment movement near the beach (see fig. 65). The green-coded change that forms an extended west to east linear shape is likely the result of a small ridge of buildup at the high-water line.

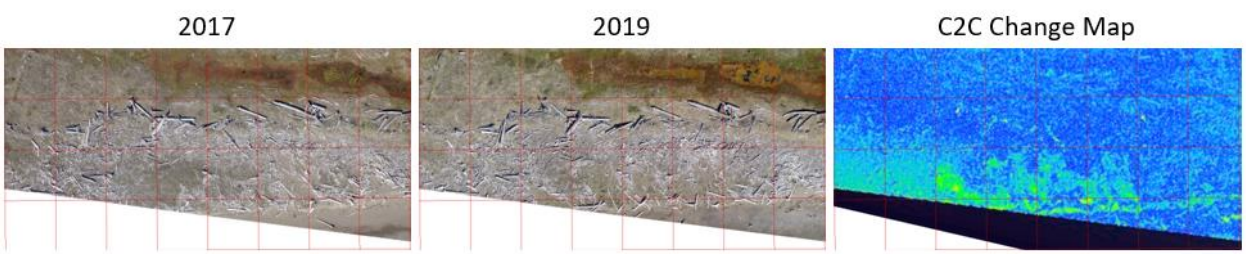


Figure 65. *Area "N" C2C and VIA comparison.* © Katelyn O'Keefe, 2022.

The change labeled "O" is found along the northern margin of the study area, north of St. Patrick's Anglican Mission House, and in the vicinity of several Inuvialuit sod houses (see fig. 66). Much of the green-coded change is the result of driftwood deposition and movement. In

2019, there is more driftwood and larger fragments of driftwood than there was in 2017. The driftwood gets deposited in low-lying areas, which for the most part is around the base of the sod house features. Another noticeable change is the increase in vegetation in the 2019 imagery versus the 2017 imagery. This change coincides with areas of light-blue and green-coded change on the C2C change map.

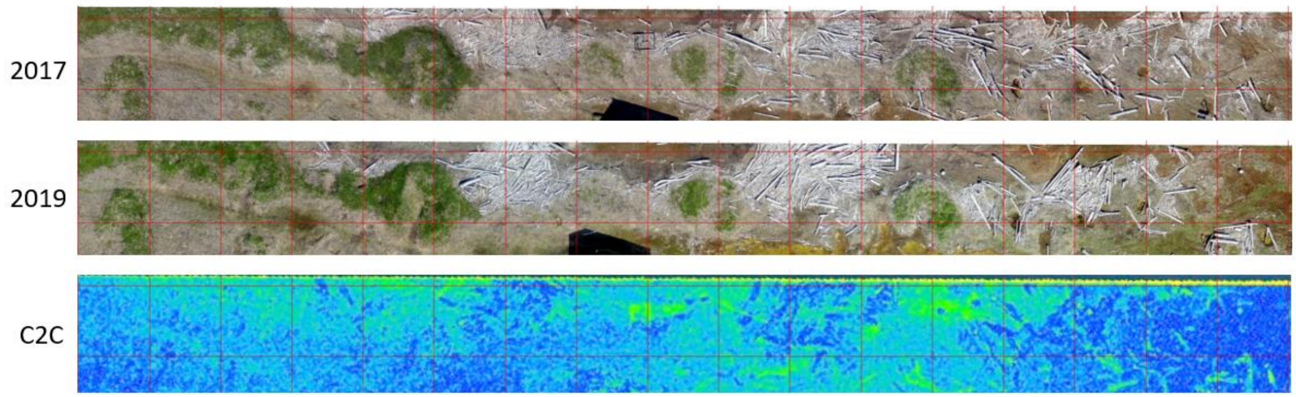


Figure 66. *Area "O" C2C and VIA comparison.* © Katelyn O’Keefe, 2022.

The change within the area labeled 'P" is caused by three main contributing factors (see fig. 67). In 2019, there is significantly more vegetation around the water body and behind the Mission House. This change shows as a light speckled blue on the C2C change map. The second change, the green-coded linear features on the change map, is the result of driftwood accumulation or movement. In 2019, there is more driftwood to the north and east of the water body. Lastly, the most evident change is the increase in standing water within the water body, which has expanded the horizontal extent of the water body, explaining the green-coded and yellow-coded change around the perimeter.

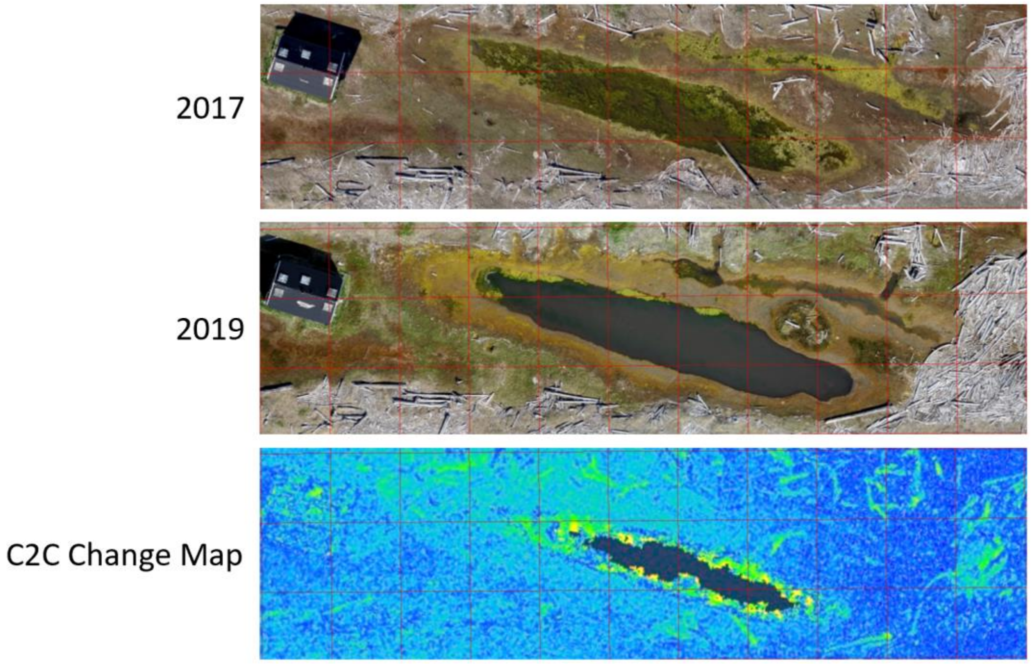


Figure 67. *Area "P" C2C and VIA comparison.* © Katelyn O'Keefe, 2022.

The change previously identified as "Q" results from increased driftwood accumulation in 2019 compared to 2017 (see fig. 68). This driftwood explains the linear outlines of green-coded change and the unsorted appearance. In 2019, the driftwood was more numerous, with larger, more tightly packed fragments, especially around the base of the two sod house features slightly left of center. There is also considerable driftwood accumulation in the southeast portion of "Q" compared to 2019. Lastly, more algae in the low-lying area at the center of "Q" suggests more moisture there in 2019. This last change does not appear clearly on the C2C change map.

The change identified as "R" (see fig. 69) is change along the beach and in the vicinity of two sod houses that have been previously identified as at-risk. As mentioned in section 6.2.2, the change is green-coded and close to the high-water mark. Visual inspection analysis shows that this change results from sand washing over behind what appears to be a small berm parallel with the beach. The sand accumulation is most noticeable to the east of the sod house features since there is less driftwood in this location. Sand wash-over and berm creation are common on gently sloping sandy beaches exposed to storm action (Trenhaile, 2013:442). Another change between the 2017 and 2019 imagery is the amount and size of the driftwood accumulated around the at-risk sod houses. In 2019, the fragments were larger and more plentiful than in 2017, with more driftwood within the semi-circular boundary of the sod house closer to the beach. In 2018, this driftwood was removed by an archaeologist examining the sod house, explaining some of the change. Some green-coded change is detected on the western side of the sod house further from the beach. This change is likely due to the structure being more exposed in 2019 than in 2017.

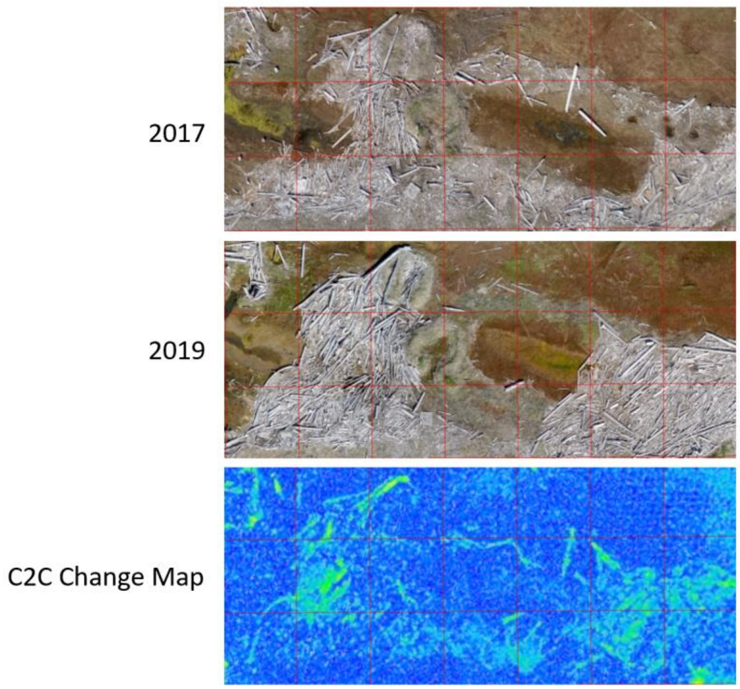


Figure 68. *Area "Q" C2C and VIA comparison.* © Katelyn O'Keefe, 2022.

The change associated with "S" is the most dramatic change noticed in Study Area 2 (see fig. 70). This change is associated with a dramatic increase in driftwood between 2017 and 2019. In 2019, the driftwood fragments were larger and far more plentiful than in 2017. In addition, the driftwood was deposited further inland by 2019, partially covering the drainage channel at the top center.

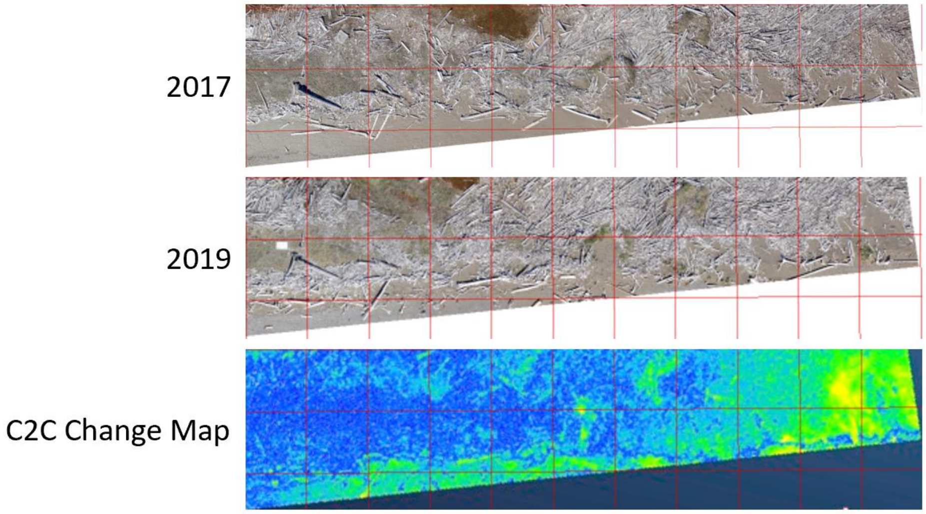


Figure 69. *Area "R" C2C and VIA comparison.* © Katelyn O’Keefe, 2022.

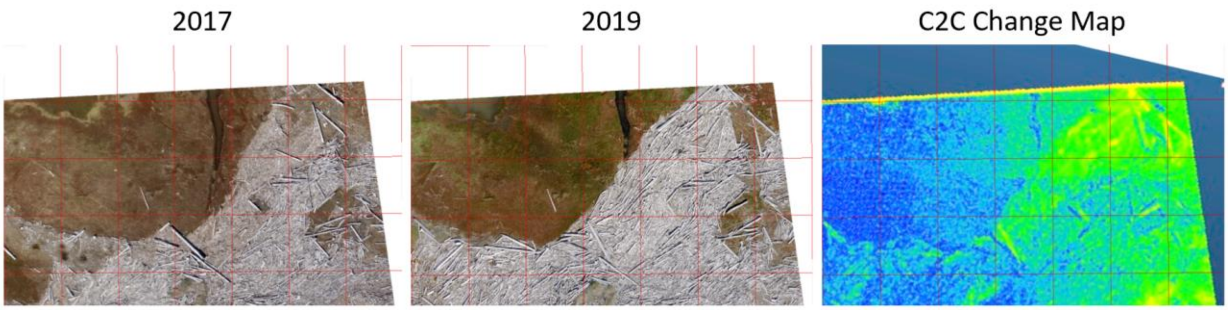


Figure 70. *Area "S" C2C and VIA comparison.* © Katelyn O’Keefe, 2022.

Visual inspection of the change detected using the C2C distance computation method confirms the validity of the change. Should the change have been related to registration or alignment errors, the color-coded change would not have been associated with real change in the imagery. The one exception may be the expansive green-coded change detected in area "A" within Study Area 1. While a widespread increase in standing water and vegetation in this area was confirmed, the density of the green-coded change in the southwestern corner does not correspond to increased change compared to elsewhere in the area. As a result, it is hypothesized that a minor alignment error in this corner of the point cloud, the furthest from points used to align the clouds in CloudCompare©, is possible.

6.3.2 Additional Change Detected

Two changes were detected using VIA that C2C did not detect. These are the enlargement of pathways made by foot traffic and the development of cracks on the ground surface around the sod house features in Study Area 1. In this section, these two changes will be discussed.

Figure 71. *Cracks around a sod house feature in Study Area 1.* © Katelyn O'Keefe, 2022.

In the 2019 imagery, several cracks in the ground surface were documented in the eastern end of Study Area 1, around several Inuvialuit sod house features (see fig. 71). These cracks were not present in the 2017 imagery. The ground where the crevices appear consists of coarse clastic sediment, with no ground ice in the upper 1 m of sediment (Radosavljevic et al., 2016). The area is in proximity to the alluvial fan to the east. The sediment composition is not typical of areas with ice-wedge polygons; however, the crevices resemble frost cracks photographed in ice-rich sediments in the Mackenzie Delta (Kerfoot, 1972). Additional research is needed to determine the cause of these cracks, and monitoring may be needed to determine if they are growing on an annual basis.

The second change not detected by the C2C method is the enlargement of multiple pathways between 2017 and 2019 (see fig. 72). In 2019, the pathways appeared to be slightly broader and more incised into the ground surface. The increasing size of multiple pathways suggests increased use by visitors to the island, whether researchers, tourists, park staff, or Inuvialuit. The results from the visual analysis showed that the pathways between the main settlement buildings and off towards the archaeological features and St. Patrick's Anglican Mission House were more prominent in 2019 than they were in 2017. How these have changed varies by pathway section. The pathways in front and between the buildings have generally increased and have a sandier appearance in Study Area 1. The pathway in the southeast that runs towards the Mission House in Study Area 2 has not noticeably changed in size but has become somewhat more vegetated in the two years between the imagery. The continuation of the Mission House pathway in the study area is greener in 2019 than in 2017; however, further trenching is also visible in the 2019 imagery. This trenching may be due to increased soil moisture in this region. Overall, the pathways within the two study areas have changed between 2017 and 2019. Interestingly, the pathway change was detected visually but not with the C2C. The pathway change is more subtle than other changes within the scene, which is likely why it went unnoticed by the software. The relationship between visitors and pathway creation within *Herschel Island – Qikiqtaruk Territorial Park* is evident. Increased visitors significantly impact the vegetation, thus creating more prominent pathways (Heinemann, 2019). The pathways are created or expanded when foot traffic tramples the delicate tundra vegetation (Heinemann, 2019). Three variables that influence pathway development are the number of visitors, visitor type, and the vegetation type within the pathway area. There is no statistical trend in the number of visitors to the island; however, there is an increase in cruise ship visitors and researchers and a decrease in Inuvialuit and Inupiaq visitors (Heinemann, 2019). Table 6, below, shows the yearly visitors at *Herschel Island – Qikiqtaruk Territorial Park* between 2010-2021. Cruise ship visitors arrive in large groups and explore for several hours. The park rangers take the cruise ship visitors on a specific walking tour of the island, and the trail taken gets used extensively.

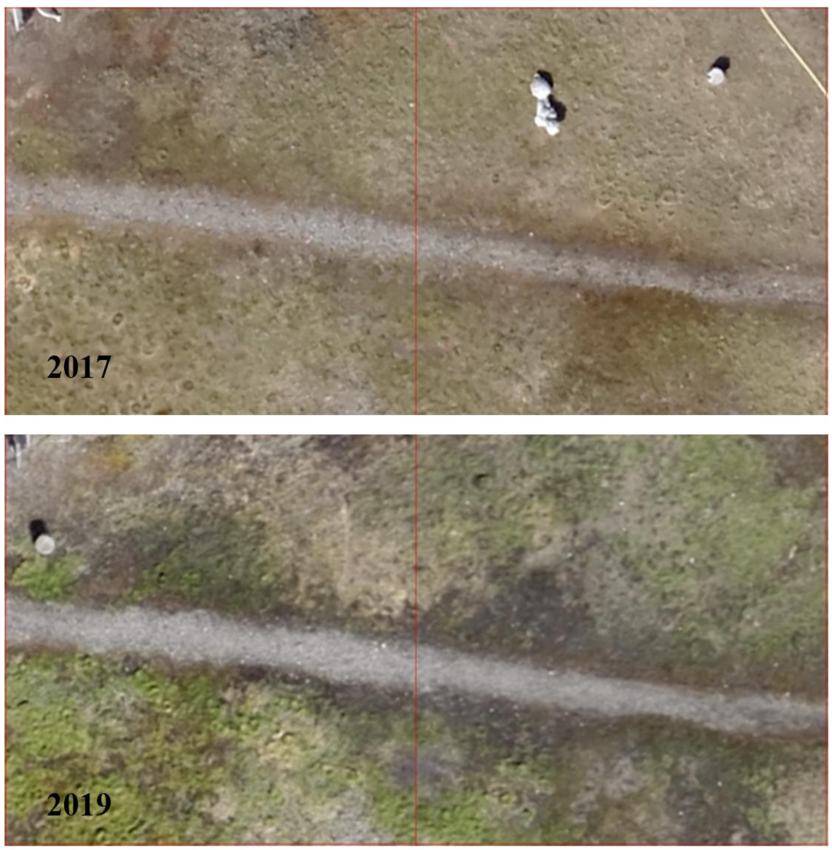


Figure 72. *Pathway change in Study Area 1.* © Katelyn O'Keefe, 2022.

In contrast, most researchers (ecologists, biologists, etc.) do not follow this walking trail. They create diffuse pathways to their study sites, producing lighter but more dispersed steady trampling (Heinemann 2019). The vegetation along most of the walking trail in proximity to the study areas within this research is within the Thrasher and Plover-jaeger ecological classes.

Thrasher vegetation (dwarf willows and grasses) is drastically impacted by cryoturbation, overshadowing visitor impacts. Small willows and substantial moss cover characterize the Plover-jaeger ecological class. This vegetation class is susceptible to disturbance, and trails quickly form (Heinemann, 2019). Figure 73, below, shows the distribution of vegetation classes relative to the walking trail location used by cruise ship visitors and the study area boundaries used in this study.

***Herschel Island – Qikiqtaruk Territorial Park* Visitors**		
Year	**Cruise Ship Visitors**	**Total Visitors**
2010	189	403
2011	143	318
2012	363	521
2013	533	750
2014	300	410
2015	351	509
2016	230	395
2017	151	525
2018	0	107
2019	485	657
2020	0	17
2021	0	25

Table 6. *Number of visitors on Qikiqtaruk from 2010-2021 (R. Gordon, pers comm. 2020).*

Most of the walking trail within the study areas is located within Thrasher ecological zones, which is less impacted by repetitive trampling. One portion of the walking pathway intersects highly sensitive plover-jaeger vegetation. This same area is one of the locations where pathway change was documented using VIA. Increased soil moisture is related to increased vegetation damage in plover-jaeger vegetation, which could explain the incising in the 2019 imagery when combined with foot traffic. According to Heinemann (2019), the park rangers have re-routed cruise ship visitors from this area in the last few years by walking them along the coast when returning from the Mission House. Continuous UAV monitoring of the trails at Pauline Cove would be beneficial, as it would yield valuable information about the impact of visitors within the park.

Figure 73. *Map of the cruise ship walking trail at Pauline Cove. Modified from the original, published in Heinemann (2019:43).*

6.4 Cause of Widespread Patterns of Change

Aside from the changes in areas A-S, several patterns of widespread landscape change were documented throughout the visual inspection process. The widespread landscape changes between 2017 and 2019 were an increase in standing water, vegetation, erosion, and driftwood deposition. The increase in standing water and vegetation is explored using Environment Canada Climate Data (Environment Canada, 2021). A change in shoreline morphology due to erosion is also explored further in this section. Lastly, the additional driftwood in 2019 is discussed.

6.4.1 Environment Canada Climate Data

On a basic level, vegetation growth and color can be attributed to seasonal conditions, such as monthly temperature, hours of sunlight, and precipitation (Myers-Smith et al., 2011b). Therefore, the climate data from Environment Canada's weather station at Pauline Cove can be used to investigate the vegetation increase. Likewise, precipitation data from Pauline Cove is a useful source of information for interpreting the additional water source in the water bodies. The temperature and precipitation data listed in Tables 7, 8, and 9 summarize Environment Canada data in this section. The data is used as the primary source of information to interpret the vegetation change and the water level change between 2017 and 2019. From October of 2017 to June of 2018, there was no temperature data recorded at Pauline Cove; therefore, the data from the weather station at Komakuk Beach, 40 km west of *Qikiqtaruk*, has been included in Table 7. In Table 8, long-term monthly precipitation data averages from 1971-2000 at Komakuk Beach have been included for comparison purposes. Unfortunately, there is no data for sunlight hours on *Qikiqtaruk*.

Pauline Cove Monthly Mean Temperature (C°)												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2016	-13.7	-20.4	-20.4	-12.5	-0.1	5.7	9.4	7.7	2.8	-3.1	-12.5	-18.2
2017	-18.5	-21.1	-20.2	-14.5	-1.2	3.8	10.4	9.2	5.3	-4.9	-13.1	-13.3
2018	-19.1	-16.4	-20.0	-15.7	-6.2	2.0	9.7	3.7	0.3	-4.1	-13.3	-18.0
2019	-20.4	-14.4	-10.8	-11.7	-1.7	5.0	10.1	5.4	5.4	-1.4	-12.2	-21.7
* Red indicates data missing from Pauline Cove, substituted with data from Komakuk Beach												

Table 7. *Environment Canada mean monthly temperatures for Pauline Cove 2016-2019.*

Pauline Cove – Total Monthly Precipitation (mm)												
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2016	1.1	4.1	12.6	6.4	15	37	51.2	20	25.4	7.9	10.4	4.2
2017	17.4	11.8	15.3	1.5	12	8	33.5	136	25.6	ND	ND	ND
2018	ND	ND	ND	ND	ND	ND	30.5	59	42.5	15	13.3	7
2019	10.8	13	24	2.3	17	7.8	3.8	70	17.3	14	6.6	1.2
Avg*	5.7	4.7	3.6	4.3	5.2	18	27.3	35	22.9	20	9	5.8
* Average for 1971-2000, from Komakuk Beach.												

Table 8. *Environment Canada total monthly precipitation for Pauline Cove 2016-2019. Months with no data (ND) supplemented with data from Komakuk beach.*

Pauline Cove - Days with Precipitation >1mm												
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2016	0*	1*	6	3	3	11	8	5	7	3	3	1
2017	5	2*	3*	0	3	1	5	13	4	ND	ND	ND
2018	ND	ND	ND	ND	ND	ND	8*	10	10	3	3	2
2019	3	2	6	0	6	2	1	N/A	N/A	N/A	N/A	N/A
Pauline Cove - Days with Zero Precipitation												
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2016	11*	8*	15	23	17	12	18	18	14	20	11	17
2017	13	13*	21*	21	20	17	21	11	8*	ND	ND	ND
2018	ND	ND	ND	ND	ND	ND	10*	13	14	12	13	13
2019	14	22	12	20	18	21	23	N/A	N/A	N/A	N/A	N/A

Table 9. *Precipitation trends at Pauline Cove 2016-2019. ND is no data, and N/A is not applicable.*

The temperature data included in Table 7 was selected to give information about the mean monthly temperature conditions leading up to the July 2017 and July 2019 imagery. The lead-up period was between August of the previous year and data collection the following July. For the 2017 imagery, this period is from August 2016 to July 2017, and for the 2019 imagery, this period is from August 2018 to July 2019. The patterns were that the fall (August-November) of 2016 was warmer than the same period in 2018, with August and September 2016 being the warmest compared to August and September of 2018. There was minimal difference between the mean monthly temperatures of December 2016, January 2017, and December 2018 and January 2019, respectively. From February to April, it was considerably colder in 2017 than during those same months in 2019. For the months of May-July, there is no consistent pattern. May of 2017 was slightly warmer than May of 2019, June of 2017 was slightly colder than June of 2019, and July temperatures are comparable both years, right before the imagery was collected. Overall, the fall of 2016 was warmer than the fall of 2018, but the late winter of 2017 was colder than the late winter of 2019.

The precipitation data included in Tables 8 and 9 provide information about the total precipitation and temporal distribution of precipitation for each month leading up to data collection in July 2017 and July 2019. As discussed in the section on temperature pattern, the same interval of August-July was considered the lead-up period before data collection. There was considerably more precipitation from August to December 2018 than from August to December 2016. This pattern was disrupted in January, with more precipitation in 2017 than in 2019. From February to May, however, there was slightly more precipitation in 2019 than during the same period in 2017. The months of June and July have very little precipitation difference between the two years, and the 33.5 mm of rain recorded in July 2017 does not fall until after the 2017 data was collected. Overall, there was more moisture between August 2018 and July 2019 than between August 2016 and July 2017.

6.4.2 Standing Water

In 2019, there was significantly more standing water in low-lying areas within the two study areas on Simpson Point. In 2017, the water in these areas appeared to be in the process of drying out, and the depth of the water was less than it appeared in 2019. Since the elevation between the low-lying areas and the surrounding area is similar, additional water led to a horizontal expansion of the water bodies. The standing water is found in low-lying areas across Simpson Point, not just in proximity to the beach; however, this is not unexpected since the entirety of the spit is less than 1 m above sea level. The source of the standing water is unknown; however, there are three potential sources: freshwater in the form of snowmelt or the melt of landfast ice that was pushed inland throughout the winter, freshwater in the form of rain during the summer months, and saltwater, associated with overland flooding and storm surge events.

According to the Environment Canada Climate Data, there was more precipitation in the months leading up to July 2019 than in July 2017. However, there was more precipitation in the winter months before the 2017 data collection than average (averages from 1971-2000 at Komakuk Beach). In June 2017, the month before image collection, there was 10 mm less precipitation than the average. In August 2017, there was nearly four times the average monthly precipitation which may have contributed to the additional standing water in the 2019 imagery. Unfortunately, there is missing data from October 2017 to July 2018. Any rain or snow that fell between this period cannot be accounted for when considering the accumulation seen in the water bodies. The following summer (2018) began with an average precipitation for July, shifting to above-average precipitation for August and September. November and December of 2018 and January, February, March, and May of 2019 had above-average precipitation. In summary, there was slightly more precipitation leading up to July 2019 than July 2017, and this precipitation likely contributed to the increase in standing water seen in 2019.

Another source of water is overland flooding due to positive storm surge events. Low-lying coastlines are most venerable to storm surge events during periods of consistent high wind and vast swaths of the ice-free ocean (fetch), conditions met in the summer and fall on

Qikiqtaruk (Lantuit and Pollard, 2008; Radosavljevic et al., 2016). Storms from the southeast and south-southeast have the potential to flood Simpson Point, especially in the main settlement area, which is only 0.30 to 0.40 m above sea level (Lantuit and Pollard, 2008; Pollard et al., 2012; Radosavljevic et al., 2016). The additional standing water in Study Area 1 in 2019 could be due to a storm surge event; however, this is unlikely since moisture from saline inundation adversely impacts vegetation (Lapka, 2013), something that is not apparent. A water salination test may be a useful way to determine the source of the additional water.

6.4.3 Vegetation

This research indicates that there has been vegetation change in both study areas between 2017 and 2019. For both, there is more vegetation or greener vegetation in 2019 than in 2017. In addition, there is significant algae growth along the perimeter of the water bodies in 2019, compared to 2017. As mentioned in section 6.3.2, the ecological classes on Simpson Point are Thrasher and Plover-Jaegar. Global warming is causing a large-scale change in vegetation height, biomass, cover, and abundance in the arctic. However, numerous ever-changing variables impact tundra vegetation, making it increasingly complex to study (Myers-Smith et al., 2020). A logical hypothesis would be that when there are warmer temperatures, there is a longer growing season, meaning that there would be more vegetation growth. Based on the Environment Canada climate data from Pauline Cove, it is possible to conclude that the fall preceding the 2017 imagery was warmer than the fall preceding the 2019 imagery. Still, the winter of 2017 was colder than the late winter of 2019. The mean springtime temperatures of 2017 and 2019 were comparable immediately before the data was captured. Therefore, it does not appear that temperature alone significantly impacted the additional vegetation seen in 2019. Likewise, research regarding tundra vegetation growth patterns in northern coastal Alaska has found that warmer temperatures leading to earlier snowmelt do not necessarily correlate to increased vegetation productivity. Rather, precipitation and soil moisture play a more significant role (Gamon et al., 2013). According to the Environment Canada data, there was more moisture between August 2018 and July 2019 than between August 2016 and July 2017. Therefore, the additional precipitation likely increased soil moisture and contributed to the additional vegetation seen in the 2019 imagery; however, further research is needed to determine the variables contributing to the increased vegetation.

6.4.4 Shoreline Morphology

As discussed in section 6.3.1, the change in areas "B" and 'R" can be attributed to changes in shoreline morphology. In area "B," there is evidence of sand pile-up beside the Northern Whaling and Trading Co. buildings. These buildings have already been moved inland and raised in response to wave action (Yukon Government, 2019b:5). In area "R," there is evidence of coastal erosion in front of two archaeological sod house features. Based on aerial photography of the island and personal communication with the Yukon Historic Sites Unit personnel, this area receives a significant amount of wave action. Research by Lantuit and Pollard (2008) and Radosavljevic et al. (2016) has demonstrated that this stretch of coastline has been retreating for decades. Archaeologists have recognized erosion since the mid-to-late 20th Century (MacNeish, 1956; Yorga, 1980). Between 2017 and 2019, the beach further encroached on two at-risk Inuvialuit sod house features, putting them at significant risk of eroding within the next few years. Figure 74, below, is a visual aid showing the approximate shoreline change between 1910, 2017, and 2019. The 1970 coastline is based on a Government of Canada air photo (Dept. of Energy, Mines and Resources, 1970). The photo was georeferenced in GIS software, and the shoreline was traced along the inland extent on the beach face. Defining the location of the shoreline can be challenging, however, it is crucial to be consistent between datasets (Boak and Turner, 2005). Small-scale errors attributed to georeferencing, and manual shoreline tracing are unavoidable for this comparison; however, these cannot account for the several-meter difference between the beach in 2017 and the beach in 2019. In addition, both sets of UAV data were collected in the afternoon, and the region is microtidal, therefore water level differences due to the tide cannot be responsible for the magnitude of change detected.

Figure 74. *Southeastern shoreline extent from 1970, 2017 and 2019.* © Katelyn O’Keefe, 2022.

6.4.5 Driftwood

The driftwood on *Qikiqtaruk* is especially prevalent on the southern and eastern shores of the island, including Simpson Point (Pollard et al., 2012). The wood is deposited into the Mackenzie River and the Firth River downstream as the riverbanks erode. The driftwood is transported to the coast during springtime ice breakup and transported towards *Qikiqtaruk* (Eggertsson, 1994). The erosional export of driftwood downstream is episodic, meaning that the delivery of driftwood to the coast occurs in "pulses" (Kramer et al., 2017). When a driftwood pulse coincides with one or more storm events at Pauline Cove, significant quantities of driftwood would likely become stranded on the beach. Alternatively, the driftwood inland and on the beach may also be supplied by landfast ice thrusts (Reimnitz et al., 1990). There was a noticeable change in the driftwood's amount, position, and size in both study areas. It is plausible that the 2019 imagery was collected after a pulse of driftwood was delivered to the coast. If left along the beach, the driftwood can benefit beach accretion since sediment and organic material build up behind the driftwood fragments if left undisturbed. Long-lasting driftwood accretions, called driftcretions, deliver nutrients to the beach throughout decomposition. These nutrients encourage vegetation growth, which acts as a buffer from erosion (Kramer and Wohl, 2015). Should the significant accumulations of driftwood visible in the 2019 imagery be undisturbed by storm events, flooding, and wave action, it may serve to protect the heritage features from further erosion, assuming they are not displaced by overland flooding or ice.

6.5 Chapter Summary

This chapter provides the data processing outputs for the 2017 and 2019 datasets. The outputs included high-quality orthomosaics and point clouds. As described in the methods chapter, these outputs were used for change detection analysis in two study areas. The most significant component of this chapter is the description and explanation of the change detected using the C2C method and the VIA method, respectively. Much of the change is associated with driftwood deposition and movement, inland flooding, vegetation increase, coastal erosion, and park ranger activities. In addition, restoration work undertaken by the Yukon Historic Sites Unit was detected by the C2C and explained using VIA or through personal communication. One change stood out: the widespread change to Building 11, which alone could not be explained using the change detection methods. Although an elevation change was suspected, the reason for the change was confirmed through personal communication. Especially interesting is that the building was elevated by 0.45 m, and the C2C detected a bright green-coded change of approximately 0.50 m, confirming the accuracy of the C2C results. In addition to the changes detected by the C2C and confirmed using the VIA, additional change was found during the VIA process. The additional change includes the increase in pathway size and the formation of frost cracks near several sod house features. As discussed in section 6.3, there were several changes that were not detected by the C2C method, indicating that while the method detected most of the changes that occurred, there are instances where some changes do register on the C2C change map. The merits of C2C and VIA are discussed further in section 7.1. Overall, the results of this research show that UAV photogrammetry and the selected change detection methods yield credible results, especially when the change detection methods are used in tandem.

The following chapter discusses several topics of interest pertaining to this research. The discussion chapter outlines the advantages and disadvantages of C2C and VIA, the expected change if site data is collected in 2022, the importance of heritage preservation on *Qikiqtaruk*, and a discussion on the development of a heritage monitoring program for Pauline Cove, based on the procedures in this research. Additionally, the benefits of "found" data and academic data sharing are elaborated upon.

7 DISCUSSION

This chapter is divided into five sections. The first section of this chapter summarizes the advantages and disadvantages of the change detection methods used within this research, emphasizing their compatibility. The following section outlines expected changes to heritage and the landscape at Pauline Cove should UAV data be collected in 2022. The third section outlines the importance of heritage preservation within Pauline Cove and how the research presented in this document aligns with the goals of the *Herschel Island – Qikiqtaruk Territorial Park Management Plan*. The third section outlines the development of a long-term heritage monitoring strategy at Pauline Cove, including suggested improvements to data collection procedures and the implementation of a risk matrix. The last section of this chapter discusses the benefits of data "crowd sharing" and long-term data stewardship.

7.1 Change Detection Method Compatibility

The change detection methods used in this research, C2C, and VIA, were selected due to their compatibility. The advantages and disadvantages of C2C and VIA are listed in Table 10 below. One advantage of the C2C method is that it can be done with free, open-source software. Cost-efficient software is advantageous because remote sensing applications can be extremely costly for students, small organizations, or members of the public. In addition, the software can be run on most consumer-grade computers, meaning that it is widely accessible. Another advantage of the C2C method is that it enables the analyst to view all changes within a scene at once, making it a valuable tool for a quick examination. The re-colored point cloud (change map) created by the C2C Distance tool enables the user to narrow down areas of significant change, saving time during visual inspection.

As demonstrated in the results chapter, C2C is a valuable method for detecting elevation change, which can go undetected by VIA in aerial (vertical) imagery. Lastly, the C2C method is beneficial because, unlike VIA, it quantifies the change detected in the scene. With additional information, such as personal communication with park rangers or other researchers, it is possible to confirm the accuracy of the C2C results (ex. elevation change for Building 11).

There are several disadvantages of the C2C method. First, the results provide limited insight into the cause of the detected changes, therefore the analyst must rely on a supplemental method for this information. Second, C2C requires dense point clouds with minimal gaps; otherwise, the resulting scalar index is greatly influenced by the data quality and not the change itself (Cloud Compare, 2015). An example of this problem is the dark shadow cast by the Bonehouse in the 2019 data which is depicted as a large change on the C2C map. Rather than being representative of actual change, the change detected is likely due to the difference between the 2017 and 2019 data quality (no shadow vs. dark shadow) or due to an error in the C2C computation itself. Thirdly, the workflow in CloudCompare© is not always intuitive, and there is undoubtedly a learning curve for the software. While this is expected with open-source software, many user forums and instructional web pages are continuously created. Regardless, the user will need to spend time learning the software. Another disadvantage of the C2C method is that subtle changes, such as the pathway change or the frost cracks on some of the sod house features, go unnoticed because they are drown out by larger change detected in the scene. A final disadvantage of the C2C method is the necessity of easily identifiable points within the dataset to ensure proper alignment of the point clouds. Study Area 1 was much easier to align than Study Area 2 since there are many historic buildings for reference in Study Area 1 compared to Study Area 2. Without these stationary points of reference, it becomes challenging to achieve satisfactory alignment with a low RMS error value, which is required to achieve accurate C2C results.

Method	Advantages	Disadvantages
C2C	Free, open-source software	Software is not intuitive, learning curve
	Quantifies change	Requires high-density point cloud
	Can confirm results of qualitative methods	Requires identifiable, stationary alignment points
		Subtle changes can get drown out by more prominent change in the scene
VIA	Straight forward	Time-consuming
	Yields information about the nature of change can confirm C2C method results	Results are somewhat subjective, dependent on the skill of the analyst
	It can be done with or without GIS software	
	Can detect subtle changes	

Table 10. *Advantages and disadvantages of C2C and VIA methods.*

There are several advantages to VIA. The first advantage is that it is a straightforward process. Secondly, this method can be performed with or without computer software, though GIS capabilities may be preferable to many researchers, organizations, and individuals. Because this method can be done without advanced computer software, it is widely available to northern communities and early-stage researchers. Another advantage of this method is that the viewer can decide what type of change to look for or look for multiple forms of change at once. For example, the user could look only for vegetation change and ignore all other changes in the scene. This selective change analysis is not possible with the C2C method. A third advantage is that the analyst can pick up on subtle changes that may be missed with other methods. For example, the visual analysis method helped identify pathway change between 2017 and 2019, which was too subtle to be detected by the C2C method. While visual inspection can undoubtedly be used as a standalone change detection method, it is extremely valuable for confirming the accuracy and validity of the results of quantitative change detection methods, including the C2C method. In addition, VIA can also provide insight into the nature of the change, something that could not have been determined using C2C alone.

In summary, it is evident that these methods are highly compatible. When used together, they provide comprehensive documentation of the change occurring to the landscape and the historic buildings at Simpson Point between 2017 and 2019. While VIA could undoubtedly be used independently, the C2C method is value-added since it quantifies change, detects changes in elevation within aerial imagery, and highlights areas with significant change, streamlining the otherwise time-consuming VIA process.

7.2 Expected Change by 2022

This section summarizes the expected change to Simpson Point by the time of the next data collection (summer 2022). Suspected changes by 2022 are discussed. These changes include historic structures, archaeological features, and the landscape, which is being changed by erosion, standing water, vegetation, and tourism. Throughout this research, travel restrictions related to the ongoing Covid-19 pandemic have prevented researcher and visitor access to *Qikiqtaruk*. As discussed in section 6.3.2 in the results chapter, cruise ship visitors make up most visitors to the island, followed by researchers, government officials, and Inuvialuit. In 2019, just before the Covid-19 pandemic, there were 657 visitors to the island, compared to 17 and 25 in 2020 and 2021, respectively (R. Gordon, pers. comm. 2021). The visitors in 2020 and 2021 were likely Inuvialuit and several Yukon Government employees.

Regarding the expected change to the historic buildings, it is hypothesized that there will be additional change related to routine park ranger activities around the structures (wood stacking, movement of park washroom facilities, picnic tables, etc.). The RCMP Dog Kennel fence line will likely have continued to shift naturally. There will be one significant change in future imagery. The shower building north of the Mackenzie House was destroyed by fire in 2021 and has since been rebuilt (C. Thomas, pers. comm. 2021). In addition, the Yukon Historic Sites Unit has been sending materials to the island for the past two summers in preparation for further restoration work to the historic buildings. Therefore, it is likely that these materials, in some form, will be visible in newly collected imagery.

Changes to the archaeological Inuvialuit sod houses on Simpson Point will likely depend on their location. Inland, the sod houses along "society row" will likely remain unchanged, except for driftwood movement around their bases. The two sod houses in Study Area 2 that were previously identified as at-risk of erosion will likely be closer to the actively eroding beach face than in the 2019 imagery. If this is the case, prompt excavation of these features is recommended by the author to document them before they are destroyed by erosion.

Changes to the landscape attributed to standing water and vegetation are likely; however, these changes are more difficult to predict, even with Environment Canada Climate Data for 2019 to 2021. Unfortunately, the Herschel Island station did not record data from September to December 2020. Without the climate data, it is impossible to assess the impact of temperature and precipitation for 2020. What is known from the climate data is that the mean temperatures in January and February of 2020 (minus 25.4 and minus 27.6 degrees Celsius) and 2021 (minus 23.1 and minus 30.0 degrees Celsius) were much cooler than those same months from 2016-2019. March of 2019 was warmer than that month in 2020 or 2021, and the weather from April to June in 2020 and 2021 was like previous years. In July of 2020, however, the mean temperature was 4.8 degrees Celsius, much colder than average.

Conversely, the mean temperature was 11.4 degrees Celsius in 2021, close to normal. Again, the data for the fall of 2020 is missing, but the temperatures in the fall of 2021 are like those from 2016 to 2019. There are no precipitation records for 2020. For 2021, the total precipitation for February and April was significantly higher than between 2016 and 2019. There was less precipitation in July 2021 than in that month from 2016 to 2019. For other months in 2021, the precipitation was like 2016 to 2019. Overall, it is challenging to determine the extent of change to vegetation and standing water based on the Environment Canada data alone. Another change to the landscape detected during VIA was the appearance of frost cracks in 2019. It would certainly be interesting to see if these cracks have expanded in the last few years.

If UAV data is collected in the summer of 2022, the most exciting change to re-document would be the appearance of the pathways between the buildings in Study Area 1 and from the Historic settlement to St. Patrick's Anglican Mission House in Study Area 2. Given how few visitors the island has seen since the onset of the pandemic, this is a unique opportunity to gather information about the recovery of vegetation and the impact of visitors on the landscape. It is hypothesized that the pathways will appear smaller, with increased vegetation growth within and adjacent to the pathways.

In summary, the collection of UAV imagery in the summer of 2022 serves not only to monitor the heritage resources and the cultural landscape of *Qikiqtaruk* but also presents a unique opportunity in scientific research because the imagery would capture the impact that a global pandemic has had on a delicate heritage site in the Canadian Arctic.

7.3 The Significance of Preserving Heritage on *Qikiqtaruk*

This section serves to further emphasize the cultural significance of the heritage features and the cultural landscape within *Herschel Island – Qikiqtaruk Territorial Park*. As previously mentioned in section 4.4, the range of heritage feature types on *Qikiqtaruk*, and their associated history is remarkable. The richness and complexity of the cultural landscape is expressed through archaeological and oral history evidence (Nagy 1994; Friesen 2012).There are several reasons that the heritage features and the cultural landscape on *Qikiqtaruk* are significant. Firstly, *Qikiqtaruk* is invaluable to the Inuvialuit, who have continuously occupied the island since their development from Thule. The island is important for traditional Inuvialuit hunting and gathering activities (Nagy, 1994; Yukon Government, 2019a). The protection of Inuvialuit lands within the Inuvialuit Settlement Region (ISR) is a stipulation of the *Inuvialuit Final Agreement* (IFA) and the protection of the landscape and the Inuvialuit archaeological features on the island fulfill the requirements of the IFA and the goals of the park management plan. This research provides a means of digitally documenting and monitoring change to the Inuvialuit heritage features and the cultural landscape. The UAV imagery and awareness of the changes detected, can be used to alongside traditional knowledge, oral history and on the land experiences such as culture camps, to facilitate knowledge sharing and a deeper understanding of the important relationship the Inuvialuit have with the island.

Secondly, the heritage features on Simpson Point should be preserved because they are representative of sustained interaction between Inuvialuit and Euro-North Americans. The Inuvialuit at Pauline Cove experienced the influx of Euro-North Americans into their traditional territory and were participants in the commotion of the whaling and fur trading periods. The sod houses on Simpson Point were built before, during, and after contact with Euro-North

Americans. Their contents reflect the influence of Euro-North American culture and the wage economy on the Inuvialuit (Friesen, 1995; Friesen, 2013). This influence has been long-lasting, and descendants of these whalers carry their surnames (Nagy 1994:37). Further evidence of the dramatic cultural transition during the late 19th and early 20th Century has been documented by elders (Nagy, 1994). This mixture of Inuvialuit and Euro-North American history makes *Herschel Island – Qikiqtaruk Territorial Park* incredibly unique.

Thirdly, the historic structures at Simpson Point are significant because they are the physical manifestation of the whaling period and the fur trade. In addition, they provide insight into the hardships of northern life in the late 19th and early 20th Century. These structures were continuously re-purposed since materials were scarce. Many of these buildings exchanged hands several times following the decline of the whaling period and are therefore tied to multiple periods. For example, the PSWC Community House, now the oldest standing wooden frame building in the Yukon, has been used continuously since its construction in 1893. Initially built for housing and social activities, it has also been used for church services, as the Western Arctic district headquarters of the RCMP, including the jail. Many of the structures at Simpson Point have a similarly complex history.

Lastly, *Qikiqtaruk* played a vital role in the exertion of Canadian sovereignty in the Western Arctic in the early 20th Century. Pressure from missionaries, the HBC, and the unsatisfactory result of the Alaskan-Boundary Dispute, resulted in the creation of the Pauline Cove detachment (Neufeld 2012:187). This detachment became the subdistrict headquarters for the Western Arctic and or the first time, Canadian presence and law were asserted, resulting in cultural and social changes (Neufeld 2012:188; Yukon Government 2019b:6).

In summary, the cultural landscape and heritage features of *Qikiqtaruk* are significant to the Inuvialuit and to Canadian history. Unfortunately, the climate change processes described in Chapter 3 are putting many of these features at risk. Preservation efforts are dictated by the type of feature being impacted. For example, the historic buildings can be raised, or relocated, if threatened by flooding or erosion (Yukon Government 2019b:5). An important consideration is that the physical displacement of the historic buildings alters the cultural context and commemorative integrity of the site itself. Sadly, due to the semi-subterranean nature of the Inuvialuit sod houses, they cannot be relocated, meaning that there are fewer preservation options available. Traditional archaeological techniques can be used to document them prior to erosion, however, excavation itself is an inherently destructive practice (Lucas, 2001:35). Digital capture technologies, such as TLS and UAV imaging, can be used with or without excavation, to rapidly record the features. These methods are beneficial because they provide a highly detailed record. By identifying and monitoring change to the landscape and to the heritage features on *Qikiqtaruk*, preservation efforts can be focused on features at highest risk. The following section discusses the implementation of a UAV heritage monitoring strategy for *Qikiqtaruk*, including a summary of an ideal monitoring strategy, the advantages and disadvantages of the procedures used in this research, improvements to the data collection strategy and the suggestion of a risk matrix.

7.4 Developing a Heritage Monitoring Strategy for *Herschel Island – Qikiqtaruk Territorial Park*

This research had two intended outcomes. The first outcome was detecting and documenting change to the heritage features and the landscape using UAV imagery and low-cost change detection methods. The second outcome was to create procedures that could be used to develop a heritage monitoring strategy for *Herschel Island – Qikiqtaruk Territorial Park*. When developing a monitoring strategy, it is crucial to consider the challenges that come with circumpolar research, including remoteness terrain and high cost, as well as the management strategy laid out by the *Herschel Island – Qikiqtaruk Territorial Park Management Plan*. This section discusses the advantages and disadvantages of repeating the procedures laid out in this document and developing a monitoring strategy based on these procedures. The second section will outline two surveying techniques that can be used to improve data collection and quality at Pauline Cove and to make the procedures more suitable for use in other circumpolar environments. Thirdly, there will be a brief discussion about developing a risk matrix for the heritage on *Qikiqtaruk*.

7.4.1 Monitoring Strategy

The ideal heritage monitoring strategy for Simpson Point is a strategy that is low-cost, easily replicable, and practical to document real-time change to the heritage features and the landscape. The proposed monitoring strategy is not predictive; instead, it serves to monitor change as it occurs. Preferably, the UAV would be flown over Simpson Point annually or bi-annually. The collection of data using a UAV compared to air photos of satellite imagery means that the data can be collected by any user that has access to and knows how to fly a UAV. UAV imagery is high-quality, and data collection timing is more flexible than traditional air surveys. In addition, the cost of UAV data collection is lower than traditional air surveys (Murison, 2020). The flight data would be processed using compatible software. Afterward, the orthomosaics and point clouds would be clipped to the same extent, and the analyst would use CloudCompare© to perform C2C. While VIA would have been sufficient to detect change on its own, the C2C method was value-added since it quantified the change and identified areas of notable change before VIA. Afterward, the analyst uses VIA to determine the nature of the change detected by the C2C method and looks for additional change in the scene. The changes are documented in a secure document, where they can be compared year after year. Alternatively, the change descriptions could be embedded into a reference raster image, with a superimposed grid. For each 10 x 10m square on the grid, a description of changes detected in previous years would be provided. In some circumstances, ground-truthing of results may be required. For instance, if the nature of a change is unclear after VIA and discussion with Yukon Government personnel, on-site analysis may be beneficial. An example is the additional standing water in low-lying areas in 2019. Without ground-truthing, it is impossible to determine with certainty whether this water is saline, and therefore the result of storm surge activity. A monitoring strategy using the procedures laid out in this thesis is advantageous because it is systematic. There is a need for more systemic heritage monitoring, apart from the strategies used by organizations like Parks Canada. Parks Canada staff sporadically use on-site repeat photography to monitor heritage sites (P. Dawson, pers comm. 2022). This method requires the reproduction of the exact camera position, camera angle and exposure, which can be challenging to replicate (Webb et al. 2010:17-19). Another advantage of the systematic monitoring strategy described here, is that it can be replicated for other circumpolar heritage sites, including those in Ivvavik National Park on the Yukon North Slope.

The feasibility of the adoption of these procedures as the basis of a monitoring strategy for *Herschel Island – Qikiqtaruk Territorial Park*, depends on several factors. It requires access to a UAV, and competent personnel to collect the data. Consistency is key when collecting UAV data, therefore, it would be beneficial to create set guidelines for the UAV data collection on *Qikiqtaruk*. Set guidelines would enable Yukon Government archaeologists, Inuvialuit rangers on the island and other researchers to collect the data while maintaining consistently high data quality. The curation and organization of the digital data files is also vital to the success the monitoring strategy described above. Data sharing is discussed at greater length in section 7.5.

7.4.2 Advantages and Disadvantages of the Procedures Used

The UAV data collection procedures used in this study are beneficial because they are relatively cost-efficient. UAV data collection is much more affordable than traditional air survey, and many have built-in GNSS. These qualities make the procedures attractive and relatively accessible to non-specialists (Murison, 2020). An understanding of photogrammetry, UAV mission planning, flight execution, data processing software, GIS software and if using GCPs, basic survey skills are required, however. A subscription to the data processing software, Pix4D, is costly; however, a one-time fee is paid for a lifetime subscription to Pix4D. If further cost-reduction is a priority, free software, such as Agisoft Photoscan©, exists, however, it is not ideal for this type of work. As for the change detection methods, VIA can be done with or without GIS software and is relatively simple to complete. GIS software is often available to students and employees of large educational or governmental institutions, minimizing the cost of the software should GIS be desired. CloudCompare©, the software used for the C2C method, is open-source and widely available, further reducing costs.

Additionally, suppose the alignment procedures are followed. In that case, neither a permanent control network nor GCP's is required to achieve results, which is beneficial because the terrain within the vicinity of Pauline Cove is challenging. It is difficult to anchor permanent control points since there is little to no stable ground or sizable rocks on the Island (Burn, 2012). If permanent control points were drilled into the sediment, they would likely shift due to frost, permafrost melt, coastal erosion, flooding, or other natural hazards. Likewise, installing permanent control points on the historic buildings, which may be raised or relocated as needed, is no better.

The disadvantages of the procedures used in this research are that the resulting accuracy is relative rather than absolute. In addition, the alignment steps are somewhat complex. As mentioned previously, the 2019 data was collected for visualization purposes rather than for change detection analysis. While alignment post-processing yields data suitable for the change detection conducted in this research, without ground control points, other forms of analysis may be limited because of the relative accuracy. Suggestions for enhancing the future data collection strategy are provided in subsection 7.4.3. While the 2019 dataset was geolocated using the image coordinates, alignment was still required in the data preparation step to scale the dataset to match the 2017 dataset properly. The manual alignment of the 2017 and 2019 datasets introduces some human error into the process. In addition, the alignment step may be problematic due to how it functions. By instructing the software to align or match the two datasets based on a series of alignment points, the software must, to some extent, ignore any widespread differences for best fit. This process means that widespread changes on the spit, such as hypothetical subsidence of the entire area, would go undetected in the change detection analysis step because the software has adjusted the datasets to match. However, the alignment step does not prevent anomalies between the datasets, and changes to buildings and particular locations on the landscape can still be detected.

Overall, the procedures laid out in this research are cost-effective and suitable as the basis of a heritage monitoring strategy. They can be replicated in the future to document change at Pauline Cove or other circumpolar heritage sites. However, improvements can be made to these procedures to improve the quality of the data, which would increase functionality and streamline data preparation requirements. These improvements involve incorporating traditional survey techniques for the data collection process. The following section summarizes two survey techniques that can be incorporated into the current procedures of this research, which would improve the current methodology. Furthermore, these improvements would increase the procedure's suitability as part of a long-term heritage and landscape monitoring strategy for *Herschel Island – Qikiqtaruk Territorial Park*.

7.4.3 Improvements to Data Collection Strategy

The key improvements to the procedures laid out in this research are improvements to the data collection strategy by incorporating advanced survey techniques. As mentioned previously, incorporating a permanent control network on Simpson Point is challenging due to constantly shifting sediment and overland flooding. Two alternatives are presented in this section, both of which are meant to improve the spatial constraint of the data. It is important to remember that if incorporating GCPs, the precision of the GCPs must be better than what can be achieved through photogrammetry alone (D. Lichti, pers. comm. 2022).

The first technique is called precise point positioning (PPP) into the data collection process, which would increase achievable accuracy and streamline post-processing data preparation. PPP is a survey technique that uses a standalone Global Positioning System (GPS) receiver to record the GPS coordinates of several control points on the landscape (EMLID, n.d.a). The type of GPS receiver being used is critical because it will determine the achievable accuracy of the collected data. For this technique to be viable for monitoring, a dual-frequency receiver, which is a receiver that can receive two signals from each satellite system, is required (Macleod and Tétreault, 2014). In contrast with single-frequency receivers (also called code-only receivers), dual-frequency receivers have centimeter-level accuracy versus half a meter or meter-level accuracy (Macleod and Tétreault, 2014). Centimeter level accuracy is optimal for monitoring subtle changes, like those documented in the results section of this research. Additionally, high accuracy will ensure that the dataset is functional for future studies and studies by other researchers if desired.

For PPP, a dual or multi-frequency receiver is left for several hours at each control point location (having 5-10 GCP's is recommended by Pix4D), each time collecting raw satellite information (EMLID, n.d.a.; Pix4D, 2019). A physical target is temporarily placed at each control point location for the UAV flight. No connection is needed between the GPS receiver and the UAV, and the GPS location of the control points is not required until the data is processed. Once the UAV work is complete, the temporary targets can be removed and stored for the following year. When the research team is back from the field, the raw data file from the GPS receiver, called a rinex file, is run through a PPP solution (example: Government of Canada's NRCAN). The solution accounts for satellite and orbit corrections at data collection and delivers accurate coordinates for each control point on the ground. This technique is advantageous because no connection is needed between the GPS receiver and the UAV during flight, making it ideal for remote locations (Alawi and Martin, 2015; Bash et al., 2018; van der Sluijs et al., 2020). Data corrected using PPP is geolocated, with point locations up one hundred times more precise than uncorrected points (Macleod and Tétreault, 2014). A disadvantage of this data collection method is that the researcher needs to establish the temporary GCP locations, have knowledge of survey techniques, and incorporate the control points into the processing steps. Thankfully, Pix4D and other photogrammetry software have developed tools to streamline GCP incorporation during processing. If the UAV being used has RTK / GNSS capabilities, then PPP can also be used during RTK surveys, if there is dual frequency data. By using PPP and RTK, the minimum number of GCP's required is reduced to four (D. Lichti, pers. comm. 2022).

The second option is a survey technique called a post-processed kinematic (PPK) solution. This technique can be used alone, though it is best when used with PPP. PPK is like PPP in that it requires a GPS receiver; however, it also needs a UAV with a built-in GNSS (EMLID, n.d.b). The GPS receiver is placed on a point with known coordinates in the field. This point may be one of the points used during the PPP, meaning that the location of the point can be determined later in the lab, or it can be a single point with known coordinates if PPP is not performed. Once the GPS receiver is running, the UAV is flown. Once back at the lab, the two raw data files (one from the GPS receiver and one from the UAV) can be processed. The data file from the GPS receiver is run through a PPP solution (EMLID, n.d.b). Afterward, the specialized computer software will compare the corrected GPS file with the UAV rinex file to determine corrections. PPK is advantageous because it can be done without connecting the GPS receiver and the UAV like PPP. The resulting data is accurately geolocated, and any error is minimalized using the PPK technique. A limitation of this method is the increased cost of a GNSS-equipped UAV.

Overall, the procedures outlined in this research could be improved by incorporating PPP or PPK survey techniques in the data collection process. PPP and PPK are beneficial because they would eliminate scaling and alignment-related errors. Ideally, PPP and PPK would be used together since PPK can be used to confirm the accuracy of the data by confirming the location of the physical GCP's in the imagery and completing PPK can reduce the amount of GCP's required by the PPP (D. Lichti, pers. comm. 2021). Regardless, the standardization and improvement of the survey techniques used at Simpson Point, combined with the change detection methods used in this research, would facilitate the development of an accurate long-term monitoring strategy. The resulting data would be higher quality, and users would be able to detect widespread change to the landscape (rebound, ground subsidence, etc.), which is challenging due to the current alignment step. Additional analysis, including precise distance measurements, would be possible with improved spatial constraints. Precise distance measurements would be valuable to measure and monitor the ongoing erosion encroaching on the sod house features to the northeast of St. Patrick's Anglican Mission House. The improved procedures would be a more appropriate starting point for developing monitoring strategies at other polar heritage sites and sites without built heritage. It would remove the requirement to use stationary buildings as alignment points.

Ongoing dialogue with the Yukon Historic Sites Unit of the Cultural Services Branch, Government of Yukon, would also be beneficial for future heritage monitoring at Simpson Point since the changes made by the crew are visible in the C2C change map and the orthomosaic. Personal communication with crew members was integral to the interpretation of several changes described in the results of this research.

In summary, the procedures outlined in this research are suitable for developing a future heritage monitoring strategy for *Herschel Island – Qikiqtaruk Territorial Park*. By incorporating relatively simple improvements to the UAV data collection strategy, the limitations of the current procedures can be eliminated while simultaneously enhancing data quality and functionality. Additionally, by removing the need to have historic structures or identifiable landmarks in the scene to align the datasets, the general procedure becomes suitable for monitoring heritage that is less visible from the air or within a homogenous landscape. Overall, post-improvement, the procedures within this research are suitable to detect the change and for use as part of a monitoring strategy for heritage at Pauline Cove and in other circumpolar environments.

7.4.4 Risk Matrix

The previous section outlines the suitability of the procedures developed in this research to develop a monitoring strategy. Another critical aspect of a heritage monitoring strategy is evaluating risk and developing procedures to deal with risk, a process called risk assessment (Stapp et al., 2009). In heritage management, risk is defined as the likelihood of adverse consequences to cultural property (Ramalhinho and Macedo, 2019:39). By this definition, heritage features can be ranked and thus prioritized by the likelihood that these adverse consequences will be realized. The process of categorizing the likelihood and severity of risk is called risk assessment, and the tool or chart used is called a risk matrix. Many risk assessments prioritize physical vulnerability (coastal erosion, flooding, etc.) (Reeder-Myers, 2015). However, while physical vulnerability is crucial, other factors, including adaptability (related to physical vulnerability) and cultural significance, are equally essential to consider. For instance, many historic buildings can be moved, but archaeological features cannot, meaning that the archaeological features are at greater risk. Within the focus areas of this research, there are numerous Inuvialuit archaeological features and historic structures associated with Euro-North American activities.

The results of the change detection analysis show that some heritage features are at higher risk of climate change impacts, including the Inuvialuit sod houses and whaling buildings in proximity to the beach. Therefore, the sod houses would be at greater risk than the historic buildings, assuming that the historic buildings can be raised or moved elsewhere if required. An important consideration regarding building relocation is maintaining site context and sense of place. Sense of place is a concept that explains the relationship between people and a physical place, due to the meaning that that place has (Buonincontri et al. 2017:2). Relocation of the historic buildings may impact the sense of place and alter perceptions of authenticity (Buonincontri et al. 2017). The position of the heritage buildings is critical to the commemorative integrity of Qikiqtaruk. Therefore, careful consideration of the impact of moving the buildings on the heritage site, is required.

It is relatively easy to prioritize heritage features within *Herschel Island – Qikiqtaruk Territorial Park* based on the risk of flooding or erosion. Still, it is more challenging to anticipate human impacts since visitor activities vary. As mentioned previously in the results chapter, there is a growing number of tourists on the island, so it is possible to account for tourist-related activities when ranking the features. The most complex variable, however, is cultural significance. Cultural significance can be determined by period, culture, preservation, and other criteria, but regardless, it is subjective. It is extraordinarily complex to determine which heritage features should be prioritized based on their cultural value. Likewise, these decisions are best made following extensive collaboration between all stakeholders. For *Herschel Island – Qikiqtaruk Territorial Park,* these stakeholders are the Inuvialuit, Yukon heritage specialists, and park management (Yukon Government, 2019a). Regardless of the specifications, implementing a risk matrix would benefit the long-term heritage monitoring strategy within *Herschel Island – Qikiqtaruk Territorial Park.*

7.5 Academic Data Sharing

The Covid-19 pandemic influenced the final direction of this research since fieldwork was not possible in the summer of 2020 or 2021. The initial scope of this research was to excavate two at-risk sod houses northeast of St. Patrick's Anglican Mission House, using the UAV data for visualization purposes. It is only because of the generosity of Dr. Andrew Cunliffe and colleagues that the 2017 data was available for this research and change detection analysis became feasible. This section stresses the importance of found data and academic data sharing. In addition, the storage and long-term curation of previously collected data is emphasized. Increased academic data sharing has vast potential for scientific advancement. A benefit of sharing data is that it contributes to new research otherwise stalled by changing circumstances, like travel restrictions imposed due to the Covid-19 pandemic. Secondly, scientific data collection is expensive to collect due to travel requirements, equipment, and other logistics. Re-purposing found data is cost-efficient and ecologically friendly compared to acquiring new data from the same target area. Should several researchers pay to collect or use a dataset, it can be considered academic crowd-funding or academic crowd-sharing. Thirdly, academic data sharing fosters collaboration between researchers or research groups from various disciplines, driving interdisciplinary research. Interdisciplinary collaboration frames new research questions, which is undoubtedly beneficial for scientific advancement (Morss et al., 2021).

Unfortunately, in many instances, data continues to go un-shared. There are several explanations behind the lack of sharing. Many researchers acknowledge that a lack of data sharing results from concerns regarding time, data control and access, individual recognition, and in younger academics, competition for tenure (Fecher et al., 2015a, 2015b; Morss et al., 2021). Other research has shown that early-career academics are more likely to share their data than more senior academics in an academic custodian role (Campbell et al., 2019). A lack of incentives to share research data must be addressed to improve data sharing. An additional setback is the feasibility of data sharing because of the challenges associated with long-term data curation. If previously collected data is to be found by and shared with other researchers in the future, the custodian of the data must store it in a large repository. This repository may be at the research group level, university level, or ultimately, open to the public. Unfortunately, many researchers lack the time and resources to share their data in a public repository (Perrier et al., 2020). Regardless of the storage method, the responsible stewardship of digital data includes making the data available for additional research and ensuring that the data is appropriately stored.

The development and standardization of a set of UAV data collection guidelines would make UAV data, regardless of its original purpose, more usable and sharable across disciplines. To facilitate digital data sharing, an online data repository with a metadata tagging system is necessary. A UAV data repository would improve data transfer capabilities and provide a digital backup of data for data custodians. For contributors, it may introduce them to researchers with similar interests, growing their professional network. A metadata tagging system is a critical aspect of the repository, since it would allow data users to search for appropriate data, and provide critical details about its collection, spatial extent, and content. Overall, a repository and a metadata tagging system for UAV data, whether it be small-scale, for *Herschel Island – Qikiqtaruk Territorial Park* data, or large-scale, open to all UAV data collectors and users, would improve data-sharing.

The 2019 UAV data collected for and used in this research is stored in ScholarsPortal in the University of Calgary's open source data sharing repository, PRISM Dataverse, within the *Digitally Preserving Herschel Island – Qikiqtaruk Territorial Park, Yukon Territory* Dataverse. This data is searchable under several keywords, subject and by author. An alternative to the data curation strategy for the 2019 *Qikiqtaruk* UAV data would be the creation of a data sharing network where the Cultural Services Branch, Government of Yukon, would be the custodian of the data, and the IRC would determine how the data is used. A memorandum of understanding (MOU) is a non-binding agreement between two or more entities in which the intent and responsibilities of each party is outlined. An MOU could be used to formalize a new data curation partnership between the Cultural Services Branch, Government of Yukon, and the IRC.

7.6 Chapter Summary

This chapter discussed the compatibility of the two change detection methods in depth. Each method can be performed individually; however, they work best when used in tandem. This section was followed by a summary of the importance of preserving the heritage features within *Herschel Island – Qikiqtaruk Territorial Park*. The cultural significance of the archaeological sod houses and the cultural landscape to the Inuvialuit was stressed as a critical factor for preservation. Additionally, the value of the historic settlement at Pauline Cove was summarized concerning early exploration, the whaling industry, and the exertion of Canadian sovereignty in the Western Arctic. This section also described how this research addresses goals 4, 5, and 9 (goals on preserving cultural heritage) of the *Herschel Island – Qikiqtaruk Territorial Park Management Plan*. Section 7.4 outlined how the procedures developed in this research could build a heritage monitoring strategy for the park and how the procedures could be improved by incorporating advanced survey techniques. Also in this section is the suggestion of a risk matrix, based on the priorities of the Inuvialuit, Yukon Government officials, and the park management. This chapter was concluded with a brief discussion on the importance of academic "crowd sharing" and long-term data stewardship, both of which were vital parts in the success of the change detection component of this research.

8 CONCLUSION

Climate change is a wickedly complex problem that disproportionately impacts the Arctic, due to high sensitivity to surface air temperature (SAT) change, a concept called Arctic amplification. Arctic amplification results from a positive feedback loop due to sea ice loss and ice-albedo feedback (Serreze et al., 2009). Climate change processes are highly interconnected, with warming oceanic temperatures and a longer ice-free season resulting in increased thermoerosion of unlithified ice-rich coastlines. In addition, rising sea level and a reduction of ice covered sea, results in an increase in overland flooding and more frequent storm surge events.

Along the Yukon north coast, these processes are causing the destruction of heritage sites, including Inuvialuit and Thule archaeological sites and Euro-North American historic structures. As a result of traditional Inuvialuit coastal lifeways, most archaeological sites in this region are situated along the eroding ice-rich coastline, or in low-lying areas prone to flooding. Documenting and monitoring the condition of heritage sites is challenging in remote areas, including the Yukon North Slope. The timely documentation of at-risk heritage sites is prudent due to the aforementioned risk-factors.

Aerial photogrammetry is an efficient documentation strategy, however, traditional aerial platforms, such as airplanes, are costly, and flight time is limited. In recent years, unmanned aerial vehicle (UAV, i.e., drone) technology has replaced traditional air survey in many disciplines including the environmental sciences and in heritage management. UAV photogrammetry is lower-cost, more accessible, and offers the researcher more control over the data collection process. Heritage professionals have recognized the value of UAV imagery for visualizing large heritage sites, documenting excavations, performing archaeological reconnaissance, documenting heritage in remote or challenging to reach areas and for heritage monitoring. UAV imagery provides an unbiased record of a heritage site that can easily communicate the condition of a site and the surrounding landscape. When appropriately collected and processed, UAV data yields high-quality outputs, including highly accurate orthomosaics and 3D point clouds. These outputs can be used for visualization and change detection analysis.

Change detection analysis is a remote sensing technique that identifies differences in a subject through the multi-temporal observation of that subject. Photogrammetric outputs, including orthomosaics and point clouds can be used to detect change to landscapes and structures. Change detection analysis is a powerful research tool for land-use and land-cover (LULC) change studies, vegetation change studies, hazard management and impact assessments, climate change research, urban planning, civil engineering and heritage monitoring and management.

Digital data, specifically raw imagery, orthomosaics and point clouds, require proper archiving and curation, due to their large size. Digital, open source data repositories are becoming increasingly common, which facilitates data sharing. Data sharing is invaluable, because it fosters interdisciplinary research, and new research questions. The re-use of found data is also environmentally friendly, as it reduces travel requirements and lessens the impact that researchers have on the sensitive landscapes.

This research presents a case study that evaluates the suitability of UAV-derived imagery for change detection analysis and heritage monitoring at an Arctic heritage site. The site used is Simpson Point on *Qikiqtaruk* (also known as Herschel Island), an island off the Yukon North Slope. As discussed in Chapter 4, the cultural landscape and heritage features of Simpson Point are significant for many reasons. Firstly, the features represent 800 years of nearly continuous occupation by the Thule and their descendants, the Inuvialuit. As a result, the Inuvialuit have a strong attachment to the island. In addition, the island was occupied by Euro-North Americans, who built numerous structures. Rarely does a site have such a lengthy period of occupation and such a diverse array of heritage feature types. The features on Simpson Point include numerous historic structures, which are from the late 19th and early 20th century, and Inuvialuit sod houses, some of which are from the same period. The historic structures are associated with the whaling period, the fur trade, missionary activity, and the arrival of the NWMP (later the RCMP). Together, these activities resulted in the congregation of people and extensive inter-societal interaction between the Inuvialuit, Iñupiat, Dene, and Euro-North Americans. Long-lasting interaction and intermarriage with Euro-North Americans resulted in significant change to Inuvialuit culture. Towards the end of the whaling period, the Canadian Government exerted its presence in the northern Yukon by setting up a detachment at Simpson Point that would later become the district headquarters of the region. This was the first assertion of Canadian sovereignty in the Western Arctic. Therefore, the heritage features are representative of Inuvialuit history, Canadian maritime affairs, long-distance trade, and Canadian policing. Unfortunately, the low-relief of Simpson Point combined with increasing coastal erosion and overland flooding, is threatening these valuable cultural resources. Imminent damage to these resources prompted the research project that is the subject of this thesis.

In this study, UAV imagery from 2017 and 2019 was compared using two change detection techniques, Cloud-to-Cloud distance computation (C2C), and visual inspection analysis (VIA). These methods detected change to the heritage features and the landscape within two study areas on Simpson Point. C2C Distance is a tool within CloudCompare©, an open-source software program. The tool uses a nearest-neighbor type analysis to measure the distance between a point in the reference point cloud and that point in the compared point cloud. The methods selected were chosen because they are highly- compatible and low cost. VIA was used to verify the C2C results and identify the nature of each respective change. VIA was then performed again, for each 10 x 10 m square within the two study areas, to check for additional change. Using these methods, numerous changes were documented by the author. Several widespread patterns of change were observed, including increased vegetation around the historic buildings and throughout the spit, and increased standing water in low-lying areas in 2019. Additionally, there was significantly more driftwood in 2019 than in 2017. The causality of these widespread patterns of change were explored in Chapter 7. Changes to the historic buildings were also detected, including a natural shift in the RCMP dog kennel fence line, building restoration to the RCMP kennel and the raising of two buildings: the Northern Whaling and Trading Co. Customs Warehouse and Building 11. The change to Building 11 between 2017 and 2019 is of particular interest. The C2C method identified a 0.50 m change to the entire building. This difference was suspected to be due to a change in elevation. This was verified through personal communication with the heritage restoration crew as being the result of the building being lifted 0.45 m. This confirms the accuracy and the value of the C2C method.

The methods detected changes to shoreline morphology include sand deposition adjacent to the Northern Whaling and Trading Co. Customs Warehouse in Study Area 1 and coastal erosion in the vicinity of two at-risk Inuvialuit sod houses in Study Area 2. Another notable change between 2017 and 2019 was the widening and deepening of the pathways between the historic buildings and St. Patrick’s Anglican Mission House. This change was caught using VIA but was not detected by the C2C method, likely because it is subtle compared to other changes in the scene. Pathways are of interest because they are evidence of the impact that tourists, researchers, and other visitors have on the delicate landscape. Other changes detected using C2C, and VIA include park ranger activities, such as deck construction, firewood stacking, and outhouse facility relocation. Overall, the two change detection methods used were highly compatible, serving as checks for one another. While VIA could have been used alone, the C2C method was value-added since it enables the analyst to view all changes at once, identify areas of notable change and quantify the change.

The procedures developed in this research can be used towards the development of a heritage monitoring strategy for Simpson Point and can be applied to other areas on the island, like *Avadlek* Spit. The C2C and VIA methods can be used not only to document natural change to the landscape, but also to track changes resulting from restoration work, which adds value to the suggested monitoring strategy. Furthermore, these procedures can be employed for monitoring at other Arctic heritage sites. Minor modifications to the data collection strategy, such as improved geo-location, would further increase data quality and functionality. Implementing a risk matrix, which would identify heritage features at greatest risk, would be a beneficial addition to the monitoring strategy. The inclusion of a risk matrix could be used to prioritize archaeological excavation and heritage preservation efforts. Ranking and prioritizing the preservation of heritage is inherently complex, often requiring extensive consultation and collaboration amongst stakeholders. For *Qikiqtaruk – Herschel Island Territorial Park*, these stakeholders are the Inuvialuit and Yukon Government officials. The creation of set guidelines for UAV data collection on the island, would be beneficial because it would enable various personnel, including Yukon Government archaeologists, the Inuvialuit rangers, or other researchers, to collect the data while maintaining consistently high data quality.

Future heritage work planned for *Qikiqtaruk* depends on the easement of travel restrictions in place due to Covid-19. Should travel be possible in the summer of 2022, the intent is to collect UAV data of the same study areas, and of *Avadlek* Spit. Additional UAV data would be a beneficial addition for the monitoring strategy discussed at length in Chapter 7. The UAV data collected in 2022 also presents a unique scientific opportunity. Given how few visitors the island has seen since the onset of the pandemic, this is a chance to learn about the time required for landscape recovery and pathway reduction. It is hypothesized that the pathways will be smaller and there will be more vegetation growth, since it has not been trampled. In addition, the excavation originally planned as the subject of this thesis, is scheduled for 2022. The excavation of these sod houses will provide further information about the impact of flooding and beach encroachment.

The data used in this study also stresses the importance of academic data sharing and digital data curation. The onset of the Covid-19 pandemic and its impact on travel meant that the initial direction of this research, was no longer feasible. It is only because of found data, graciously shared by A. Cunliffe and colleagues, that change detection analysis was possible. The availability of this data not only facilitated new research questions but minimized the impact of the pandemic on the academic progress of the author. The importance of digital data curation cannot be emphasized enough, considering the raw data from A. Cunliffe was transferred entirely over the cloud. Set guidelines for UAV data collection in heritage, or across disciplines would also be beneficial for data sharing. The development of an online data repository for UAV data with a corresponding metadata tagging system is highly recommended, as this would increase data sharing capacity and encourage multi-disciplinary research collaborations. In addition, the re-purposing of found data is environmentally friendly and low-cost, compared to collecting original data.

The Digital Archaeology Research Group, led by Dr. Peter Dawson, has ensured that data collected by its members is digitally curated, archived, and available to the public. Data, including the 2019 UAV imagery and the 2018 TLS scans of the historic structures on *Qikiqtaruk*, is available on the Herschel Island – Qikiqtaruk Digital Preserve website (https://herschel.preserve.ucalgary.ca/) and the University of Calgary's open source data repository, PRISM Dataverse (Capture to Preserv, 2021). As such, this data is accessible for future research, whether that research relates to heritage management or other disciplines. This encourages further collaboration, while minimizing the physical impact that researchers have on *Qikiqtaruk's* delicate landscape. An alternative to the data curation strategy for the *Qikiqtaruk* UAV data would be the creation of a data sharing network that reflects the co-management agreement already in place for the territorial park. For example, the Cultural Services Branch, Government of Yukon, could act as the custodian of the data, which would make them responsible for the archiving of the imagery. The Inuvialuit Regional Corporation (IRC) would then determine who can use the data and how the data is used. A memorandum of understanding (MOU) could be used to formalize a new data curation partnership. This arrangement would be beneficial because it strengthens stakeholder partnerships and enables the IRC to be more directly involved in future research endeavors.

In summary, climate change processes, such as coastal erosion and overland flooding, are causing extensive damage to heritage sites on the Yukon North Slope and elsewhere in the Inuvialuit Settlement Region. This research emphasizes the applicability of repeat UAV photogrammetry for change detection and heritage monitoring purposes for *Qikiqtaruk* –

Herschel Island Territorial Park and other circumpolar heritage sites. Using the change detection methods applied in this research, C2C and VIA, it was possible to accurately detect, and document change to the heritage resources and to the cultural landscape. Using the procedures outlined in this document, the framework for a heritage monitoring strategy for *Qikiqtaruk – Herschel Island Territorial Park* has been developed and the importance of data sharing has been emphasized. The methods presented within this research are interdisciplinary, combining heritage management with the fields of geomatics engineering and remote sensing. This research addresses goals 4, 5, and 9 of the *Herschel Island – Qikiqtaruk Territorial Park Management Plan* by detecting and monitoring change to the archaeological features, historic structures, and the landscape, which aid in preservation efforts. Also emphasized is the importance of utilizing found data, data sharing and digital data curation. Lastly, future UAV data collection at Simpson Point and *Avadlek* Spit, along with the excavation work planned for Simpson Point, will contribute to knowledge of Inuvialuit culture and of the historic period on *Qikiqtaruk*.

9 REFERENCES

Abate, D. 2019. Documentation of paintings restoration through photogrammetry and change detection algorithms. Heritage Science 7(1): 1-19. https://doi.org/10.1186/s40494-019-0257-y

Aber, J. S., Marzolff, I., Ries, J. B., and ebrary, Inc. 2010. Small-format aerial photography principles, techniques, and geoscience applications. Elsevier.

Adhikari, R. S., Moselhi, O., and Bagchi, A. 2013. Image-based change detection for bridge inspection. In ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction (Vol. 30: 1-11). IAARC Publications. https://doi.org/10.22260/ISARC2013/0039

Afify, H. A. 2011. Evaluation of change detection techniques for monitoring land-cover changes: A case study in new Burg El-Arab area. Alexandria engineering journal 50(2): 187-195. https://doi.org/10.1016/j.aej.2011.06.001

Agapiou, A. 2020. Detecting looting activity through earth observation multi-temporal analysis over the archaeological site of Apamea (Syria) during 2011–2012. Journal of Computer Applications in Archaeology. http://doi.org/10.5334/jcaa.56

Ahmad, Y. 2006. The scope and definitions of heritage: from tangible to intangible. International Journal of Heritage Studies 12(3): 292-300. https://doi.org/10.1080/13527250600604639

Ahmad, Anuar, and Abd Manan Samad. 2010. Aerial Mapping Using High Resolution Digital Camera and Unmanned Aerial Vehicle for Geographical Information System. 6th International Colloquium on Signal Processing and Its Applications IEEE:1-6. https://doi.org/10.1109/CSPA.2010.5545303

Alawi, R.M., and Martin, A. 2015. An Assessment of the Accuracy of PPP in Remote Areas in Oman. FIG Working Week Sofia, Bulgaria, 17-21 May 2015.

Al-doski, J., Mansor, S. B., and Shafri, H. Z. M. 2013. Change detection process and techniques. Civil and Environmental Research 3(10).

Al-Rawabdeh, A., Moussa, A., Foroutan, M., El-Sheimy, N., and Habib, A. 2017. Time series UAV image-based point clouds for landslide progression evaluation applications. Sensors 17(10), 2378. https://doi.org/10.3390/s17102378

Alunik, I. 2003. A Trapper's Life in the 20th Century. In: Alunik, I., Kolausok, E.D., and Morrison, D., eds. Across Time and Tundra: The Inuvialuit of the Western Arctic. Raincoast Books. 145-159.

Alunik, I., Kolausok, E.D., and Morrison, D. 2003. Across Time and Tundra: The Inuvialuit of the Western Arctic. Raincoast Books.

American Society of Civil Engineers. 1996. Photogrammetric mapping. Technical Engineering and Design Guides as Adapted from the US Army Corps of Engineers, NO. 14. ASCE Press.

American Society of Photogrammetry. 1966. Manual of Photogrammetry. Falls Church, Va: American Society of Photogrammetry.

Andersen, O. B. and Piccioni, G. 2016. Recent Arctic Sea Level Variations from satellites. Science (3):76. https://doi.org/10.3389/fmars.2016.00076

Arnold, C.D. 1988. Vanishing Villages of the Past: Rescue Archaeology in the Mackenzie Delta. Northern Review (1).

Arnold, C.D. 2016. Development of Mackenzie Inuit Culture. In: Friesen, T.M., and Mason, O.K., eds. The Oxford Handbook of the Prehistoric Arctic. Oxford: Oxford University Press. 385-606.

Arnold, C.D., and Hart, E.J. 1992. Winter Houses of the Mackenzie Inuit. Bulletin (Society of the Study of Architecture in Canada).

Asner, G. P., Keller, M., Pereira Jr, R., and Zweede, J. C. 2002. Remote sensing of selective logging in Amazonia: Assessing limitations based on detailed field observations, Landsat ETM+, and textural analysis. Remote Sensing of Environment 80(3): 483-496. https://doi.org/10.1016/S0034-4257(01)00326-1

Ayele, G. T., Tebeje, A. K., Demissie, S. S., Belete, M. A., Jemberrie, M. A., Teshome, W. M., Mengistu, D.E., and Teshale, E. Z. 2018. Time series land cover mapping and change detection analysis using geographic information system and remote sensing, Northern Ethiopia. Air, Soil and Water Research 11: 1-18. https://doi.org/10.1177/1178622117751603

Bash, E. A., Moorman, B. J., and Gunther, A. 2018. Detecting short-term surface melt on an Arctic Glacier using UAV surveys. Remote Sensing 10(10): 1547. https://doi.org/10.3390/rs10101547

Barbier, B. A., Dziduch, I., Liebner, S., Ganzert, L., Lantuit, H., Pollard, W. and Wagner, D. 2012. Methane-cycling communities in a permafrost-affected soil on Herschel Island, Western Canadian Arctic: active layer profiling of mcrA and pmoA genes. FEMS microbiology ecology 82(2): 287-302. https://doi.org/10.1111/j.1574-6941.2012.01332.x

Barlindhaug, S., Holm-Olsen, I. M., and Tømmervik, H. 2007. Monitoring archaeological sites in a changing landscape–using multitemporal satellite remote sensing as an 'early warning' method for detecting regrowth processes. Archaeological Prospection, 14(4): 231-244. https://doi.org/10.1002/arp.307

Barnhart, K. R., Overeem, I., and Anderson, R.S. 2014. The effect of changing sea ice on the physical vulnerability of Arctic coasts. The Cryosphere 8(5): 1777–1799. https://doi.org/10.5194/tc-8-1777-2014

Barnhart, K. R., Miller, C. R., Overeem, I. and Kay, J. E. 2016. Mapping the future expansion of Arctic open water. Nature Climate Change 6(3): 280. https://doi.org/10.1038/nclimate2848

Berquist, S., Spence-Morrow, G., Gonzalez-Macqueen, F., Rizzuto, B., Álvarez, W. Y., Bautista, S., and Jennings, J. 2018. A new aerial photogrammetric survey method for recording inaccessible rock art. Digital Applications in Archaeology and Cultural Heritage 8: 46-56. https://doi.org/10.1016/j.daach.2018.03.001

Betts, M.W. 2008. Subsistence and culture in the Western Canadian Arctic: A multi-contextual approach. University of Ottawa Press.

Betts, M.W. 2009. Chronicling Siglit Identities: Economy, Practice and Ethnicity in the Western Canadian Arctic. Alaska Journal of Anthropology 7(20): 1-28.

Bettinger, P., Boston, K., Siry, J. P., and Grebner, D. L. 2017. Forest management and planning. Academic Press.

Bishop, B.P., Young, B.W., Huo, D., and Chi, Z. 2020. Spatial Analysis and Modelling in Geomorphology. In: Reference Module in Earth Systems ad Environmental Sciences. Elsevier.

Boak, E. H., and Turner, I. L. 2005. Shoreline definition and detection: a review. Journal of Coastal Research 21(4 (214)): 688-703. https://doi.org/10.2112/03-0071.1

Bockstoce, J. R. 2012. Whaling. In: Burn, C.R., eds. Herschel Island Qikiqtaryuk: A Natural and Cultural History of Yukon's Arctic Island. Calgary: University of Calgary Press. 158-168.

Bockstoce, J.R., Ingram, R., and Helene Dobrowolsky. 2012. Fur Traders. In: Burn, C.R., eds. Herschel Island Qikiqtaryuk: A Natural and Cultural History of Yukon's Arctic Island. Calgary: University of Calgary Press. 176-185.

Bogucka, E., and Osińska-Skotak, K. 2016. Use of cartography and remote sensing in heritage landscape change detection on the example of the Royal Castle gardens in Warsaw. Teledetekcja Środowiska 54(1): 33-49.

Bonsal, B. R. and Kochtubajda, B. 2009. An assessment of present and future climate in the Mackenzie Delta and the near-shore Beaufort Sea region of Canada. International Journal of Climatology: A Journal of the Royal Meteorological Society 29(12): 1780-1795. https://doi.org/10.1002/joc.1812

Booysen, R., Gloaguen, R., Lorenz, S., Zimmermann, R., and Nex, P.A.M. 2021. Geological remote sensing. In: Alderton, D and Elias, S.A., eds. Encyclopedia of Geology (Second Edition) Academic Press. 301-314.

Buonincontri, P., Maraso, A., and Ramkissoon, H. 2017. Visitor's Experience, Place Attachment and Sustainable Behaviour at Cultural Heritage Sites: A Conceptual Framework. Sustainability 9(1112): 1-19.

Burn, C.R. 2012. Physical Setting. Physical Setting. In: Burn, C.R., eds. Herschel Island Qikiqtaryuk: A Natural and Cultural History of Yukon's Arctic Island. Calgary: University of Calgary Press. 30-37.

Burn, C.R., Hoskin, M. and Hattendorf, J.B. 2012a. Introduction. In: Burn, C.R., eds. Herschel Island Qikiqtaryuk: A Natural and Cultural History of Yukon's Arctic Island. Calgary: University of Calgary Press. 1-28.

Burn, C.R., Lane, L., Roots, C., Fraser, T., Williams, B., Carmack, E., Zazula, G., Pollard, W.H., Couture, N. and Lantuit, H. 2012. Land and Water. In: Burn, C.R., eds. Herschel Island Qikiqtaryuk: A Natural and Cultural History of Yukon's Arctic Island. Calgary: University of Calgary Press. 30-72.

Burn, C.R., and Jenness, S.E. 2012. Scientists and Explorers. In: Burn, C.R., eds. Herschel Island Qikiqtaryuk: A Natural and Cultural History of Yukon's Arctic Island. Calgary: University of Calgary Press. 192-199.

Burn, C. R., and Kokelj, S. V. 2009. The environment and permafrost of the Mackenzie Delta area. Permafrost and Periglacial Processes 20(2): 83-105. https://doi.org/10.1002/ppp.655

Burn, C. R. and Zhang, Y. 2009. Permafrost and Climate Change at Herschel Island (Qikiqtaryuk), Yukon Territory, Canada. Journal of Geophysical Research: Earth Surface 114 (F2). https://doi.org/10.1029/2008JF001087

Burton, C., Mitchell, J. T., and Cutter, S. L. 2011. Evaluating post-Katrina recovery in Mississippi using repeat photography. Disasters 35(3): 488-509. https://doi.org/10.1111/j.1467-7717.2010.01227.x

Campana, S. 2017. Drones in archaeology. State-of-the-art and future perspectives. Archaeological Prospection 24(4): 275-296. https://doi.org/10.1002/arp.1569

Campbell, H. A., Micheli-Campbell, M. A., and Udyawer, V. 2019. Early career researchers embrace data sharing. Trends in Ecology and Evolution 34(2): 95-98. https://doi.org/10.1016/j.tree.2018.11.010

Capture 2 Preserv. 2021.Data Repository, Digitally Preserving Herschel Island – Qikiqtaruk Territorial Park, Yukon Territory (University of Calgary). PRISM Dataverse: University of Calgary's Data Repository. Retrieved from: https://dataverse.scholarsportal.info/dataverse/hershelisland, 9 February 2022.

CBC News. 2019. Protecting Tuktoyaktuk from coastal erosion could cost $50M, says mayor. Retrieved April 2020 from: https://www.cbc.ca/news/canada/north/coastal-erosion-tuktoyaktuk-needs-more-money-1.5095115

Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., Merrifield, M.A., Milne, G.A., Nerem, R.S., Nunn, P.D., Payne, A.J., et al. 2013. Sea Level Change. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge, UK and NY, USA: Cambridge University Press.

Civco, D. L., Hurd, J. D., Wilson, E. H., Song, M., and Zhang, Z. 2002. A comparison of land use and land cover change detection methods. In ASPRS-ACSM Annual Conference (Vol. 21).

Cloud Compare. 2015. Cloud-to-Cloud Distance. Retrieved from: https://www.cloudcompare.org/doc/wiki/index.php?title=Cloud-toCloud_Distance#:~:text=Whenpercent20nopercent20localpercent20modelpercent20is,surfacepercent20representedpercent20bypercent20thepercent20cloud on 13 April 2021.

Coppin, P. R., and Bauer, M. E. 1996. Digital change detection in forest ecosystems with remote sensing imagery. Remote Sensing Reviews, 13(3-4): 207-234.

Coppin, P., Jonckheere, I., Nackaerts, K., Muys, B., and Lambin, E. 2004. Review Article. Digital change detection methods in ecosystem monitoring: a review. International Journal of Remote Sensing 25(9): 1565-1596. https://doi.org/10.1080/0143116031000101675

Coppinger, James .2019. Autodesk ReCap: What is it, Really? Lifewire. Electronic document. Retrieved from: https://www.lifewire.com/autodesk-recap-485205, 19 April 2021.

Cunliffe, A. M., Tanski, G., Radosavljevic, B., Palmer, W.F., Sachs, T., Lantuit, H., Kerby, J.T., and Myers-Smith, I.H. 2019. Rapid retreat of permafrost coastline observed with aerial drone photogrammetry. The Cryosphere 13(5):1513–1528. https://doi.org/10.5194/tc-13-1513-2019

Danard, M., Munro, A. and Murty, T. 2003. Storm surge hazard in Canada. Natural Hazards 28(2-3): 407-434. https://doi.org/10.1023/A:1022990310410

Dawson, P. D., Levy, R. M., Oetelaar, G., Arnold, C., Lacroix, D., and Mackay, G. 2009 Documenting Mackenzie Inuit architecture using 3D laser scanning. Alaska Journal of Anthropology 7(2): 29-44.

Dawson, P. C., Bertulli, M. M., Levy, R., Tucker, C., Dick, L., and Cousins, P. L. 2013. Application of 3D laser scanning to the preservation of Fort Conger, a historic polar research base on northern Ellesmere Island, Arctic Canada. Arctic: 147-158.

Dawson, P., Robinson, C., Litchi, D., and O'Keefe, K. 2021a. Blubber House – Herschel Island – Laser Scanning -2018/19. Scholars Portal PRISM Dataverse, V1. https://doi.org/10.5683/SP3/3YFNK7

Dawson, P., Robinson, C., Litchi, D., and O'Keefe, K. 2021b. Bonehouse – Herschel Island – Laser Scanning -2018/19. Scholars Portal PRISM Dataverse, V1. https://doi.org/10.5683/SP3/BWJMLZ

Dawson, P., Robinson, C., Litchi, D., and O'Keefe, K. 2021c. Captain McKenna's Cabin Herschel Island – Laser Scanning -2018/19. Scholars Portal PRISM Dataverse, V1. https://doi.org/10.5683/SP2/JYGVFD

Dawson, P., Robinson, C., Litchi, D., and O'Keefe, K. 2021d. Community House – Herschel Island – Laser Scanning -2018/19. Scholars Portal Dataverse, V1. https://doi.org/10.5683/SP2/ABXP2B

Dawson, P. C., Brink, J., Farrokhi, A., Fengman, J., and Lichti, D. 2022. A Method for Detecting and Monitoring Changes to the Okotoks Erratic – "Big Rock" Provincial Historic Site. Journal of Cultural Heritage Management and Sustainable Development. Manuscript submitted for publication.

Department of Energy, Mines and Resources, Government of Canada [Air Photo]. 1:13,000. Photo A21921-152.6 Photo Agency National Airphoto Library.

Department of Public Works. 1971. Investigation of Storm September 13-16, 1970: Mackenzie Delta Region, Beaufort Sea. In: EP Branch (Ed.). Ontario: Government of Canada.

Dessler, A.E. 2016. Introduction to Modern Climate Change (Second edition) Cambridge: Cambridge University Press.

Domingues, C. M., Church, J. A., White, N. J., Gleckler, P. J., Wijffels, S. E., Barker, P. M., and Dunn, J. R. 2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. Nature 453(7198): 1090-1093. https://doi.org/10.1038/nature07080

Do, T. H., and Yoo, M. 2018. Visible light communication-based vehicle positioning using LED street light and rolling shutter CMOS sensors. Optics Communications 407:112-126. https://doi.org/10.1016/j.optcom.2017.09.022

Doong, D. J., Chuang, H. C., Shieh, C. L. and Hu, J. H. 2011. Quantity, distribution, and impacts of coastal driftwood triggered by a typhoon. Marine Pollution Bulletin 62(7): 1446-1454. https://doi.org/10.1016/j.marpolbul.2011.04.021

Dumond, D. E. 2016. Norton hunters and fisherfolk. In: Friesen, T.M., and Mason, O.K., eds. The Oxford Handbook of the Prehistoric Arctic. 395-415.

Dumas, J., Carmack, E. and Melling, H. 2004. Climate change impacts on the Beaufort shelf landfast ice. Cold Regions Science and Technology 42(1): 41–51. https://doi.org/10.1016/j.coldregions.2004.12.001

Dyke, L. 2000. Climate of the Mackenzie River valley. In: Dyke, L.D., and Brooks, G.R., eds. The Physical Environment of the Mackenzie Valley: A Baseline for the Assessment of Environmental Change. Chapter 2. Geological Survey of Canada, Bulletin 547:21-30.

Eckerstorfer, M., Bühler, Y., Frauenfelder, R., and Malnes, E. 2016. Remote sensing of snow avalanches: Recent advances, potential, and limitations. Cold Regions Science and Technology, 121:126-140. https://doi.org/10.1016/j.coldregions.2015.11.001

Eckerstorfer, M., and Malnes, E. 2015. Manual detection of snow avalanche debris using high resolution Radarsat-2 SAR images. Cold Regions Science and Technology, 120: 205-218. https://doi.org/10.1016/j.coldregions.2015.08.016

Eggertsson, O. 1994. Mackenzie River driftwood—A dendrochronological study. Arctic: 128-136.

EMLID. n.d.a. Precise Point Positioning (PPP). Retrieved from: https://docs.emlid.com/reachrs/tutorials/post-processing-workflow/ppp-introduction/, 20 September 2021.

EMLID. n.d.b. How PPK works. Retrieved from: https://docs.emlid.com/reach/tutorials/basics/ppk-introduction/, 20 September 2021.

Environment Canada. Herschel Island Station Results Historical Data. Retrieved from https://climate.weather.gc.ca/historical_data/search_historic_data_e.html, 3 January 2022.

ESRI. n.d.a. Change Detection in ArcGIS Pro. Retrieved from: https://pro.arcgis.com/en/pro app/latest/help/analysis/image-analyst/change-detection-in-arcgis-pro.htm, 13 April 2021.

ESRI. n.d.b. ArcGIS Pro 2.7: Georeference a raster to another raster automatically. Retrieved from: https://pro.arcgis.com/en/pro-app/latest/help/data/imagery/georeferencing-a-raster automatically-to-another-raster.htm, 29 April 2021.

ESRI. n.d.c. Point cloud scene layer. Retrieved from: https://pro.arcgis.com/en/pro app/latest/help/mapping/layer-properties/point-cloud-scene-layer-in-arcgis-pro.htm, 29 April 2021.

Farmer, J.R., Cronin, T.M., De Vernal, A., Dwyer, G.S., Keigwin, L.D. and Thunell, R.C. 2011. Western Arctic Ocean temperature variability during the last 8000 years. Geophysical Research Letters 38(24):1-6. https://doi.org/10.7916/D8GT5XXT

Fecher, B., Friesike, S., Hebing, M., Linek, S., and Sauermann, A. 2015a. A reputation economy: results from an empirical survey on academic data sharing. arXiv Preprint arXiv:1503.00481.

Fecher, B., Friesike, S., and Hebing, M. 2015b. What drives academic data sharing?. PloS One, 10(2): e0118053. https://doi.org/10.1371/journal.pone.0118053

Fernández-Hernandez, J., González-Aguilera, D., Rodríguez-Gonzálvez, P., and Mancera Taboada, J. 2015. Image-based modelling from unmanned aerial vehicle (UAV) photogrammetry: an effective, low-cost tool for archaeological applications. Archaeometry 57(1): 128-145. https://doi.org/10.1111/arcm.12078

Ford, J. D., Couture, N., Bell, T., and Clark, D. G. 2018. Climate change and Canada's north coast: Research trends, progress, and future directions. Environmental Reviews 26(1): 82 92.

Franklin, J., and Richardson, J. 1828. Narrative of a Second Expedition to the Shores of the Polar Sea, in the Years 1825, 1826, and 1827. Carey, Lea, and Carey.

Friesen, T. M. 1995. " Periphery" as centre: long-term patterns of intersocietal interaction on Herschel Island, Northern Yukon Territory. Doctoral Dissertation, McGill University, Montreal, Québec.

Friesen, T. M. 1999. Resource Structure, Scalar Stress, and the Development of Inuit Social Organization. World Archaeology 31(1): 21-37. https://doi.org/10.1080/00438243.1999.9980430

Friesen, T.M. 2004. Kitigaaryuit: A Portrait of the Mackenzie Inuit in the 1890s, Based on the Journals of Isaac O. Stringer. Arctic Anthropology 41(2): 222-237. https://doi.org/10.1353/arc.2011.0050

Friesen, T.M. 2012. Inuvialuit archaeology. In: Burn, C.R., eds. Herschel Island Qikiqtaryuk: A Natural and Cultural History of Yukon's Arctic Island. Calgary: University of Calgary Press.146-150.

Friesen, T.M. 2013. When Worlds Collide: Hunter- Gatherer World System Change in the 19th Century Canadian Arctic. The University of Arizona Press.

Friesen, T. M. 2015a. On the naming of Arctic archaeological traditions: The case for Paleo Inuit. Arctic 68(3) iii-iv. https://dx.doi.org/10/14430/arctic4504

Friesen, T. M. 2015b. The Arctic CHAR Project: Climate Change Impacts on the Inuvialuit Archaeological Record. Les Nouvelles de Larchéologie (141) : 31-37. https://doi.org/10.4000/nda.3098

Friesen, T.M. 2017. Arctic Cultural Heritage at Risk (Arctic CHAR): Climate Change Impacts on the Inuvialuit Archaeological Record. Progress Report on the 2017 Field Season. Obtained from: https://www.irc.inuvialuit.com/system/files/Arcticpercent20CHAR percent202017.pdf, 19 April 2021.

Friesen, T.M., and Arnold, C.D. 1995. Prehistoric Beluga Whale Hunting at Gupuk, Mackenzie Delta, Northwest Territories, Canada. In: McCartney, A.P. eds. Hunting the Largest Animals: Native Whaling in the Western Arctic and Subarctic.109-125.

Friesen, T. M., and Arnold, C. D. 2008. The timing of the Thule migration: New dates from the Western Canadian Arctic. American Antiquity: 73(3) 527-538. https://doi.org/10.1017/S000273160004850

Friesen, T.M., and Hunston, J. 1994. Washout – The Final Chapter: 1985-86 NOGAP Salvage Excavations on Herschel Island. In: Pilon, J.L. eds. Bridges Across Time: The NOGAP Archaeology Project. Canadian Archaeological Association Occasional Paper, No. 2: 39-60.

Friesen, T. M., and O'Rourke, M. J. 2019. Biogeographic barriers and coastal erosion: understanding the lack of interaction between the Eastern and Western Regions of the North American Arctic. World Archaeology 51(3): 484-501. https://doi.org/10.1080/00438243.2019.1705179

Gamon, J. A., Huemmrich, K. F., Stone, R. S., and Tweedie, C. E. 2013. Spatial and temporal variation in primary productivity (NDVI) of coastal Alaskan tundra: Decreased vegetation growth following earlier snowmelt. Remote sensing of environment 129: 144-153. https://doi.org/10.1016/j.rse.2012.10.030

Girardeau-Montaut, D., Roux, M., Marc, R., and Thibault, G. 2005. Change detection on points cloud data acquired with a ground laser scanner. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 36(part 3), W19.

Girardeau-Montaut, D. 2016. CloudCompare. France: EDF R&D Telecom ParisTech.

Government of the Northwest Territories (GNWT). 1991. Inuvialuit Pitqusiit: The Culture of the Inuvialuit.

Government of the Northwest Territories (GNWT). 2007. Living with the Land: A Manual for Documenting Cultural Landscapes in the Northwest Territories. Electronic document. Retrieved from: http://www.pwnhc.ca/programs/ downloads/Living_with_the_Land.pdf, 8 October 2020.

Graham, R., and Koh, A. 2002. Digital aerial survey: theory and practice. CRC Press.

Greer, S. 1991. The Trout Lake archaeological locality and the British Mountain problem. In: Cinq-Mars, J. and Pilon, J.-L., eds. N.O.G.A.P. Archaeology Project : an integrated archaeological research and management approach. Canadian Archaeological Association. Canadian Archaeological Association Occasional Paper No 1:15-31.

Green, D.R., and Gómez, C. 2020. From Radio- Controlled Model Aircraft to Drones. In: Green, D.R., Gregory, B.J., and Karachok, A.R., eds. Unmanned Aerial Remote Sensing: UAS for Environmental Applications. Boca Raton, Florida: CRC Press. 13-34.

Guilyardi, E., Lescarmontier, L., Matthews, R., Point, S. P., Rumjaun, A. B., Schlüpmann, J. and Wilgenbus, D. 2018. IPCC Special Report "Global Warming of 1.5° C": Summary.

Hain, R., Kähler, C. J., and Tropea, C. 2007. Comparison of CCD, CMOS and intensified cameras. Experiments in fluids 42(3): 403-411. https://doi.org/10.1007/s00348-006-0241-1

Hamilton, S., and Stephenson, J. 2016. Testing UAV (drone) aerial photography and photogrammetry for archaeology. Lakehead University, Tech. Rep.

Harwood, L.A., and Smith, T.G. 2002. Whales of the Inuvialuit Settlement Region in Canada's Western Arctic: An Overview and Outlook. Arctic: 77-93. https://doi.org/10.14430/arctic736

Heinemann, K. 2019. What is the Impact of a UNESCO Status Due to Visitors on the Environment of Herschel Island? A Survey of the Influence of Trampling on Vegetation. MA Thesis, University of Potsdam, Brandenburg, Germany.

Hexagon GPS. 2021. ERDAS IMAGINE Brochure. Retrieved October 2, 2021, from: https://bynder.hexagon.com/m/57a0703769b73f32/original/Hexagon_GSP_ERDAS_IMAGNE_Brochure.pdf?_ga=2.61650284.1594248360.1638811359-305096919.1638811359

Hill, A. C. 2019. Economical drone mapping for archaeology: Comparisons of efficiency and accuracy. Journal of Archaeological Science: Reports 24: 80-91. https://doi.org/10.1016/j.jasrep.2018.12.011

Hollesen, J., Matthiessen, H., Møller, A.B., Westergaard-Nielsen, A. and Elberling, B. 2016. Climate change and the loss of organic archaeological deposits in the Arctic. Scientific Reports 6(1): 1-9. https://doi.org/10.1038/srep28690

Hoque, M. A. and Pollard, W. H. 2016. Stability of permafrost dominated coastal cliffs in the Arctic. Polar Science 10(1): 79-88. https://doi.org/10.1016/j.polar.2015.10.004

Huber, D. 2011. The ASTM E57 file format for 3D imaging data exchange. In *Three-* Dimensional Imaging, Interaction, and Measurement (Vol. 7864, p. 78640A). International Society for Optics and Photonics. https://doi.org/10.1117/12.876555

Hudak, D.R. and Young, J.M.C. 2002. Storm climatology of the Southern Beaufort Sea. Atmosphere-Ocean 40(2): 145-158. https://doi.org/10.3137/ao.400205

Huss, M., and Hock, R. 2015. A new model for global glacier change and sea-level rise. Frontiers in Earth Science 3:54. https://doi.org/10.3389/feart.2015.00054

Hvidberg, M. 2019. The Use of Reality Capture Technologies to Mediate Relocation Impacts: A Case Study at the Perrenoud Homestead Provincial Historic Resource, Alberta. MA Thesis. University of Calgary, Calgary, Alberta. Retrieved from: https://prism.ucalgary.ca

Iceton, G. 2012. Missionaries. In: Burn, C.R., eds. Herschel Island Qikiqtaryuk: A Natural and Cultural History of Yukon's Arctic Island. Calgary: University of Calgary Press. 169-175.

Imaging Resource. n.d. Sony RX100 II specifications. Retrieved from: https://www.imaging resource.com/PRODS/sony-rx100-ii/sony-rx100-iiDAT.HTM, 12 April, 2022.

Inuvialuit Cultural Centre Digital Library. n.d. Inglangasuk, Lennie, “RCMP Building,” Inuvialuit Cultural Centre Digital Library, retrieved from: https://inuvialuitdigi tallibrary.ca/items/show/3398, 3 November 2020.

Inuvialuit Regional Corporation. 2011. Taimani Inuvialuit Timeline Visual Guide. Edited by Arnold, C., Hoe, Z., Simpson, B., and Stephenson, W.

Inuvialuit Regional Corporation. n.d.a. Culture. Retrieved from: https://www.irc.inuvialuit.com/ culture, 12 February 2020.

Inuvialuit Regional Corporation. n.d.b. Lands. Retrieved from: https://irc.inuvialuit.com/lands, 14 April 2021.

IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Firth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, RK Pachauri and L.A. Meyers (eds.)]. IPCC, Geneva, Switzerland.

Irrgang, A. M., Lantuit, H., Manson, G. K., Günther, F., Grosse, G., and Overduin, P. P. 2018. Variability in rates of coastal change along the Yukon coast, 1951 to 2015. Journal of Geophysical Research: Earth Surface 123(4): 779-800. https://doi.org/10.1002/2017JF004326

Irrgang, A.M., Lantuit, H., Gordon, R.R., Piskor, A., and Manson, G.K. 2019. Impacts of past and future coastal changes on the Yukon coast — threats for cultural sites, infrastructure, and travel routes. Arctic Science 5(2): 107–126. https://doi.org/10.1139/as-2017-0041

Jenness, D. 1964. Eskimo Administration II: Canada. Arctic Institute of North America, Technical Paper No. 14, Montreal.

Jensen, A. M. 2016. Archaeology of the Late Western Thule/Iñupiat in North Alaska (AD 1300–1750). In: Friesen, T.M., and Mason, O.K., eds. The Oxford Handbook of the Prehistoric Arctic. 513-536.

Karl, T. R. and Trenberth, K. E. 2003. Modern global climate change. Science 302(5651):1719-1723. https://doi.org/10.1139/as-2017-0041

Keeping, J. 1984. The Inuvialuit Final Agreement. Canadian Institute of Resources Law.

Kell, P. E. 2013. Protecting Historical Heritage: The Commemorative Integrity Evaluation Program at Parks Canada's National Historic Sites. In The George Wright Forum 30(3): 280-286. George Wright Society.

Kerfoot, D. E. 1972. Thermal contraction cracks in an arctic tundra environment. Arctic:142-150.

Kindle, E. M. 1921. Mackenzie River driftwood. Geographical Review 11(1): 50-53.

Klett, M. 2011. Repeat photography in landscape research. The Sage Handbook of Visual Research Methods:114-131.

Klinkenberg, B. 2009. History of Photogrammetry. Geography 373: Remote Sensing Class Notes. Electronic document retrieved from: https://ibis.geog.ubc.ca/courses/geob373/lectures/Handouts/History_of_Photogrammetry.pd, 30 September 2021.

Kokelj, S. V., Lantz, T. C., Solomon, S., Pisaric, M. F., Keith, D., Morse, P., Thienpont, J.R., Smol, J.P., and Esagok, D. 2012. Using multiple sources of knowledge to investigate northern environmental change: regional ecological impacts of a storm surge in the outer Mackenzie Delta, NWT. Arctic: 257-272. https://doi.org/10.14430/arctic4214

Komar, D. 2020. The Court of Better Fiction: Three Trials, Two Executions, and Arctic Sovereignty. Dundurn Press.

Kowalik, Z. 1984. Storm Surges in the Beaufort and Chukchi Seas. Journal of Geophysical Research 89(C6): 10570.

Kramer, N. and Wohl, E. 2015. Driftcretions: The legacy impacts of driftwood on shoreline morphology. Geophysical Research Letters 42(14): 5855–5864. https://doi.org/10.1002/2015GL064441

Kramer, N., Wohl, E., Hess-Homeier, B., and Leisz, S. 2017. The pulse of driftwood export from a very large forested river basin over multiple time scales, Slave River, Canada. Water Resources Research 53(3): 1928-1947. https://doi.org/10.1002/2016WR019260

Kraus, K. 2011. Photogrammetry: geometry from images and laser scans. Walter de Gruyter.

Krauß, T., and Tian, J. 2020. Automatic change detection from high-resolution satellite imagery. Remote Sensing for Archaeology and Cultural Landscapes: 47-58. Springer, Cham.

Krech, S. 1989. A Victorian Earl in the Arctic: The Travels and Collections of the Fifth Earl of Lonsdale 1888-89. University of Washington Press, Seattle.

Lamoureux, S., Forbes, D. L., Bell, T., Manson, G. K., Rudy, A. C. A., Lalonde, J., Brown, M., Smith, I.R., James, T.S., Couture, N.J., and Whalen, D.J.R. 2015. The impact of climate change on infrastructure in the western and central Canadian Arctic. From Science to Policy in the Western and Central Canadian Arctic: 301.

Lantuit, H. and Pollard, W. 2008. Fifty years of coastal erosion and retrogressive thaw slump activity on Herschel Island, Southern Beaufort Sea, Yukon Territory, Canada. Geomorphology 95(1-2): 84-102. https://doi.org/10.1016/j.geomorph.2006.07.040

Lantz, T. C. and Kokelj, S.V. 2008. Increasing rates of retrogressive thaw slump activity in the Mackenzie Delta region, N.W.T., Canada. Geophysical Research Letters 35(6): L06502. https://doi.org/10.1029/2007GL032433

Lapka, S. 2013. Oceanic storm surges in the outer Mackenzie Delta, NWT Canada: Remote Sensing of tundra disturbance and restoration from saline intrusion. Unpublished Master's Thesis. University of Calgary, Calgary, Alberta. https://doi.org/10.11575/PRISM/27163

Lasaponara, R., Murgante, B., Elfadaly, A., Qelichi, M. M., Shahraki, S. Z., Wafa, O., and Attia, W. 2017. Spatial open data for monitoring risks and preserving archaeological areas and landscape: Case studies at Kom el Shoqafa, Egypt and Shush, Iran. Sustainability 9(4):572. https://doi.org/10.3390/su9040572

LeBlanc, R.J. 1986. Report of field activities – NOGAP 1985: Northern Yukon-Western Mackenzie Delta: Permits 85-3ASR (Yukon); 85-584 (N.W.T.); Parks Canada (85-49). Canadian Museum of History Archives (Ms. 2632, V.1).

Leo-Paul, D., Meis-Mason, A., and Anderson, R. B. 2008. Oil and gas and the Inuvialuit people of the Western Arctic. Journal of Enterprising Communities 2(2): 151. https://doi.org/10.1108/17506200810879970

Lercari, N. 2019. Monitoring earthen archaeological heritage using multi-temporal terrestrial laser scanning and surface change detection. Journal of Cultural Heritage 39:152-165. https://doi.org/10.1016/j.culher.2019.04.005

Levy, R. M., Dawson, P. C., and Arnold, C. 2004. Reconstructing Traditional Inuit house Forms Using Three-dimensional Interactive Computer Modeling. Visual Studies 19(1): 26-36. https://doi.org/10.1080/1472586042000204825

Lewkowicz, A. G. 1990. Morphology, frequency, and magnitude of active-layer detachment slides, Fosheim Peninsula, Ellesmere Island, NWT. In Proceedings of the 5th Canadian Permafrost Conference 54: 111-118.

Lillesand, T. M., Kiefer, R. W., and Chipman, J. W. 2008. Digital Image Processing. In Remote sensing and image interpretation 6th Ed. John Wiley and Sons. 482-625.

Lim, M., Whalen, D., Mann, P., Fraser, P., Berry, H. B., Irish, C., and Woodward, J. 2020. Effective monitoring of permafrost coast erosion: Wide-scale storm impacts on outer islands in the Mackenzie Delta area. Frontiers in Earth Science: 454. https://doi.org/10.3389/feart.2020.561322

Linder, W. 2006. Digital Photogrammetry: A Practical Course, 2nd Ed. Springer Science and Business Media.

Lowe, R. 1984. Uummarmiut uqalungiha mumikhitchiȓutingit: basic Uummarmiut Eskimo dictionary. Committee for Original Peoples Entitlement.

Lu, D., Mausel, P., Brondizio, E., and Moran, E. 2004. Change detection techniques. International Journal of Remote Sensing 25(12): 2365-2401. https://doi.org/10.1080/0143116031000139863

Lucas, G. 2001. Destruction and the rhetoric of excavation. Norwegian archaeological review, 34(1): 35-46. https://doi.org/10.1080/00293650119347

Ludwig, D. 2001. The era of management is over. Ecosystems 4(8): 758-764. https://doi.org/10.1007/s10021-001-0044-x

Lunardini, V. J. 1996. Climatic warming and the degradation of warm permafrost. Permafrost and Periglacial Processes 7(4): 311-320.

Lyons, N. 2009. Inuvialuit Rising: The Evolution of Inuvialuit Identity in the Modern Era. Alaska Journal of Anthropology 7(2): 63-79.

Marín-Buzón, C., Pérez-Romero, A., López-Castro, J. L., Ben Jerbania, I., and Manzano-Agugliaro, F. 2021. Photogrammetry as a new scientific tool in archaeology: Worldwide research trends. Sustainability, 13(9): 5319. https://doi.org/10.3390/su13095319

Macciotta, R., and Hendry, M. T. 2021. Remote Sensing Applications for Landslide Monitoring and Investigation in Western Canada. Remote Sensing, 13(3): 366. 1-23. https://doi.org/10.3390/rs13030366

Macleod, K., and Tétreault, P. 2014. NRCan Precise Point Positioning (PPP) Service. Canadian Geodetic Survey (CGS) Surveyor General Branch. Civil GPS Service Interface Committee. Presentation, 8 September 2014. Tampa, Florida.

MacNeish, R.S. 1954. Field Notes 1954. Canadian Museum of History Archives (Ms. 861, V.2.).

MacNeish, R.S. 1956a. Archaeological Reconnaissance of the Delta of the Mackenzie River and Yukon Coast. Annual Report of the National Museum of Canada, 46-81.

MacNeish, R.S. 1956b. The Engigstciak Site on the Yukon Arctic Coast. Anthropological Papers of the University of Alaska 4(2).

MacRae, G., and Nielsen, S. 2012. Park History. In: Burn, C.R. eds., Herschel Island Qikiqtaryuk: A Natural and Cultural History of Yukon's Arctic Island, ed Burn, C.R. University of Calgary Press, Calgary. 210-215.

Manajitprasert, S., Tripathi, N. K., and Arunplod, S. 2019. Three-dimensional (3D) modeling of cultural heritage site using UAV imagery: A case study of the pagodas in Wat Maha That, Thailand. Applied Sciences 9(18): 3640.

Manson, G. K. and Solomon, S. M. 2007. Past and future forcing of Beaufort Sea coastal change. Atmosphere-Ocean 45(2):107-122. https://doi.org/10.3137/ao.450204

Mason, O.T. 1890. The Ulu, or Women's Knife, of the Eskimos. Report of the United States National Museum for the Year Ending the thirtieth of June 1890.

Mason, O. K. 2016a. From the Norton culture to the Ipiutak cult in northwest Alaska. In: Friesen, T.M., and Mason, O.K., eds. The Oxford Handbook of the Prehistoric Arctic. 443-67.

Mason, O. K. 2016b. Thule Origins in the Old Bering Sea Culture: The Interrelationship of Punuk and Birnirk Cultures. In: Friesen, T.M., and Mason, O.K., eds. The Oxford Handbook of the Prehistoric Arctic. 489-512.

Mathiassen, T. 1927. Archaeology of the Central Eskimos. Report of the Fifth Thule Expedition 1921-24: 4.

McCullough, K. M. 1989. Ruin Islanders: Thule Culture Pioneers in the Eastern High Arctic. Ottawa, University of Ottawa Press.

McGhee, R. 1974. Beluga Hunters: An Archaeological Reconstruction of the History and Culture of the Mackenzie Delta Kittegaryumiut. Toronto, University of Toronto Press.

McGhee, R. 1976. Western Alaskan Influences in Mackenzie Eskimo Culture. In: Hall, E. Jr., eds. Contributions to Anthropology: The Interior Peoples of Northern Alaska, Archaeological Survey of Canada Mercury Series Paper 49, National Museum of Man, Ottawa. 177-192.

McGlone, J. C., Mikhail, E. M., Bethel, J. S., Mullen, R., and American Society for Photogrammetry Remote Sensing. 2004. Manual of photogrammetry. American Society for Photogrammetry and Remote Sensing.

McGuire, A. D., Anderson, L. G., Christensen, T. R., Dallimore, S., Guo, L., Hayes, D. J. and Roulet, N. 2009. Sensitivity of the carbon cycle in the Arctic to climate change. Ecological Monographs 79(4): 523-555.

McKay, N. P., Overpeck, J. T. and Otto-Bliesner, B. L. 2011. The role of ocean thermal expansion in Last Interglacial sea-level rise. Geophysical Research Letters 38(14). https://dx.doi.org/10.1029/2011GL048280

Meinen, B. U., and Robinson, D. T. 2020. Mapping erosion and deposition in an agricultural landscape: Optimization of UAV image acquisition schemes for SfM-MVS. Remote Sensing of Environment, 239, 111666. https://doi.org/10.1016/j.rse.2020.111666

Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L. T., Lamarque, J.-F., et al. 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change 109(1): 213–241. https://doi.org/10.1007/s10584-011-0156-z

Morrison, D. 1990. Report on the 1990 NOGAP field season archaeological investigations at Whitefish Station (NfVc-1), Yukon Arctic Coast. Canadian Museum of History Archives (Ms.3333, V.1).

Morrison, D. 1997. An Ethnohistory of the Inuvialuit from Earliest Times to 1902. Revista de Arqueologia Americana. 29-54.

Morrison, D. 1999. The earliest Thule migration. Canadian Journal of Archaeology/Journal Canadien d'Archéologie (1999):139-156.

Morrison, D. 2000. Inuvialuit Fishing and the Gutchiak Site. Arctic Anthropology 37(1): 1-42.

Morrison, D. 2003a. Ingilraqpaaluk. In: Alunik, I., Kolausok, E.D., and Morrison, D., eds. Across Time and Tundra: The Inuvialuit of the Western Arctic. Raincoast Books. 1-47.

Morrison, D. 2003b. The Arrival of Strangers, 1789-1889. In: Alunik, I., Kolausok, E.D., and Morrison, D., eds. Across Time and Tundra: The Inuvialuit of the Western Arctic. Raincoast Books, 55-77.

Morrison, D. 2003c. The Winds of Change Blow Hard: The Whaling Era, 1890-1910. In: Alunik, I., Kolausok, E.D., and Morrison, D., eds. Across Time and Tundra: The Inuvialuit of the Western Arctic. Raincoast Books, 79-111.

Morss, R. E., Lazrus, H., and Demuth, J. L. (2021). The "inter" within interdisciplinary research: Strategies for building integration across fields. Risk Analysis 41(7): 1152-1161. https://doi.org/10.1111/risa.13246

Mouat, D. A., Mahin, G. G., and Lancaster, J. 1993. Remote sensing techniques in the analysis of change detection. Geocarto International 8(2): 39-50.

Myers-Smith, I. H., Hik, D. S., Kennedy, C., Cooley, D., Johnstone, J. F., Kenney, A. J., and Krebs, C. J. 2011a. Expansion of canopy-forming willows over the twentieth century on Herschel Island, Yukon Territory, Canada. Ambio 40(6): 610-623. https://doi.org/10.1007/s13280-011-0168-y

Myers-Smith, I. H., Forbes, B. C., Wilmking, M., Hallinger, M., Lantz, T., Blok, D., Tape, K.D., Marcias-Fauria, M., Sass-Klaassen, U., Lévesque, E. and Boudreau, S. 2011b. Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities. Environmental Research Letters 6(4): 045509. https://doi.org/10.1088/1748-9326/6/4/045509

Myers-Smith, I. H., Kerby, J. T., Phoenix, G. K., Bjerke, J. W., Epstein, H. E., Assmann, J. J., John, C., Andreu-Hayles, L., Angers-Blondin, S., Beck, P.S. and Berner, L.T. 2020. Complexity revealed in the greening of the Arctic. Nature Climate Change 10(2): 106-117. https://doi.org/10.1038/s41558-019-0688-1

Myhre, G., Shindell, D., Bréon, F. M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J-F., Lee, D., Mendoza, T., Nakajima, A., et al. 2013. Anthropogenic and natural radiative forcing. In: Stocker, T., Qin, D., Plattner, GK, Tignor, M., Allen, S., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.(eds) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Climate Change, 505.

Murison, M. 2020. Lidar vs. Photogrammetry for Aerial Surveying: A comparative guide to help you select your surveying sensors. Blog Post. Retrieved from: https://enterprise-insights.dji.com/blog/lidar-vs-photogrammetry, 20 October 2021

Nagy, M. I. 1988. Caribou exploitation at the Trail River site (northern Yukon) (Doctoral dissertation, Simon Fraser University, Burnaby, British Columbia.

Nagy, M.I. 1994. Yukon North Slope Inuvialuit Oral History (No. 1). Yukon Tourism, Heritage Branch.

Nagy, M.I. 2012. Inuvialuit Ancestors. In: Burn, C.R. eds., Herschel Island Qikiqtaryuk: A Natural and Cultural History of Yukon's Arctic Island, ed Burn, C.R. University of Calgary Press, Calgary. 153-157.

National Research Council. 2001. Climate, climate forcings, climate sensitivity and transient climate change. In: Climate change science: An analysis of some key questions. Washington, DC: The National Academies Press. 6-7. https://doi.org/10.17226/10139

National Snow and Ice Data Center. 2020. Thermodynamics: Albedo. Retrieved from: https://nsidc.org/cryosphere/seaice/processes/albedo.html#:~:text=Sea%20ice%20has%20a%20much,from%20approximately%200.5%20to%200.7, 13 April, 2022.

National Trust for Canada. n.d. Hershel Island (Qikiqtaruk), Yukon Territory. Online resource retrieved from: https://archive.nationaltrustcanada.ca/issues-campaigns/top-ten endangered/explore-past-listings/territories/herschel-island, 12 December 2021.

Neufeld, D. 2012. Police. In: Burn, C.R. eds., Herschel Island Qikiqtaryuk: A Natural and Cultural History of Yukon's Arctic Island, ed Burn, C.R. University of Calgary Press, Calgary. 186-191.

Nichols, T., Berkes, F., Jolly, D., Snow, N.B., and The Community of Sachs Harbour (NWT.).2004. Climate Change and Sea Ice: Local Observations from the Canadian Western Arctic. Arctic: 57(1). https://doi.org/10.14430/arctic484

Nikolakopoulos, K. G., Soura, K., Koukouvelas, I. K., and Argyropoulos, N. G. 2017. UAV vs. classical aerial photogrammetry for archaeological studies. Journal of Archaeological Science: Reports 14: 758-773. https://doi.org/10.1016/j.jasrep.2016.09.004

Northwest Territories (N.W.T.) Government. 1991. Inuvialuit Pitqusiit: The Culture of the Inuvialuit. Northwest Territories Education, Yellowknife.

Nuligak, M. 1966. I, Nuligak: Edited and Translated from the Eskimo by Maurice Metayer; Illustrated by Ekootak. Peter Martin Associates.

Obu, J., Lantuit, H., Grosse, G., Günther, F., Sachs, T., Helm, V. and Fritz, M. 2017. Coastal erosion and mass wasting along the Canadian Beaufort Sea based on annual airborne LiDAR elevation data. Geomorphology 293: 331-346. https://doi.org/10.1016/j.geomorph.2016.02.014

O'Connor, J., Smith, M. J., and James, M. R. 2017. Cameras and settings for aerial surveys in the geosciences: Optimising image data. Progress in Physical Geography 41(3): 325-344. https://doi.org/10.1177/0309133317703092

Olynyk, D. 2012. Buildings. In: Burn, C.R., eds. Herschel Island Qikiqtaryuk: A Natural and Cultural History of Yukon's Arctic Island. Calgary: University of Calgary Press. 202-209.

O'Rourke, M. J. E. 2017. Archaeological Site Vulnerability Modelling: The Influence of High Impact Storm Events on Models of Shoreline Erosion in the Western Canadian Arctic. Open Archaeology 3(1): 1-16. https://doi.org/10.1515/opar-2017-0001

Overeem, I., Anderson, R.S., Wobus, C.W., Clow, G.D., Urban, FE and Matell, N. 2011. Sea ice loss enhances wave action at the Arctic coast. Geophysical Research Letters 38(17). https://doi.org/10.1029/2011GL048681

Overland, J. E., Wood, K.R. and Wang, M. 2011. Warm Arctic—cold continents: climate impacts of the newly open Arctic Sea. Polar Research 30(1): 15787. https://doi.org/10.3402/polar.v30i0.15787

Panavision. 2015. Sensor Size and Field of View. Electronic document retrieved from: https://www.panavision.com/sites/default/files/docs/documentLibrary/2percent20Sensorpercent20Sizepercent20FOVpercent20(2).pdf, 16 October 2021.

Parks Canada. n.d. An Approach to Aboriginal Cultural Landscapes. Online document, retrieved from: http://www.pc.gc.ca/leg/docs/r/pca-acl/ sec4/index_e.asp, 13 April 2021.

Parks Canada. 2011. A guide to the landscape of the Firth River Valley: Ivvavik National Park. PDF document, retrieved from: http://parkscanadahistory.com/geology/firth-river-valley.pdf, 13 April 2021

Payne, D. P., and Kiser, J. D. 2003. Aerial photography and image interpretation, 2nd edition. John Wiley and Sons.

Pearce, T., Ford, J. D., Duerden, F., Smit, B., Andrachuk, M., Berrang-Ford, L., and Smith, T. 2011. Advancing adaptation planning for climate change in the Inuvialuit Settlement Region (ISR): a review and critique. Regional Environmental Change 11(1): 1-17. https://doi.org/10.1007/s10113-010-0126-4

Pennanen, K.A. 2019. The Application of Terrestrial Laser Scanning for the Documentation and Monitoring of a Threatened Buffalo Jump Heritage Site in South-central Alberta. Master's Thesis. University of Calgary, Calgary, Alberta. Retrieved from: https://prism.ucalgary.ca/ bitstream/handle/1880/111035/ucalgary_2019 pennanen_kelsey.pdf?sequence=2&isAllowed=y, 21 May 2021.

Pepe, M., Fregonese, L. and Crocetto, N. 2022. Use of SfM-MVS approach to nadir and oblique images generated through aerial cameras to build 2.5D map and 3D models in urban areas. Geocarto International 37(1): 120-141. https://doi.org/10.1080/10106049.2019.1700558

Perrier, L., Blondal, E., and MacDonald, H. 2020. The views, perspectives, and experiences of academic researchers with data sharing and reuse: A meta-synthesis. PloS One 15(2): e0229182.
https://doi.org/10.1371/journal.pone.0229182

Phares, B. M., Rolander, D. D., Graybeal, B. A., and Washer, G. A. 2001. Reliability of visual bridge inspection. Public Roads, 64(5): 22-29.

Pix4D. n.d.a Getting Started: Image Acquisition. Retrieved from: https://support.pix4d.com/hc/en-us/articles/115002471546-Image-acquisition, 17 October 2021.

Pix4D. n.d.b. Ground Sampling Distance (GSD) in Photogrammetry. Retrieved from https://support.pix4d.com/hc/en-us/articles/202559809-Ground-sampling-distance-GSD-in-photogrammetry, 28 May 2021.

Pix4D. n.d.c. What is the relative and absolute accuracy of drone mapping. Retrieved from https://support.pix4d.com/hc/en-us/articles/202558889-What-is-the-relative-and-absolute-accuracy-of-drone-mapping, 28 May 2021.

Pix4D. n.d.d. Step 1. Before Starting a Project: Getting GCPs on the field or through other sources. Retrieved from: https://support.pix4d.com/hc/en-us/articles/202557489-Step-1-Before-Starting-a-Project-4-Getting-GCPs-on-the-field-or-through-other-sources-optional-butrecommended, 19 October 2021.

Pix4D. n.d.e. What is… (a densified point cloud? An orthomosaic? Etc.). Retrieved from: https://support.pix4d.com/hc/en-us/articles/206455126-What-is-a-densified-point-cloud-an-orthomosaic-etc#label7, 1 October 2021.

Pix4D. 2019. Ground Control Points: Why Are They Important? Retrieved from: https://www.pix4d.com/blog/why-ground-control-points-important, 20 September 2021.

Pix4D. 2021. Pix4Dmapper photogrammetry software. Retrieved from: www.pix4d.com/product/pix4dmapper-photogrammetry-software, 19 April 2020.

Pollard, W.H., Coulture, N. and H. Lantuit. 2012. Coastal Environment. In: Burn, C.R. eds. Herschel Island Qikiqtaruyk: A Natural and Cultural History of Yukon's Arctic Island, University of Calgary Press, Calgary, AB. 72-77.

Radosavljevic, B, Lantuit, H., Pollard, W., Overduin, P., Couture, N., Sachs, T., Helm, V. and Fritz, M. 2015. Erosion and Flooding—Threats to Coastal Infrastructure in the Arctic: A Case Study from Herschel Island, Yukon Territory, Canada. Estuaries and Coasts 39(4): 900–915.
https://doi.org/10.1007/s12237-015-0046-0

Ramalhinho, A. R., and Macedo, M. F. 2019. Cultural heritage risk analysis models: An overview. International Journal of Conservation Science 10(1): 39-58.

Reeder-Myers, L. A. 2015. Cultural heritage at risk in the twenty-first century: A vulnerability assessment of coastal archaeological sites in the United States. The Journal of Island and Coastal Archaeology 10(3): 436-445. https://doi.org/10.1080/15564894.2015.1008074

Reeves, D. M. 1936. Aerial photography and archaeology. American Antiquity 2(2):102-107.

Reimnitz, E. and Maurer, D.K. 1979. Effects of Storm Surges on the Beaufort Sea Coast, Northern Alaska. Arctic 32(4).

Reimnitz, E., Barnes, P. W., and Harper, J. R. 1990. A review of beach nourishment from ice transport of shoreface materials, Beaufort Sea, Alaska. Journal of Coastal Research: 439-469.

Riedlinger, D. 2001. Chapter Four: Inuvialuit Knowledge of Climate Change. Community-Based Assessments of Change: Contributions of Inuvialuit Knowledge to Understanding Climate Change in the Canadian Arctic. MSc thesis, University of Manitoba, Winnipeg, Manitoba. 51-86.

Rinaudo, F., Chiabrando, F., Lingua, A., and Spanò, A. 2012. Archaeological site monitoring: UAV photogrammetry can be an answer. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 39(B5): 583-588.

Rittel, H. W. and Webber, M. M. 1973. Dilemmas in a general theory of planning. Policy Sciences 4(2) : 155-169.

Saleri, R., Cappellini, V., Nony, N., De Luca, L., Pierrot-Deseilligny, M., Bardiere, E., & Campi, M. 2013. UAV photogrammetry for archaeological survey: The Theaters area of Pompeii. In: 2013 Digital heritage International Congress (DigitalHeritage) IEEE (2) 497-502. https://doi:10.1109/DigitalHeritage.2013.6744818

Savoie, D. 1970. Amerindians of the Canadian Northwest in the 19th Century, as seen by Emile Petitot. Volume 1: The Tchiglit Eskimos. Department of Indian and Northern Affairs, Ottawa.

Saxberg, N. J. 1993. Citizens of Canada and of the empire: The archaeology and history of an arctic mission. MA Thesis, University of Toronto, Toronto, Ontario.

Schenk, T. 2005. Introduction to photogrammetry. The Ohio State University, Columbus, 106.

SenseFly. n.d. Camera Collection: A professional sensor for every application. PDF document, Retrieved from: https://www.sensefly.com/app/uploads/2021/02/camera-collection-2022 digital.pdf, 12 April 2022.

Serreze, M. C., Barrett, A.P., Stroeve, J.C., Kindig, D.N. and Holland, M.M. 2009. The emergence of surface-based Arctic amplification. The Cryosphere 3(1): 11-19. https://doi.org/10.5194/tc-3-11-2009

Shaw J., R.B. Taylor, D.L. Forbes, S. Solomon, and M.H. Ruz. 1998. Sensitivity of the coasts of Canada to sea-level rise. Ottawa: Geological Survey of Canada.

Shine, K. P. 2010. Radiative forcing and climate change. Encyclopedia of Aerospace Engineering.

Short, N., Brisco, B., Couture, N., Pollard, W., Murnaghan, K. and Budkewitsch, P. 2011. A comparison of TerraSAR-X, RADARSAT-2 and ALOS-PALSAR interferometry for monitoring permafrost environments, case study from Herschel Island, Canada. Remote Sensing of Environment 115(12): 3491-3506. https://doi.org/10.1016/j.rse.2011.08.012

Sima, A., and Kay, S. 2007. Optimizing the use of digital airborne images for 2.5 D visualizations. EARSeL eProceedings, 6(2):58.

Singh, A. 1989. Review article digital change detection techniques using remotely sensed data. International Journal of Remote Sensing 10(6): 989-1003.

Slater, J., and Brown, R. 2000. Changing landscapes: monitoring environmentally sensitive areas using satellite imagery. International Journal of Remote Sensing 21(13-14): 2753-2767. https://doi.org/10.1080/014311600050110278

Stone, T. A., and Lefebvre, P. 1998. Using multi-temporal satellite data to evaluate selective logging in Para, Brazil. International Journal of Remote Sensing 19(13): 2517-2526. https://doi.org/10.1080/014311698214604

Solomon Steven M. 2005. Spatial and temporal variability of shoreline change in the Beaufort Mackenzie region, Northwest Territories, Canada. Geo-Marine Letters 25: 127-137. https://doi.org/10.1007/s00367-004-0194-x

Smith, T. 2007. Repeat photography as a method in visual anthropology. Visual Anthropology, 20(2-3), 179-200.

Snow, Gonlin, N., and Siegel, P. E. 2019. The Archaeology of Native North America. Milton Park, Abingdon, Oxon ; New York, NY : Routledge; 2nd Ed.

Stanford, D. 1976. The Walakpa Site. Smithsonian Contributions to Anthropology 20, Washington.

Staples, L. 2012. Inuvialuit Final Agreement and Co-Management. In: Burn, C.R., eds. Herschel Island Qikiqtaryuk: A Natural and Cultural History of Yukon's Arctic Island. Calgary: University of Calgary Press. 216-221.

Stapp, D. C., Longenecker, J. G., Sprague, R., and Smith, A. 2009. Avoiding archaeological disasters : a risk management approach. Left Coast Press.

Stefánsson, V. 1909. The Eskimo trade jargon of Herschel island. American Anthropologist 11(2): 217-232.

Stefánsson, V. 1913. My Life with the Eskimo. Collier Books. Retrieved from: https://ia600200.us.archive.org/9/items/mylifewitheskimo01stef/mylifewitheskimo01stef.Pdf, 20 October 2021.

Stefánsson, V. 1919. The Mackenzie Eskimo. The Stefánsson-Anderson Arctic Expedition of the American Museum: Preliminary Ethnological Report. Anthropological Papers of the A.M.N.H. 4(1).

Stone, T. A., and Lefebvre, P. 1998. Using multi-temporal satellite data to evaluate selective logging in Para, Brazil. International Journal of Remote Sensing 19(13): 2517-2526 https://doi.org/10.1080/014311698214604

Streletskiy, D., Anisimov, O. and Vasiliev, A. 2015. Permafrost Degradation. In: Haeberli, W., Whiteman, C., and Shroder. J.F., eds. Snow and Ice- Related Hazards, Risks, and Disasters. Elsevier Academic Press, Amsterdam, Netherlands. 303–344.

Swayze, K. 1992. Previously unpublished Neoeskimo collections from the Beaufort Sea coast. Canadian Journal of Archaeology/Journal Canadien d'Archéologie 16: 102-111.

Tal, D., and Altschuld, J. 2021. Drone Technology in Architecture, Engineering and Construction. Newark: John Wiley & Sons.

Tapete, D. 2018. Remote sensing and geosciences for archaeology. Geosciences Switzerland (8)41: 1-10. https://doi.org/10.3390/geosciences8020041

Tapete, D., Cigna, F., Masini, N., and Lasaponara, R. 2013. Prospection and monitoring of the archaeological heritage of Nasca, Peru, with ENVISAT ASAR. Archaeological Prospection 20(2): 133-147. https://doi.org/10.1002/arp.1449

Terenzi, J., Jorgenson, M. T., Ely, C. R. and Giguère, N. 2014. Storm-surge flooding on the Yukon-Kuskokwim delta, Alaska. Arctic: 360-374. https://doi.org/10.14430/arctic4403

Théau, J. 2008. Change Detection. In: Shekhar, S., Xiong, H. (eds) Encyclopedia of GIA. Springer, Boston. 77-84.

Themistocleous, K. 2017. The use of UAVs to monitor archeological sites: the case study of Choirokoitia within the PROTHEGO project. In Fifth International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2017). International Society for Optics and Photonics. 10444:104441I. https://doi.org/10.1117/12.2292351

Themistocleous, K. 2020. The use of UAVs for cultural heritage and archaeology. In: Hadjimitsis, D.G., Thermistocleous, K., Uca, B., Agapiou, A., Lysandrou, V., Lasaponara., R., Masini, N., and Schreier, G., eds. Remote Sensing for Archaeology and Cultural Landscapes: Best practices and Perspective's Across Europe and the Middle East. Springer. 241-269. https://doi.org/10.1007/978-3-030-10979-0_14

Thomson, J. and Rogers, W. E. 2014. Swell and sea in the emerging Arctic Ocean. Geophysical Research Letters 41(9): 3136-3140. https://doi.org/10.1002/2014GL059983

Transport Canada. 2021. Canadian Aviation Regulations. Online Document. Retrieved from: https://laws-lois.justice.gc.ca/eng/regulations/SOR-96-433/FullText.html#s-900.01, 19 April 2021.

Trenhaile, A.S. 2013. Geomorphology: A Canadian Perspective. 5th edition. Oxford University Press.

Tremayne, A. H. 2015. New evidence for the timing of Arctic Small Tool tradition coastal settlement in Northwest Alaska. Alaska Journal of Anthropology 13(1): 1-18.

USGS. n.d.a. What does "georeferenced" mean? Retrieved from: https://www.usgs.gov/faqs/what-does-georeferenced-mean?qt newsscienceproducts=0#qt-news_science_products, 18 October 2021.

USGS. n.d.b. Repeat Photography Project. Retrieved from: https://www.usgs.gov/centers/norock /science/repeat-photography-project?qt-science_center_objects=0#qt science_center_objects, 18 October 2021.

Usher, P. 1971. The Western Canadian Arctic: A Century of Change. Anthropologica: 169-183.

Usher, P.J. 2002. Inuvialuit Use of the Beaufort Sea and it's Resources, 1960-2000. Arctic: 18-20. https://doi.org/10.14430/arctic732

Van der Sluijs, J., MacKay, G., Andrew, L., Smethurst, N., and Andrews, T. D. 2020. Archaeological documentation of wood caribou fences using unmanned aerial vehicle and very high-resolution satellite imagery in the Mackenzie Mountains, Northwest Territories. Journal of Unmanned Vehicle Systems 8(3): 186-206. https://doi.org/10.1139/juvs-2020-0007@cjfrjuvs-uav.issue1

Vermaire, J.C., Pisaric, M.F.J., Thienpont, J.R., Courtney Mustaphi, C.J., Kokelj, S.V., and Smol, J.P. 2013. Arctic climate warming and sea ice declines lead to increased storm surge activity. Geophysical Research Letters 40(7): 1386–1390. https://doi.org/10.1002/grl.50191

Waugh, D., Pearce, T., Ostertag, S. K., Pokiak, V., Collings, P., and Loseto, L. L. 2018. Inuvialuit traditional ecological knowledge of beluga whale (Delphinapterus leucas) under changing climatic conditions in Tuktoyaktuk, NT. Arctic Science 4(3): 242-258. https://doi.org/10.1139/as-2017-0034

Webb, R.H., Boyer, D.E., and Turner, R.M. 2010. Repeat Photography: Methods and Applications in the Natural Sciences. Island Press.

Whittaker, C.E. 1912. The Eskimo Mission on the Mackenzie (CIHM/ICMH Microfiche series; no. 87707). Missionary Prayer and Study Union, M.S.C.C. Toronto.

Whitridge, P. 1999. The prehistory of Inuit and Yupik whale use. Revista de arqueología americana: 99-154.

Wigley, T. M., and Raper, S. C. B. 1987. Thermal expansion of sea water associated with global warming. Nature 330(6144): 127-131.

Williams, B., and Carmack, E. 2012. Ocean Water and Sea Ice. In: Burn, C.R. eds. Herschel Island Qikiqtaryuk: A Natural and Cultural History of Yukon's Arctic Island, University of Calgary Press, Calgary, AB. 54-59.

Wilson, G.N., and Alcantara, C. 2012. Mixing Politics and Business in the Canadian Arctic: Inuit Corporate Governance in Nunavik and the Inuvialuit Settlement Region. Canadian Journal of Political Science 45(4): 781-804. https://doi.org/10.1017/S0008423912000996

Wolf, P. R., Dewitt, B. A., and Wilkinson, B. E. 2014. Elements of Photogrammetry with Applications in GIS. McGraw-Hill Education.

Yukon Ecoregions Working Group. 2004. Yukon Coastal Plain. In: Smith, C.A.S., Meikle, J.C., and Roots, C.F. eds., Ecoregions of the Yukon Territory: Biophysical properties of Yukon landscapes, Agriculture and Agri-Food Canada, Summerland, British Columbia. PARC Technical Bulletin No. 04-0:63-72

Yukon Government. 2019a. Herschel Island – Qikiqtaruk Territorial Park Management Plan 2019. PDF document retrieved from: https://yukon.ca/en/herschel-island-qikiqtaruk-territorialpark-management-plan, 18 November 2020.

Yukon Government. 2019b. Herschel Island: Qikiqtaruk – A Guide to the Historic Resources. PDF document retrieved from: https://yukon.ca/en/herschel-island-qikiqtaruk-guide historic-resources, 9 January 2022.

Yukon Government. 2021. Yukon North Slope Archaeological Site Database. Unpublished database accessed 3 May 2021.

Yorga, B. 1980. Washout: A Western Thule Site on Herschel Island, Yukon Territory. National Museum of Man. Mercury Series, Archaeological Survey of Canada (98).

Zazula, G.D. 2012. Ice Age. In: Burn, C.R. eds. Herschel Island Qikiqtaryuk: A Natural and Cultural History of Yukon's Arctic Island, ed Burn, C.R. University of Calgary Press, Calgary, Alberta. 60-64.

Zhang, Z. 2014. Camera Parameters (Intrinsic, Extrinsic). In: Ikeuchi K. eds. Computer Vison. Springer, Boston, MA. 81-85.

Zhang, D., He, F., Han, S., Zou, L., Wu, Y., and Chen, Y. 2017. An efficient approach to directly compute the exact Hausdorff distance for 3D point sets. Integrated Computer-Aided Engineering 24(3): 261-277. https://doi.org/10.3233/ICA-170544

Zhang, X., Flato, G., Kirchmeier-Young, M., Vincent, L., Wan, H., Wang, X., Rong, R., Fyfe, J., Li, G., Kharin, V.V. 2019. Changes in Temperature and Precipitation Across Canada. In: Bush, E. and Lemmen, D.S. eds. Canada's Changing Climate Report. Government of Canada, Ottawa, Ontario. 112-193.

10 APPENDIX

Yukon North Slope Place Names				
English Name	**Inuvialuktun Name**	**Inuvialuktun Meaning**	**English Name Given By**	**English Name Named After**
Babbage River	Cooghkiaktak (S)	Rocky river	Capt. John Franklin	Charles Babbage, Mathematician
Beaufort Sea	Tariuq (U & S)	Salt	Capt. John Franklin	Rear-Admiral Sir Francis Beaufort
Calton (Catton) Point	Unknown	Unknown	Capt. John Franklin	Unknown
Firth River	Unknown	Unknown	Unknown	John Firth, HBC Trader
Kay Point	Tikiaq (S)	Index finger	Capt. John Franklin	Kay Family
King Point	Kiinaq (S)	Face	Capt. John Franklin	Capt. Philip King, Surveyor
Shingle Point	Tapqaq (S & U)	Unknown	Unknown	Unknown
Stokes Point	Ikpigyuk (S)	Unknown	Capt. John Franklin	Charles Stokes, Naturalist
Qikiqtaruk (Herschel Island) Place Names				
English Name	**Inuvialuktun Name**	**Inuvialuktun Meaning**	**English Name Given By**	**English Name Named After**
Avadlek Spit	Avalliq (S)	Furthest away	N/A	N/A
Bell Bluff	Manikraq (U)	Like an egg	Lt. Crd. Charles Stockton	John Bell, USS *Thetis*
Collinson Head	Nuvugyuaq (S)	Big point	Lt. Crd. Charles Stockton	Capt. Sir Richard Collison
Herschel Island	Qikiqtaruk (U)	Big island	Capt. John Franklin	Herschel Family
Lopez Point	Kublualuk (S)	Old thumb	Lt. Crd. Charles Stockton	Robert Lopez, USS *Thetis*
Orca Cove	Ilukrarnaq (U)	Inside a cove	Lt. Crd. Charles Stockton	*Orca*, whaling vessel
Osborn Point	Nuvugyuaq (S)	Big point	Lt. Crd. Charles Stockton	Arthur Osborn, USS *Thetis*
Pauline Cove	Ilutaq (S)	Inside a bay	Lt. Crd. Charles Stockton	Pauline Lethihon King
Simpson Point	Kubluuyaq (S)	Like a thumb	Lt. Crd. Charles Stockton	Edward Simpson, USS *Thetis*
Thetis Bay	Unknown	Unknown	Lt. Crd. Charles Stockton	USS *Thetis*, US Navy
Thrasher Bay	Iluksaq (S)	Inside a bay	Lt. Crd. Charles Stockton	*Thrasher*, whaling vessel
Workboat Passage	Unknown	Unknown	Canadian Hydrographic Service	CSS *Richardson*, a "workboat"

Table 11. *English and Inuvialuktun place names for geographic features on the Yukon North Slope and on Qikiqtaruk. Based on Burn (2012) and Burn and Hattendorf (2011).*

Inuvialuktun Word	**English Meaning**	**Inuvialuktun Word**	**English Meaning**
Angatkuq (S & U)	Shaman, religious practitioner	*Qingaq* (S)	Vent
Atigi (S & U)	Parka	*Quangma* (S), *Uvlupak* (U)	Today
Igluryuaq (S)	Traditional semi-subterranean sod house, winter house	*Qulliq* (S)	Stone lamp
Engigstciak (S)	New or young mountain	*Silaliq Panga* (S)	A porch on sod house
Ingilranni (S)	Legend	*Taimani* (S)	Recent past
Ingilrawpaaluk (S), *Ingilran* (U)	A very long time ago	*Tunit* (S)	Paleo-Inuit
Kabloonacht (S), *Tan'ngit* (U)	White men, newcomers	*Tuqsuuq* (S)	Entrance passage
Katak (S)	Door	*Tuunriat* (S)	Evil spirits
Kuukpak (S)	Great river	*Tuutak* (S)	Labret
Nappan (S)	Souls or spirits	*Tuyurmiat* (S), *Tuyurmiaq* (U)	Strangers or guests
Qaluurvik (S)	Summer tent	*Ulu* (S & U)	Semi-lunar knife, women's knife
Qarlik (S)	Caribou skin pants	*Umiak* (S), *Umiaq* (U)	Large skin boat
Qatdjgit (S)	Council house, dance building	*Umialik* (S)	The family head, leader
Qilalugaq (S & U)	Beluga		

Table 12. *Inuvialuktun terminology used in this text. Terms used in this text are in the Siglitun (S) dialect. When known, Uummarmiutun (U) translations of these words are included in the table. Based on Alunik et al. (2003), IRC (2011) and Lowe (1984) and Parks Canada (2011).*

Instructional Procedures – Methods

Pix4D Processing Workflow

1. Create new *Pix4Dmapper©* project
2. Upload UAV imagery from file
3. Confirm coordinate system or select projected coordinate system
4. Upload GCP file or image location text file
5. Select *3D Maps* template option
6. Do not select "start processing now"
7. Under processing options, select LAS file under point cloud options and "merge tiles into one file"
8. Press "OK" and "Start" to begin initial processing
9. Review quality report once initial processing is complete
10. If satisfied with results, proceed with steps 2 and 3 of processing
11. Post-processing, check the quality of the outputs (point clouds, orthomosaics, DSMs etc.)
12. Repeat for additional datasets

Data Preparation Workflow

1. Upload the point cloud files into *Autodesk Recap©*
2. Use the limit box tool to clip the point clouds to roughly the same spatial extent
3. Save the point clouds as E57 and LAS format
4. Upload the E57 point clouds into *CloudCompare©*
5. Use the *Point-Pair Registration* tool to select alignment points
    - Set the older cloud as the reference cloud and the newer point cloud as the aligned cloud
    - Carefully select the alignment points
6. Once satisfactory alignment is achieved, use *Clone* tool to duplicate point clouds
7. Use the *Segmentation* tool to trim the edges of the clouds if they do not match
8. Use *Cross-section Analysis* tool to confirm the alignment of the point clouds

9. Clip the point clouds to the extent of the desired study area
    - If one of the previously used alignment points is clipped out, the clouds will no longer be aligned, and that step needs to be repeated
10. Re-align the clipped study area point clouds
11. Use the *Segment* tool to clean any non-overlapping edges
12. Use *Cross-section Analysis* tool on the study area point clouds to confirm alignment
13. Save study area 1 point clouds as separate entities, in E57 and LAS file formats
14. Repeat steps 9-13 for additional study areas

Cloud-to-Cloud Distance (C2C) Workflow

1. Using properly prepared point clouds (see data preparation workflow), select the *Cloud-to-Cloud Distance* (C2C) tool in *CloudCompare*©
2. Select older point cloud as reference point cloud
3. Use default parameters, with an AUTO octree level and absolute distances
4. Run *C2C Distance* tool
5. Inspect the re-colored point cloud, modify color ramp properties to best display results
6. Save recolored point cloud(s) in E57 and LAS file formats
7. Repeat steps 1-6 for additional study areas
8. Take screenshot of change maps and open them in any image software. Identify areas of prominent change on the change map
9. Label areas of prominent change alphabetically

Visual Inspection Analysis (VIA) Workflow

1. Upload the 2017 and 2019 orthomosaics generated by *Pix4DMapper*, into *ArcGIS Pro*©
2. Use the *Auto Georeference* tool to adjust alignment of 2017 and 2019 orthomosaics, if needed
3. Upload aligned Study Area 1 and Study Area 2 point clouds into *ArcGIS Pro*©, in LAS format
4. Modify symbology of point clouds so that they are visible in the map frame
5. Create polygon feature class called Study Area 1 by tracing the outline of the study area point clouds. Repeat with Study Area 2

6. Use the *Extract by Mask* tool in the Spatial Analyst toolbox to clip the 2017 orthomosaic to the extent of the Study Area point cloud boundary. Repeat with Study Area 2.
7. Repeat step 6 with 2019 orthomosaic
8. Name the four output raster’s (clipped orthomosaic imagery) 2017 Study Area 1, 2017 Study Area 2, 2019 Study Area 1 and 2019 Study Area 2.
9. Upload and georeference the C2C Change Maps for Study Area 1 and 2, in *ArcGIS Pro©*, to align the change maps with the orthomosaic imagery for the study areas
10. Overlay a 10 x 10 m grid in *ArcGIS Pro©*
11. Toggle on and off the 2017, 2019 and C2C change map for Study Area 1
12. Document the nature of the change responsible for the notable change labelled in step 9 of the C2C workflow
13. Repeat steps 11 and 12 for Study Area 2
14. In another document, label each 10 x 10 m square numerically in Study Area 1 and 2, using a ox-plow pattern
15. Toggle between the 2017 and 2019 imagery for Study Area 1, documenting the change in each 10 x 10m square.
16. Repeat step 15 for Study Area 2
17. Interpret change found in the VIA using Environment Canada climate data, information from Yukon Government Historic Sites Unit personnel, and other sources.

Quality Report

Generated with Pix4Dmapper version 4.5.6

Important: Click on the different icons for:

Help to analyze the results in the Quality Report

Additional information about the sections

Click here for additional tips to analyze the Quality Report

Summary

Project	Floodplain_2017_2
Processed	2021-01-19 17:11:49
Camera Model Name(s)	DSC-RX100M2_10.4_5472x3648 (RGB)
Average Ground Sampling Distance (GSD)	2.69 cm / 1.06 in
Area Covered	1.993 km^2 / 199.3459 ha / 0.77 sq. mi. / 492.8495 acres
Time for Initial Processing (without report)	03h:23m:33s

Quality Check

Images	median of 74400 keypoints per image	✓
Dataset	1094 out of 1325 images calibrated (82%), all images enabled	⚠
Camera Optimization	1.5% relative difference between initial and optimized internal camera parameters	✓
Matching	median of 14499.5 matches per calibrated image	✓
Georeferencing	yes, no 3D GCP	⚠

Preview

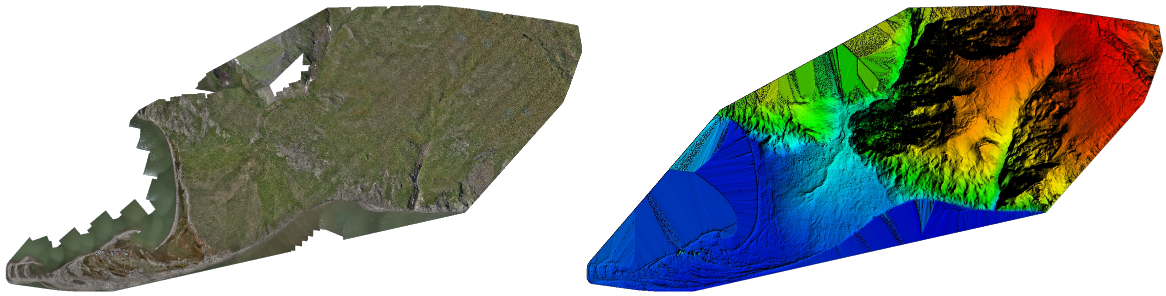


Figure 1: Orthomosaic and the corresponding sparse Digital Surface Model (DSM) before densification.

Calibration Details

Number of Calibrated Images	1094 out of 1325
Number of Geolocated Images	1046 out of 1325

Initial Image Positions

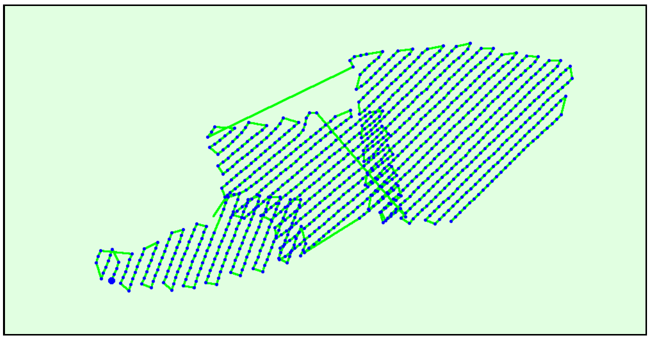
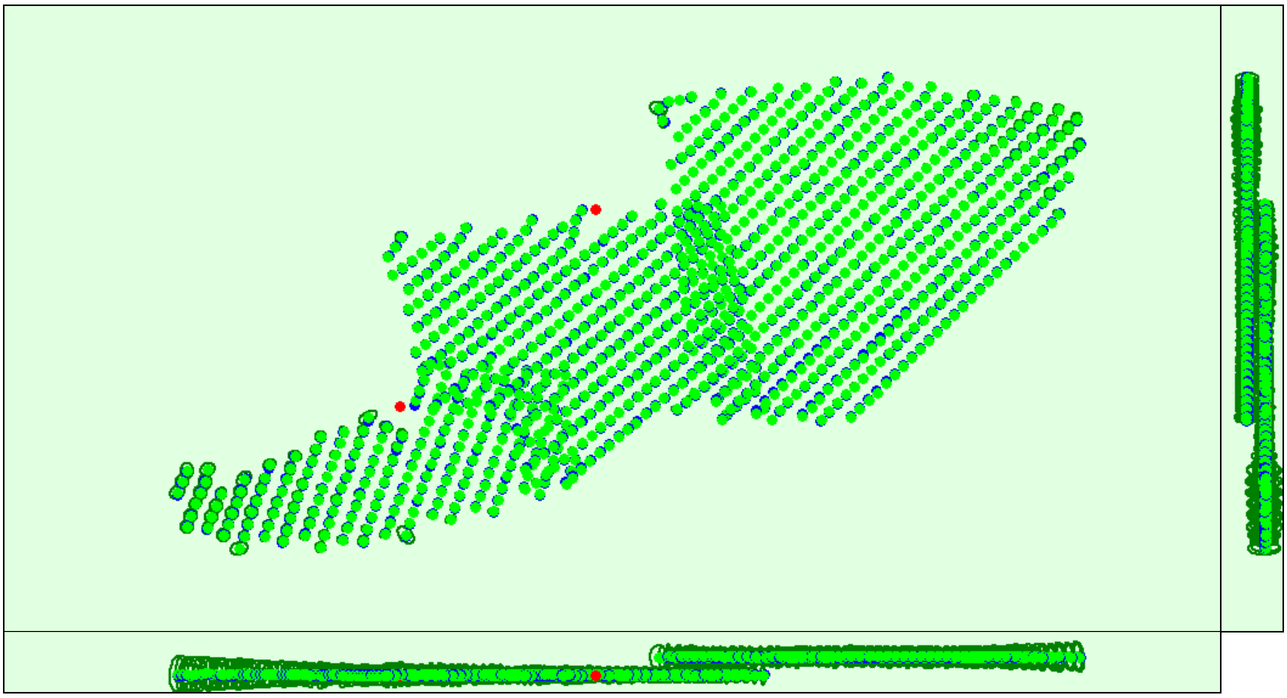


Figure 2: Top view of the initial image position. The green line follows the position of the images in time starting from the large blue dot.

Computed Image/GCPs/Manual Tie Points Positions



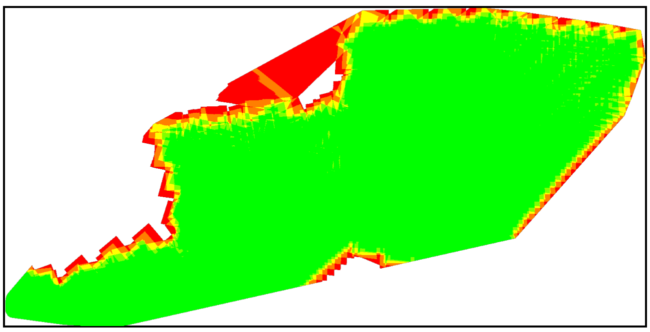
Uncertainty ellipses 100x magnified

Figure 3: Offset between initial (blue dots) and computed (green dots) image positions as well as the offset between the GCPs initial positions (blue crosses) and their computed positions (green crosses) in the top-view (XY plane), front-view (XZ plane), and side-view (YZ plane). Red dots indicate disabled or uncalibrated images. Dark green ellipses indicate the absolute position uncertainty of the bundle block adjustment result.

Absolute camera position and orientation uncertainties

	X[m]	Y[m]	Z[m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.099	0.099	0.242	0.034	0.028	0.010
Sigma	0.035	0.036	0.081	0.011	0.012	0.006

Overlap



Number of overlapping images: 1 2 3 4 5+

Figure 4: Number of overlapping images computed for each pixel of the orthomosaic.
Red and yellow areas indicate low overlap for which poor results may be generated. Green areas indicate an overlap of over 5 images for every pixel. Good quality results will be generated as long as the number of keypoint matches is also sufficient for these areas (see Figure 5 for keypoint matches).

Bundle Block Adjustment Details

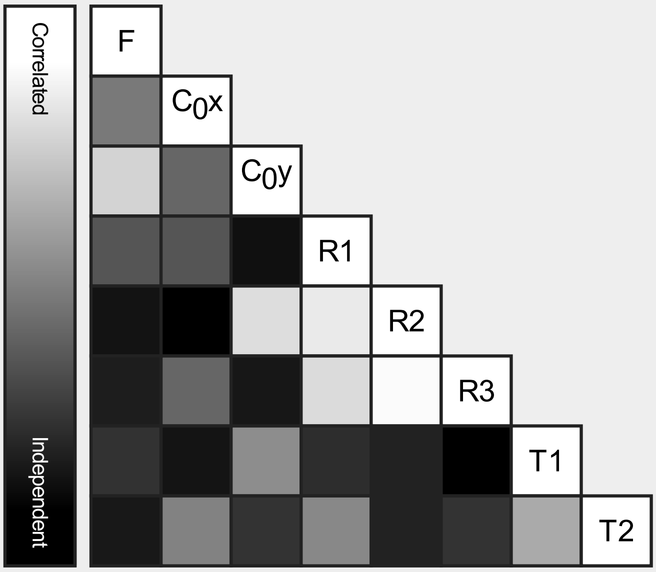
Number of 2D Keypoint Observations for Bundle Block Adjustment	13963226
Number of 3D Points for Bundle Block Adjustment	5484114
Mean Reprojection Error [pixels]	0.110

Internal Camera Parameters

DSC-RX100M2_10.4_5472x3648 (RGB). Sensor Dimensions: 13.000 [mm] x 8.667 [mm]

EXIF ID: DSC-RX100M2_10.4_5472x3648

	Focal Length	Principal Point x	Principal Point y	R1	R2	R3	T1	T2
Initial Values	4377.600 [pixel] 10.400 [mm]	2736.000 [pixel] 6.500 [mm]	1824.000 [pixel] 4.333 [mm]	0.000	0.000	0.000	0.000	0.000
Optimized Values	4311.702 [pixel] 10.243 [mm]	2694.034 [pixel] 6.400 [mm]	1814.069 [pixel] 4.310 [mm]	-0.003	0.016	-0.027	-0.003	-0.004
Uncertainties (Sigma)	0.886 [pixel] 0.002 [mm]	0.105 [pixel] 0.000 [mm]	0.182 [pixel] 0.000 [mm]	0.000	0.000	0.000	0.000	0.000



The correlation between camera internal parameters determined by the bundle adjustment. White indicates a full correlation between the parameters, ie. any change in one can be fully compensated by the other. Black indicates that the parameter is completely independent, and is not affected by other parameters.

The number of Automatic Tie Points (ATPs) per pixel, averaged over all images of the camera model, is color coded between black and white. White indicates that, on average, more than 16 ATPs have been extracted at the pixel location. Black indicates that, on average, 0 ATPs have been extracted at the pixel location. Click on the image to the see the average direction and magnitude of the re-projection error for each pixel. Note that the vectors are scaled for better visualization. The scale bar indicates the magnitude of 1 pixel error.

2D Keypoints Table

	Number of 2D Keypoints per Image	Number of Matched 2D Keypoints per Image
Median	74400	14499
Min	20353	72
Max	89256	32118

Mean	65637	12763

3D Points from 2D Keypoint Matches

	Number of 3D Points Observed
In 2 Images	3840062
In 3 Images	967485
In 4 Images	353297
In 5 Images	160107
In 6 Images	78287
In 7 Images	39429
In 8 Images	20337
In 9 Images	10871
In 10 Images	6206
In 11 Images	3533
In 12 Images	2030
In 13 Images	1068
In 14 Images	602
In 15 Images	329
In 16 Images	212
In 17 Images	113
In 18 Images	57
In 19 Images	41
In 20 Images	17
In 21 Images	16
In 22 Images	8
In 23 Images	4
In 24 Images	3

2D Keypoint Matches

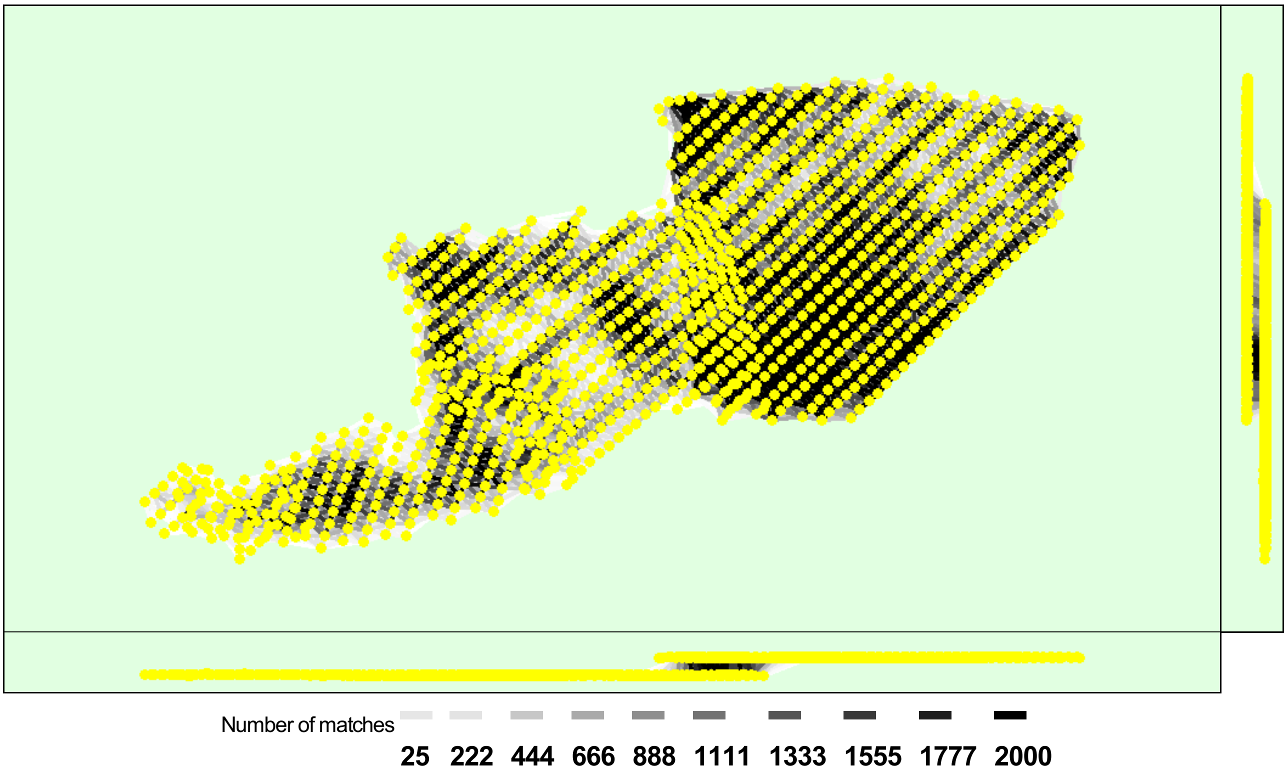


Figure 5: Computed image positions with links between matched images. The darkness of the links indicates the number of matched 2D keypoints between the images. Bright links indicate weak links and require manual tie points or more images.

Geolocation Details

Absolute Geolocation Variance

Min Error [m]	Max Error [m]	Geolocation Error X [%]	Geolocation Error Y [%]	Geolocation Error Z [%]
-	-15.00	0.00	0.00	0.00
-15.00	-12.00	0.00	0.10	0.00
-12.00	-9.00	0.00	0.38	0.00
-9.00	-6.00	0.00	0.10	0.00
-6.00	-3.00	0.48	13.98	0.19
-3.00	0.00	59.67	37.93	49.33
0.00	3.00	31.23	29.31	50.48
3.00	6.00	8.52	16.38	0.00
6.00	9.00	0.10	1.72	0.00
9.00	12.00	0.00	0.10	0.00
12.00	15.00	0.00	0.00	0.00
15.00	-	0.00	0.00	0.00
Mean [m]		-0.000000	0.000000	0.000000
Sigma [m]		1.748618	2.943637	0.948281
RMS Error [m]		1.748618	2.943637	0.948281

Min Error and Max Error represent geolocation error intervals between -1.5 and 1.5 times the maximum accuracy of all the images. Columns X, Y, Z show the percentage of images with geolocation errors within the predefined error intervals. The geolocation error is the difference between the initial and computed image positions. Note that the image geolocation errors do not correspond to the accuracy of the observed 3D points.

Relative Geolocation Variance

Relative Geolocation Error	Images X [%]	Images Y [%]	Images Z [%]
[-1.00, 1.00]	99.43	95.50	100.00
[-2.00, 2.00]	100.00	99.71	100.00
[-3.00, 3.00]	100.00	100.00	100.00
Mean of Geolocation Accuracy [m]	5.000000	5.000000	10.000000
Sigma of Geolocation Accuracy [m]	0.000000	0.000000	0.000000

Images X, Y, Z represent the percentage of images with a relative geolocation error in X, Y, Z.

Initial Processing Details

System Information

Hardware	CPU: Intel(R) Core(TM) i7-6600U CPU @ 2.60GHz RAM: 8GB GPU: Intel(R) HD Graphics 520 (Driver: 24.20.100.6293)
Operating System	Windows 10 Pro, 64-bit

Coordinate Systems

Image Coordinate System	WGS 84 (EGM96 Geoid)
Output Coordinate System	WGS 84 / UTM zone 7N (EGM96 Geoid)

Processing Options

Detected Template	No Template Available
Keypoints Image Scale	Full, Image Scale: 1

Advanced: Matching Image Pairs	Aerial Grid or Corridor
Advanced: Matching Strategy	Use Geometrically Verified Matching: no
Advanced: Keypoint Extraction	Targeted Number of Keypoints: Automatic
Advanced: Calibration	Calibration Method: Standard Internal Parameters Optimization: All External Parameters Optimization: All Rematch: Auto, no

Point Cloud Densification details

Processing Options

Image Scale	multiscale, 1/2 (Half image size, Default)
Point Density	Optimal
Minimum Number of Matches	3
3D Textured Mesh Generation	yes
3D Textured Mesh Settings:	Resolution: Medium Resolution (default) Color Balancing: no
LOD	Generated: no
Advanced: 3D Textured Mesh Settings	Sample Density Divider: 1
Advanced: Image Groups	group1
Advanced: Use Processing Area	yes
Advanced: Use Annotations	yes
Time for Point Cloud Densification	04h:36m:34s
Time for Point Cloud Classification	NA
Time for 3D Textured Mesh Generation	39m:09s

Results

Number of Processed Clusters	61
Number of Generated Tiles	7
Number of 3D Densified Points	146094433
Average Density (per m^3)	176.3

DSM, Orthomosaic and Index Details

Processing Options

DSM and Orthomosaic Resolution	1 x GSD (2.69 [cm/pixel])
DSM Filters	Noise Filtering: yes Surface Smoothing: yes, Type: Sharp
Raster DSM	Generated: yes Method: Inverse Distance Weighting Merge Tiles: yes
Orthomosaic	Generated: yes Merge Tiles: yes GeoTIFF Without Transparency: no Google Maps Tiles and KML: yes
Time for DSM Generation	06h:13m:28s
Time for Orthomosaic Generation	09h:56m:52s
Time for DTM Generation	00s
Time for Contour Lines Generation	00s
Time for Reflectance Map Generation	00s
Time for Index Map Generation	00s

Quality Report

Generated with Pix4Dmapper version 4.5.6

Important: Click on the different icons for:

Help to analyze the results in the Quality Report

Additional information about the sections

Click here for additional tips to analyze the Quality Report

Summary

Project	Pauline_Cove_2019_Project
Processed	2020-11-17 16:54:04
Camera Model Name(s)	S.O.D.A_10.6_5472x3648 (RGB)
Average Ground Sampling Distance (GSD)	2.96 cm / 1.17 in
Area Covered	0.316 km^2 / 31.6134 ha / 0.12 sq. mi. / 78.1589 acres
Time for Initial Processing (without report)	13m:13s

Quality Check

Images	median of 41507 keypoints per image	✓
Dataset	277 out of 338 images calibrated (81%), all images enabled	⚠
Camera Optimization	0.99% relative difference between initial and optimized internal camera parameters	✓
Matching	median of 17713.9 matches per calibrated image	✓
Georeferencing	yes, no 3D GCP	⚠

Preview

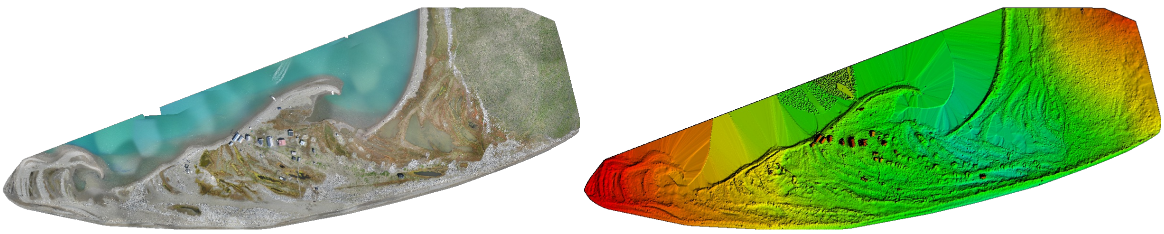


Figure 1: Orthomosaic and the corresponding sparse Digital Surface Model (DSM) before densification.

Calibration Details

Number of Calibrated Images	277 out of 338
Number of Geolocated Images	338 out of 338

Initial Image Positions

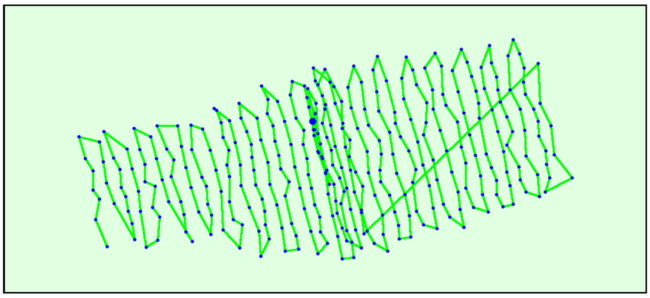


Figure 2: Top view of the initial image position. The green line follows the position of the images in time starting from the large blue dot.

Computed Image/GCPs/Manual Tie Points Positions

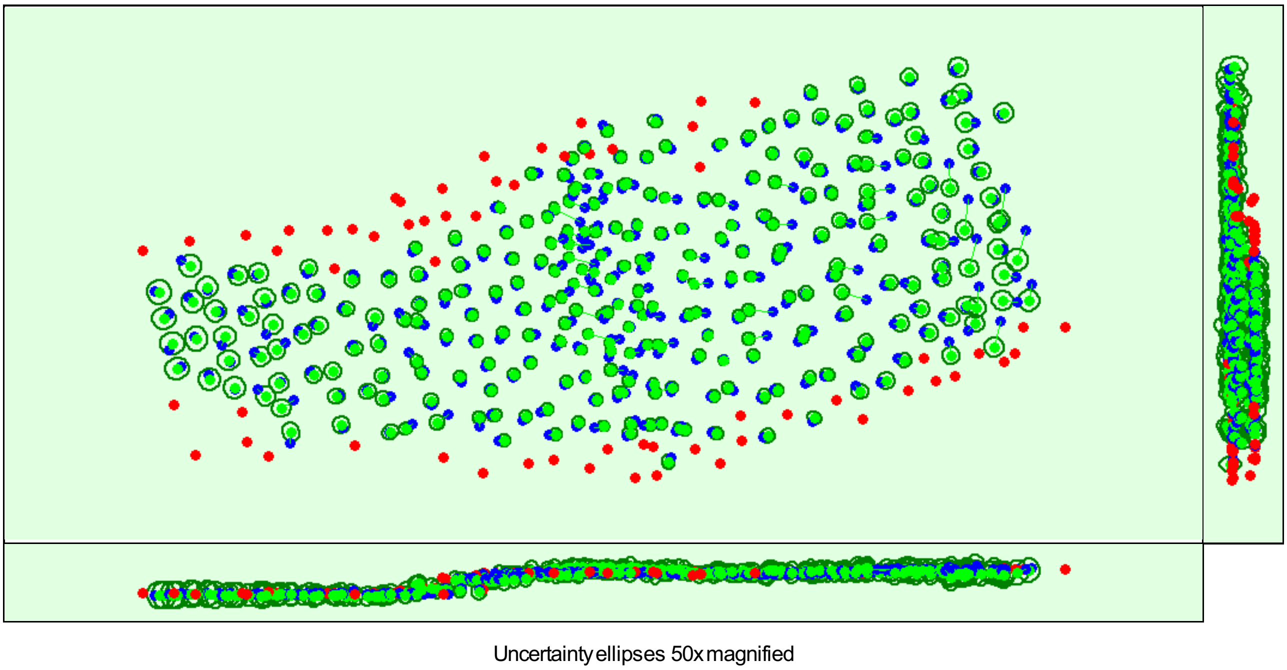


Figure 3: Offset between initial (blue dots) and computed (green dots) image positions as well as the offset between the GCPs initial positions (blue crosses) and their computed positions (green crosses) in the top-view (XY plane), front-view (XZ plane), and side-view (YZ plane). Red dots indicate disabled or uncalibrated images. Dark green ellipses indicate the absolute position uncertainty of the bundle block adjustment result.

Absolute camera position and orientation uncertainties

	X[m]	Y[m]	Z[m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.180	0.178	0.221	0.050	0.041	0.029
Sigma	0.042	0.040	0.048	0.008	0.009	0.005

Overlap

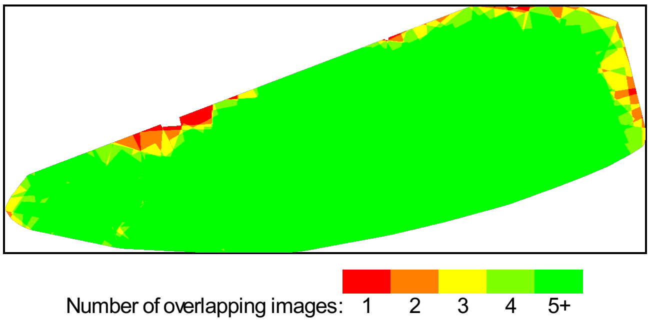


Figure 4: Number of overlapping images computed for each pixel of the orthomosaic.
Red and yellow areas indicate low overlap for which poor results may be generated. Green areas indicate an overlap of over 5 images for every pixel. Good quality results will be generated as long as the number of keypoint matches is also sufficient for these areas (see Figure 5 for keypoint matches).

Bundle Block Adjustment Details

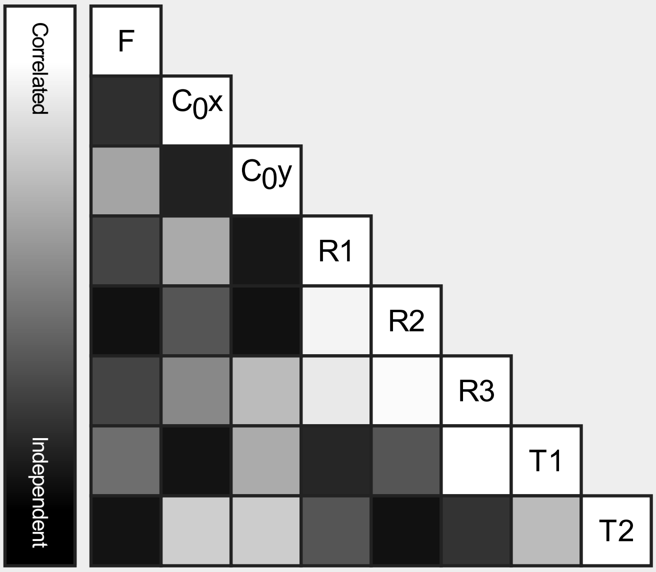
Number of 2D Keypoint Observations for Bundle Block Adjustment	5103245
Number of 3D Points for Bundle Block Adjustment	1648959
Mean Reprojection Error [pixels]	0.168

Internal Camera Parameters

S.O.D.A._10.6_5472x3648 (RGB). Sensor Dimensions: 13.133 [mm] x 8.755 [mm]

EXIF ID: S.O.D.A._10.6_5472x3648

	Focal Length	Principal Point x	Principal Point y	R1	R2	R3	T1	T2
Initial Values	4430.420 [pixel] 10.633 [mm]	2725.000 [pixel] 6.540 [mm]	1811.670 [pixel] 4.348 [mm]	0.033	-0.209	0.315	0.000	0.000
Optimized Values	4386.533 [pixel] 10.528 [mm]	2741.514 [pixel] 6.580 [mm]	1802.429 [pixel] 4.326 [mm]	0.028	-0.183	0.277	-0.001	0.000
Uncertainties (Sigma)	0.317 [pixel] 0.001 [mm]	0.120 [pixel] 0.000 [mm]	0.139 [pixel] 0.000 [mm]	0.000	0.001	0.001	0.000	0.000



The correlation between camera internal parameters determined by the bundle adjustment. White indicates a full correlation between the parameters, ie. any change in one can be fully compensated by the other. Black indicates that the parameter is completely independent, and is not affected by other parameters.

The number of Automatic Tie Points (ATPs) per pixel, averaged over all images of the camera model, is color coded between black and white. White indicates that, on average, more than 16 ATPs have been extracted at the pixel location. Black indicates that, on average, 0 ATPs have been extracted at the pixel location. Click on the image to the see the average direction and magnitude of the re-projection error for each pixel. Note that the vectors are scaled for better visualization. The scale bar indicates the magnitude of 1 pixel error.

2D Keypoints Table

	Number of 2D Keypoints per Image	Number of Matched 2D Keypoints per Image
Median	41507	17714
Min	19599	52
Max	79446	46055
Mean	43705	18423

3D Points from 2D Keypoint Matches

	Number of 3D Points Observed
In 2 Images	980226

In 3 Images	304149
In 4 Images	136820
In 5 Images	75586
In 6 Images	46141
In 7 Images	30364
In 8 Images	20843
In 9 Images	14510
In 10 Images	10603
In 11 Images	7623
In 12 Images	5725
In 13 Images	4104
In 14 Images	2879
In 15 Images	2315
In 16 Images	1737
In 17 Images	1291
In 18 Images	1136
In 19 Images	835
In 20 Images	594
In 21 Images	471
In 22 Images	364
In 23 Images	236
In 24 Images	195
In 25 Images	105
In 26 Images	50
In 27 Images	36
In 28 Images	11
In 29 Images	3
In 30 Images	6
In 31 Images	1

2D Keypoint Matches

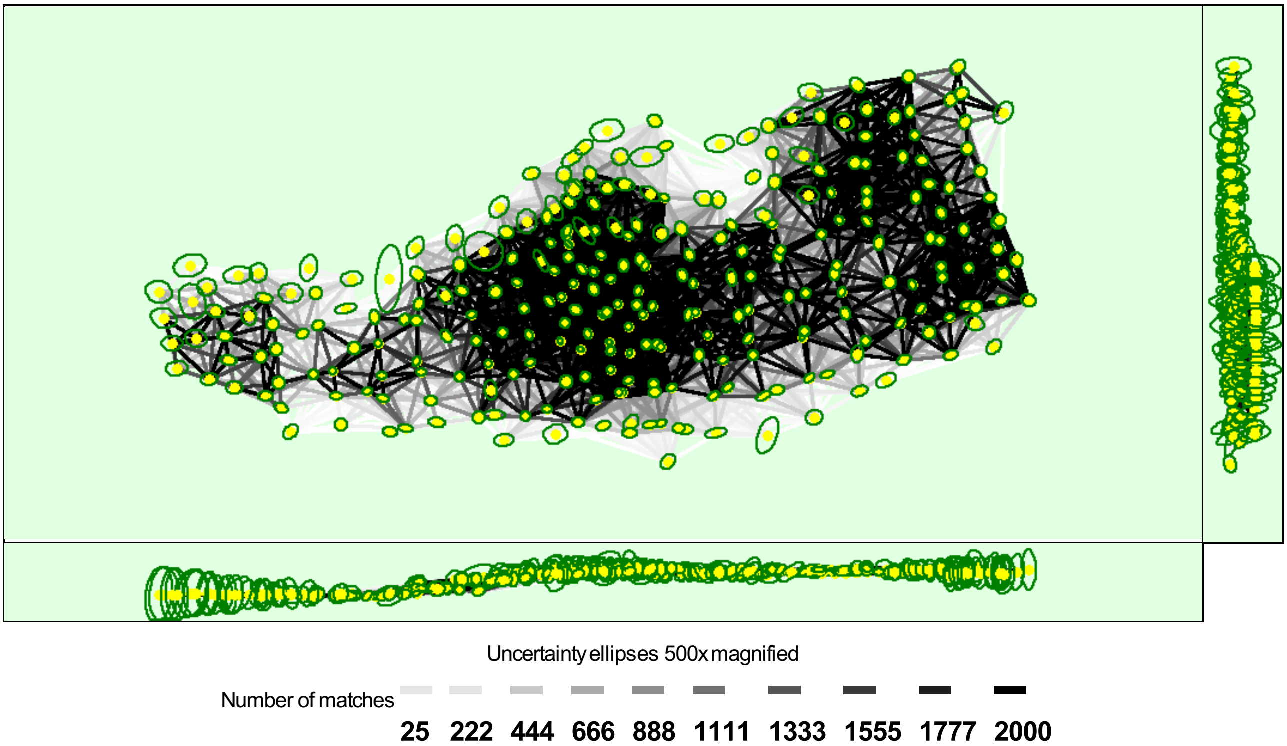


Figure 5: Computed image positions with links between matched images. The darkness of the links indicates the number of matched 2D keypoints between the images. Bright links indicate weak links and require manual tie points or more images. Dark green ellipses indicate the relative camera position uncertainty of the bundle block adjustment result.

Relative camera position and orientation uncertainties

	X [m]	Y [m]	Z [m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.017	0.016	0.023	0.009	0.009	0.004
Sigma	0.007	0.007	0.011	0.004	0.004	0.003

Geolocation Details

Absolute Geolocation Variance

Min Error [m]	Max Error [m]	Geolocation Error X [%]	Geolocation Error Y [%]	Geolocation Error Z [%]
-	-20.34	0.00	0.00	0.00
-20.34	-16.27	0.00	0.36	0.00
-16.27	-12.20	0.00	0.72	0.36
-12.20	-8.14	5.42	4.33	0.72
-8.14	-4.07	20.94	18.05	9.03
-4.07	0.00	29.60	33.57	32.49
0.00	4.07	13.72	25.27	49.46
4.07	8.14	10.83	12.27	7.58
8.14	12.20	6.14	2.17	0.36
12.20	16.27	4.33	0.00	0.00
16.27	20.34	3.25	0.36	0.00
20.34	-	5.78	2.89	0.00
Mean [m]		1.925645	0.043980	0.089537
Sigma [m]		9.065563	7.430425	3.142911
RMS Error [m]		9.267823	7.430555	3.144186

Min Error and Max Error represent geolocation error intervals between -1.5 and 1.5 times the maximum accuracy of all the images. Columns X, Y, Z show the percentage of images with geolocation errors within the predefined error intervals. The geolocation error is the difference between the initial and computed image positions. Note that the image geolocation errors do not correspond to the accuracy of the observed 3D points.

Relative Geolocation Variance

Relative Geolocation Error	Images X [%]	Images Y [%]	Images Z [%]
[-1.00, 1.00]	63.18	77.98	97.83
[-2.00, 2.00]	90.61	96.39	100.00
[-3.00, 3.00]	98.56	97.11	100.00
Mean of Geolocation Accuracy [m]	6.210347	6.210347	7.279892
Sigma of Geolocation Accuracy [m]	1.286735	1.286735	1.577998

Images X, Y, Z represent the percentage of images with a relative geolocation error in X, Y, Z.

Geolocation Orientational Variance	RMS [degree]
Omega	2.128
Phi	4.565
Kappa	7.092

Geolocation RMS error of the orientation angles given by the difference between the initial and computed image orientation angles.

Initial Processing Details

System Information

Hardware	CPU: Intel(R) Core(TM) i7-7820HQ CPU @ 2.90GHz RAM: 32GB GPU: NVIDIA GeForce GTX 1070 (Driver: 27.21.14.5167)
Operating System	Windows 10 Pro, 64-bit

Coordinate Systems

Image Coordinate System	WGS 84
Output Coordinate System	WGS 84 / UTM zone 7N

Processing Options

Detected Template	No Template Available
Keypoints Image Scale	Full, Image Scale: 1
Advanced: Matching Image Pairs	Aerial Grid or Corridor
Advanced: Matching Strategy	Use Geometrically Verified Matching: no
Advanced: Keypoint Extraction	Targeted Number of Keypoints: Automatic
Advanced: Calibration	Calibration Method: Standard Internal Parameters Optimization: All External Parameters Optimization: All Rematch: Auto, yes

Point Cloud Densification details

Processing Options

Image Scale	multiscale, 1/2 (Half image size, Default)
Point Density	Optimal
Minimum Number of Matches	3
3D Textured Mesh Generation	yes
3D Textured Mesh Settings:	Resolution: Medium Resolution (default) Color Balancing: no
LOD	Generated: no
Advanced: 3D Textured Mesh Settings	Sample Density Divider: 1
Advanced: Image Groups	group1
Advanced: Use Processing Area	yes
Advanced: Use Annotations	yes
Time for Point Cloud Densification	29m:26s
Time for Point Cloud Classification	NA
Time for 3D Textured Mesh Generation	07m:51s

Results

Number of Generated Tiles	1
Number of 3D Densified Points	23411080
Average Density (per m^3)	159.73

DSM, Orthomosaic and Index Details

Processing Options

DSM and Orthomosaic Resolution	1 x GSD (2.96 [cm/pixel])

DSM Filters	Noise Filtering: yes Surface Smoothing: yes, Type: Sharp
Raster DSM	Generated: yes Method: Inverse Distance Weighting Merge Tiles: yes
Orthomosaic	Generated: yes Merge Tiles: yes GeoTIFF Without Transparency: no Google Maps Tiles and KML: no
Time for DSM Generation	21m:29s
Time for Orthomosaic Generation	28m:12s
Time for DTM Generation	00s
Time for Contour Lines Generation	00s
Time for Reflectance Map Generation	00s
Time for Index Map Generation	00s

1. The Archaeological Sequence in the Northern Cordillera: A Consideration of Typology and Traditions. By Ruth Gotthardt. 326 pp. 1990 (Out of print.)
2. Caribou Exploitation at the Trail River Site, Northern Yukon. By Murielle I. Nagy. 157 pp. 1990. (Out of print.)
3. Salmon and Storage: Southern Tutchone Use of an "Abundant" Resource. By Beth Laura O'Leary. 129 pp. 1992. (Out of print.)
4. The Archaeology and History of an Arctic Mission, Herschel Island, Yukon. By Nancy Saxberg. 121 pp. 1993.
5. Holocene Occupations in Southern Yukon: New Perspectives from the Annie Lake Site. By Paul Gregory Hare. 155 pp. 1995.
6. Microblade Complexes and Traditions in the Interior Northwest, as Seen from Kelly Creek, West-Central Yukon. By Donald W. Clark and Ruth M. Gotthardt, with contributions from Paul Gregory Hare. 191 pp. 1999.
7. On the Periphery of the Klondike Gold Rush: Canyon City, An Archaeological Perspective. By Thomas J. Hammer. 175 pp. 1999.
8. Dechyoo Njik (MlVm-4) and the Traditional Land Use Patterns in the Southwestern Portion of the Old Crow Flats, Yukon Territory. By Mélanie Fafard. 100 pp. 2001.
9. Geoarchaeological Studies at the Dog Creek Site, Northern Yukon. By Julie Anne Esdale. 127 pp. 2001.
10. KaVn-2: An Eastern Beringian Tradition Archaeological Site in West-Central Yukon Territory, Canada. By Ty Alexander Heffner. 130 pp. 2002.
11. Special Brew: Industrial Archaeology and History of the Klondike Brewery. By David V. Burley and Michael Will. 102 pp. 2002.
12. Archaeological Investigations of Transient Residences on the Hillsides Surrounding Dawson City, Yukon. By Michael Brand. 168 pp. 2002.
13. Ta'tla Mun: An Archaeological Examination of Technology, Subsistence Economy and Trade at Tatlmain Lake, Central Yukon. By Christian Daniel Thomas. 121 pp. 2003.
14. North to the Yukon Territory via the Alcan Highway in 1948: Field Notes of the Andover-Harvard Expedition. By Elmer Harp Jr. 126 pp. 2005. (Out of print.)
15. The *Nįį'įį'* Hunting Stand Site: Understanding Technological Practice as Social Practice in Subarctic Archaeology. By Glen R. MacKay. 130 pp. 2008.
16. The A.J. Goddard: Reconstruction and Material Culture of a Klondike Gold Rush Sternwheeler. By Lindsey Hall Thomas. 189 pp. 2012.
17. Fort Selkirk: Early Contact Period Interaction Between the Northern Tutchone and the Hudson's Bay Company in Yukon. By Victoria Elena Castillo. 238 pp. 2012.
18. Schaeffer Creek Campsite (MlVm-6), a Possible Cold Season Site in Southwestern Old Crow Flats, Northern Yukon Territory. By Jo-Ann Marvin. 138 pp. 2013.
19. An archaeological investigation of subalpine and alpine use in the southeast Yukon. By Jodie MacMillan. 192 pp. 2019.
20. Human and ecological responses to the Northern White River Ash eruption. By Holly A. Smith. 159 pp. 2020
21. Women and hide-working at the Little John site (KdVo-6), Yukon Territory: a feminist application of use-wear analysis. By Jordan Danelle Handley. 131 pp. 2020.
22. Detecting and Monitoring Change to an Arctic Heritage Site Using UAV Photogrammetry: A Case Study From Qikiqtaruk / Herschel Island, YT. By Katelyn O'Keefe. 267 pp. 2022.

To order copies, email heritage.resources@yukon.ca

Or download PDFs of recent volumes yukon.ca/en/heritage-publications

Yukon

ISBN 978-1-55362-905-4