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Community-Based Bathymetric Mapping Supports Arctic Coastal Hazard Assessment

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ABSTRACT:

The disconnect between the pace of environmental change and the provision of current bathymetric data represents a critical gap in Arctic scientific knowledge, one with direct consequences for safety, subsistence access, and coastal and riverine infrastructure management. Working with the Hunters and Trappers Committees of Tuktoyaktuk and Aklavik in Canada's Inuvialuit Settlement Region, a community-owned bathymetric collection and monitoring program has been co-developed using consumer-grade sonar mounted on local vessels. Nearly 20,000 km of survey tracks have been generated, much collected from areas conventional science vessels cannot reach, particularly in the shallow nearshore zones where erosion, infrastructure risk, and navigation hazards are most acute. This complementary blend of localized marine navigation skills with researcher understanding of technology, data quality and accuracy addresses community needs and advances wider scientific understanding through improved and more sustained datasets. The program demonstrates community-led bathymetric data governance, in which local leaders rather than externally imposed research agendas determine priorities and are charged with sustaining data collection beyond single project funding cycles. As Arctic environments continue to change unpredictably, this work offers a scalable, community-driven alternative to the extractive research paradigms that have historically characterized Arctic science.

Keywords: Arctic, Community-led monitoring; Crowdsourced bathymetry; coastal hazards; Indigenous data sovereignty

Introduction

The western Canadian Arctic is undergoing rapid changes in climate which have resulted in a greater ice-free season [1, 2, 3], increasing storm intensities [4,5], and significant increases in the rates of coastal erosion in many areas [6]. These impacts are also affecting the seafloor in coastal regions, where sediment

supply, pathways, and rates of change are altering the nearshore and its habitats, navigation routes, and geomorphic interactions [7, 8, 9]. These influences are felt most acutely by Arctic communities who rely on the ocean and rivers for their travel and subsistence harvesting [10, 11]. Relatively rapid changes to bathymetry make established routes less predictable and dangerous at a range of scales, from shifting channels in shallow waters used by small local watercraft, to sedimentation that increases costly dredging to maintain deeper ports and coastal infrastructure for commercial vessels [12]. Therefore, establishing better monitoring of bathymetric changes is vital to both the Arctic and the global economy but current datasets are often outdated or focused in areas of specific interest (such as the objectives of a single research project). There is a pressing need for high-quality bathymetric datasets collected in a timely and responsive manner and for relevant data to be more accessible to community decision-makers.

Accurate and current seafloor bathymetric mapping has the potential to permit more informed ecosystem management policy, better decisions about safe navigation courses, more holistic understanding of marine geohazards, and proactive rather than reactive nearshore interventions such as dredging, beach nourishment, maintenance of coastal defenses [13]. High resolution bathymetric data are usually collected using Multibeam Echosounder Systems (MBES), one of the most valuable tools for studying the ocean floor. However, these systems are expensive, time consuming and require significant experience and training to operate effectively and derive meaningful mapping outputs [13]. In the past decades, there has been an increase in the quality and availability of recreational grade sonars that can be used for the collection of bathymetric data [14, 15]. The accessibility and utility of recreational grade sonars has led to new applications targeted the collection of scientific quality data, with examples including marine engineering [16]; marine biology and habitat mapping [17, 9, 18]; archaeology and geology [19], and shallow water bathymetric mapping [20]. These applications tend to use more spatially limited surveys focused on specific areas of research interest and hence rely on high accuracy GNSS to decrease positioning errors in the survey system.

The availability of cheaper, more accessible (less technical) mapping instrumentation has also permitted non-professionals to start to map areas and record change themselves across sites more relevant to their own needs. This democratization of data collection has supported “citizen science” or “crowd-sourced data collection” initiatives that have significant potential when they are conducted in a manner that reflects best practices and encourages thoughtful collection and dissemination of data [21,22]. The idea of a citizen science seafloor data collection has been promoted by the International Hydrographic Organization (IHO) since 2014 as a low-cost and scalable method of data collection, applied in areas that otherwise could not practically be surveyed or monitored by external agents such as researchers, scientists or consultants. The use of crowd sourced data builds upon the idea of repeated sampling can reduce the overall error, as there is limited ability to include the impacts of ship roll, sonar placement, and high precision Global Navigation Satellite Systems (GNSS) signals across different survey set-ups [13]. It is important to recognize that crowd-source bathymetric data should be used with caution as it does not have the same rigor of data checking, cleaning, and analysis, as that collected in professional surveys [23, 24, 25], although there is still significant utility in the collection of this type of data.

The communities of the Inuvialuit Settlement Region (ISR), Northwest Territories, Canada, are located within and dependent upon coastal and riverine settings and changes to these environments hold significant ramifications for their security and sustainability. The shallow bays and channels through which they must navigate to access many of their fishing and hunting grounds are easily altered during seasonal water level changes, waves, and storm events [26, 27]. Tuktoyaktuk (Tuktuuyaqtuuq), located on the Beaufort Coast, is one of the four coastal communities of the ISR. The community has highlighted the

urgent need for more timely and detailed bathymetric data to address concerns over threats to critical areas of the harbour infrastructure, its channels and deep water access and coastal erosion defenses. In contrast, the riverine communities in the ISR, such as Aklavik (Akłarvik), are primarily concerned about recent and unpredictable bathymetric changes to the waterways that provide navigation and transport routes to critical hunting and fishing grounds along the coast. Addressing these concerns requires more current and repeatable datasets of sufficient coverage and consistently. However, contracting external consultants or researchers takes time and significant funding leading to outdated and fragmented surveys, often conducted from science vessels that cannot access the shallow inlets, navigation channels and nearshore areas that are of greatest concern to Arctic communities.

The dependency loops that impact many local authorities where a lack of capacity and resources lead to reliance on fragmented projects offered by external providers are particularly acute in Arctic communities who often need to make complex or time-sensitive decisions based on limited or inappropriate information. However, the wider range of skills and capabilities within the community can provide an opportunity to redress this through the implementation of the 2018 Inuit Tapiriit Kanatami (ITK) National Inuit Strategy on Research (NISR) [28, 29, 30]. In addition to the wealth of traditional, local and Indigenous Knowledge about changes to coasts and rivers that are most relevant and significant to their safety, security and livelihoods, Arctic peoples are highly skilled in watercraft. Typically using small boats with shallow drafts, they can access waters and previously unmapped areas that are inaccessible to science vessels. The use of locally collected data of nearshore bathymetry in areas of community concern places data acquisition and data sovereignty back into the hands of the community. Here we present a co-developed method of collecting more timely and high-resolution bathymetric data with the communities of Tuktoyaktuk and Aklavik, in which the Hunters and Trappers Committee (HTC) of each community delineated the priority areas of concern and worked with researchers to organize the training, data collection and initial analysis of the data. The aims of this co-development have been to: (1) develop an effective methodology for the collection of usable bathymetric data by community members; (2) examine and evaluate the quality of the data collected in Tuktoyaktuk Harbour by the community and its research partners over the 2022 – 2024 summer seasons; (3) compare the focus and application of the community-led bathymetric data between the different coastal and riverine settings of the two Arctic communities.

Study area

The ISR was established 1984 after the signing of the Inuvialuit Final Agreement and covers the northwest part of the Northwest Territories and the northern portion of the Yukon, covering an area of 1,172,749 km^2 [31]. There are six communities of the ISR, Inuvik and Aklavik situated on the Mackenzie River and Tuktoyaktuk, Paulatuk, Sachs Harbour and Ulukhaktok located on the coast (Figure 1). This study will focus on two of the communities in the ISR, The hamlet of Tuktoyaktuk located on the Beaufort Sea Coast, east of the Mackenzie Delta and Aklavik, located on the Peel Channel of the Mackenzie River (Figure 1), although it should be noted that the approach is currently being applied in several other communities including Paulatuk and Ulukhaktok. Hunting, fishing and trapping are vitally important and culturally significant activities for these communities, which is reflected in their locations along the coast and river.

The hamlet of Tuktoyaktuk is located on the Beaufort Coast, east of Kugmallit Bay which is part of the Mackenzie River Delta (Figure 1). The community uses harvesting as a significant source of food, with 60% of households consuming country food, and 55% of households hunting, fishing and berry gathering

[32]. The coastal regions near the community of Tuktoyaktuk are generally shallow, with the bathymetry of Kugmallit Bay generally less than 4 m, with the exception of a 9 m deep channel extending to the East Channel of the Mackenzie River [33, 9]. The shallow bathymetry leads the region to be susceptible to rapid seafloor changes caused by changes to the timing, characteristics and severity of storms [34, 3], impacts from landfast ice dynamics [35, 33, 9], and high levels of sediment input from eroding coasts, river inputs or human activity. The region experiences micro-tides, with an average range of 0.4 m [36]. The significant local water level changes caused by storm surges and extreme ocean waves impact compound hazards that threaten people and cause accelerated erosion, loss of access, and damage to coastal infrastructure [37, 38].

The hamlet of Aklavik is located on a bend of the Peel River, on the western side of the Mackenzie Delta (Figure 1), about 115 km south of the Beaufort Sea [39]. Flooding, which had occurred every ten years based on knowledge from community Elders, became more frequent during the 1950s, resulting in the relocation of most major facilities to what would become Inuvik, although many residents chose to stay in Aklavik [39]. Hunting, fishing, and berry gathering are important to the community with about half of the community members participating in these activities [32]. Boaters typically travel throughout the local river network and many Aklavik residents undertake the ~130 km journey to their fishing camp at Shingle Point (Tapqaq) on the Yukon coast between June and September.

Discussion

Many papers represent science in Arctic communities, particularly those where environmental processes are posing continuous challenges to everyday activities, as being on the frontier of climate impacts. In contrast to the portrayal of Arctic communities as powerless victims [40], or research teams as extractive agents that perpetuate neo-colonialism through the portrayal of ‘saviour narratives’ or techno-fixes, there has been increasing recognition of the resilience, adaptability and innovation occurring in such communities, galvanized by the priority areas set out in the NISR. The mobilization of social enterprise initiatives supporting transport over ice, such as SmartICE [41, 42] or collective efforts such as contaminant [43] or wildlife monitoring [44] programs are proven models of achieving local sovereignty and wider collective benefits between communities and beyond with positive interactions with external support. Many of the success stories center on aligning activities with community priorities and skillssets, rather than trying to deliver externally produced objectives. Although the bathymetric mapping initiative has involved external researchers, throughout, the priorities, ownership, and logistics have been driven by the local communities involved. This has meant that both the approaches and the outcomes have differed according to their specific needs, capacity and resources.

The co-development processes have benefitted from organizational structures provided through the HTC’s that facilitate continuous dialogue between program members from within and external to the community. This flow of communication was essential to shape, refine and refocus the work as the program evolved. Whilst the exact process required flexibility depending on the specific existing roles within the community group a strong community lead was a constant requirement for successful progression. The different approaches between communities emphasized the need for flexibility and the key role in local leadership, with the identification of key markers to support repeated navigation route tracking critical to Aklavik residents, but detailed gridded mapping within and around the harbour infrastructure requiring a much more systematic approach to the organization of data collection in Tuktoyaktuk. Perhaps one of the most significant outcomes of this process has been the recognition of multi-functional deliverables for both the community needs and scientific advances. Local priorities

typically centred on achieving the most current maps to work with, supporting safe navigation and current information with which to make decisions, whilst the researcher interests tended to prioritize the rates and nature of changes occurring, comparing between datasets, a common requirement to understand geomorphic changes in bathymetry [45].

A critical requirement for mutually beneficial and multi-purpose bathymetric data was that it achieved sufficient data quality and consistency to be used in this way. Using affordable (<$3000 CAD) sonar, which are sold primarily as fish finders and generic mapping tools means wider beam width than professional multibeam echo sounders, impacting the resolution of features detectable but it is the GNSS positioning that potentially has the biggest impacts. However, the use of newer systems that integrate side-scan with GNSS provides sufficient resolution for accurate mapping [19] and in the relatively shallow waters of Beaufort Sea coastline features like small rocks and tires were easily discernible. The research team needed to be adaptable to both the local setting and the desired local applications of the bathymetric mapping to appropriately assess data quality and consistency across different boat crews and collection scenarios. A particular advantage to the sonar systems used was the simple workflow to achieving rapid visualizations of new data in the context of the wider pre-existing dataset. This enabled each survey to be seen as part of a bigger initiative and enabled many instances of reflexive improvement of data collection as crews could see where boat speeds were too fast or there were issues with the data quality that needed discussing with the research team.

All communities required specialized and tailored training that focused on the stated community priorities and progressed through practical data collection and data assessment and upload to interpretation. Fitting the sonar systems to locally owned boats enabled strong engagement throughout. In all instances the leadership of the HTCs meant that autonomously organized local data collection followed soon after the training with the research team, and because they were using their own boats data was continuously added through ad-hoc collections when they were using their boats anyway, and petrol costs covered through agreement with the HTCs. Regular communication and troubleshooting provided continuing technical support after initial training. Working through the leadership provided by the local HTC supported more sustainable data collection practices because they have the agency and resources to secure future funding to maintain the datasets beyond any single funded project. This longevity also generates significantly more valuable data in spatial and temporal extents that can be made available to researchers for more advanced analyses. The use of C-Map Genesis provided an effective balance between local sovereignty over the actual data and wider accessibility for other users (within and beyond the community) on a more superficial level.

The co-production process has evidenced how a combination of local, traditional and Indigenous knowledge and tacit experience from highly skilled local boat owners and drivers provides datasets of superior coverage and utility, even with less high-grade systems than those used for specialist bathymetric mapping. And yet the support, training, and guidance of the research team throughout the development and continued running of the program has been an essential element in producing multi-functional, useful datasets. Arctic peoples are the best students of the changes undergone by landscape and waterways, and building this into data collection has led to genuinely transformative improvements in the research outcomes as well as meaningful support for the wide range of focus points relevant to community safety and decision-making.

Methods and data quality analysis

Whilst the detailed delivery of this work has been co-developed between researchers and impacted communities, the initiative has been driven by northern communities, set up to be run and maintained by local residents, and the outcomes made directly and continuously available to community authorities to support decision-making with appropriate, current and timely information. In each community initial co-planning and collaborative funding was secured through the Crown-Indigenous Relations and Northern Affairs Canada (CIRNAC) Climate Change Preparedness in the North program; Canadian Hydrographic Service – Community Hydrography, and CINUK NUNA project to supply local boats with affordable sonar units that would produce appropriate and interpretable bathymetric surveys. The research team provided support for the installation of the units and training for their operation and data handling as well as discussing the interpretation of different bathymetric features and offering continued support remotely but from then on the program has been community owned and run. It should be noted that although specific funding was secured by the research team for the purchase of the initial sonar units, the vision of this work was to create a legacy beyond that of a single project and to develop a community owned and led program of work that they can sustain over future years.

Community bathymetric data collection program

The implementation of the community bathymetric data collection program was initially created to address the lack of updated bathymetric data in many areas of significance. The success of other large-scale crowd-sourced bathymetric data collection initiatives, for example the Olex dataset which is a commercialized charting system that allows fishing vessels to record and share bathymetry with other participating vessels [13], was used as a framework for this application on a smaller scale. While the use of recreational grade sonars cannot match the accuracy of more complex systems, it can provide datasets in areas not viable (in terms of scale, logistics, or cost) for collection by external agencies and at a frequency sufficient to identify changes occurring in the nearshore.

Based on cost accessibility and its use in past research studies the Lowrance HDS-Pro fish finder with Active Imaging™ HD 3-in-1 Transducer (CHIRP, SideScan and DownScan) was chosen and installed on participating local boats (arranged through the local HTCs). The addition of high accuracy GNSS was deemed cost prohibitive and against the accessibility and crowd-sourced ethos of the program to use repeated sampling to improve data quality [46, 13]. Therefore, the internal GNSS of the Lowrance sonar was relied upon despite it's lower accuracy compared with external real-time kinematic GNSS systems [14].

Data for the program was first collected in 2022 and has continued to present. In the beginning, 5 local vessels in Tuktoyaktuk and 14 in Aklavik were fitted with the Lowrance HDS-Pro sonars. Workshops conducted in each community specifically included instruction on the basics of surveying, how the sonars worked, their settings and capabilities, and how to record and save the data (Figure 2). This was followed by practical sessions on data collection in local waters with each boat crew, with ongoing technical discussions between boat crews and researchers to troubleshoot sonar operation and refine bathymetric data collection procedures. The implementation of this program was guided by the best practices proposed for the collection of crowd-sourced bathymetric data [47], which were used as a general framework to co-develop a series of phases for delivering usable bathymetric data within each community (Table 1). This study analyzed environmental sonar measurements and bathymetric mapping products generated through a program led by the Tuktoyaktuk and Aklavik Hunters and Trappers Committees.

Community members contributed as boat operators, data collectors and research collaborators. Meetings and ongoing technical discussions guided program planning, survey priorities and equipment operation; they were not used to collect or interview, question or expert-elicitation of data. The research did not assess individuals' behavior, attitudes or experiences.

In the first year, most bathymetric measurements were collected by community boat operators using vessel-mounted sonar during routine fishing and other recreational activities (Figure 3). This created a large area of coverage that effectively captured areas of interest to the local community, but with significant data gaps. In Tuktoyaktuk, as the area of desired coverage was significant, in the following years the HTC organized specific surveys to ensure mapping of the harbour as a critical strategic asset and peripheral areas of concern (e.g. nearby hunting and fishing grounds and important navigation routes). Individuals also collected data in their normal activities to continually add to the wider bathymetric dataset. In areas affected by coastal erosion or susceptible to storm waves smaller inflatable boats were used to capture the shore profile in the nearshore and intertidal zones often missing from datasets collected from conventional scientific or professional vessels.

The most essential role in facilitating the co-developed workflow was a dedicated central data coordinator, based at the HTC who would receive the SD cards from the collectors. The coordinator viewed the data in ReefMaster Software Limited (v.2.0) to look at the areas of data collected and visually assess any obvious issues with the overall data quality. Through this process, minimal cleaning of the data could be undertaken if necessary and it provided an opportunity to guide decisions over where to focus further surveying. In the early stages, continuous data review also allowed the optimization of boat speed for maximising coverage whilst maintaining effective data collection and integrity. The coordinator would then compile the checked data and upload it to the social map in C-Map Genesis (Figure 2) [48]. This site was chosen as it provided a mechanism to share their collected datasets directly as useable maps with the community. This method of uploading visualizes the data without any significant processing to remove errors, reducing the time and resource input but limiting the number of applications to those appropriate for general bathymetric feature identification, patterns, and for identifying areas of potential change for further investigation. Prior to this program there was minimal bathymetric data coverage of the areas of community interest on the C-Map genesis site (Figure 2). The results of mapping outcomes applied to the different Arctic community settings have been compared, highlighting the importance of local data sovereignty and leadership of the applied program objectives.

Data Quality Assessment

A high resolution multibeam bathymetric dataset of Tuktoyaktuk harbour collected in 2014 has been used as a comparison to the new community collected dataset. The Tuktoyaktuk community bathymetric data were shared with the research collaborators for further analysis and identification of areas for improvement for the survey methodology and data handling. The data were imported into Reefmaster [49] to examine the quality of the bathymetric maps and to export them for further analysis. The sonar tracks were assessed individually and errors in the data removed or corrected to ensure that the automatic depth measurements represent the observed data. Sources of error typically occurred when the speed of the vessel collecting the sonar was too fast (over 12 km/hr), sudden changes in bathymetry led to incorrect seafloor mapping by the automated depth picker, or where areas of dense seabed vegetation caused artificially shallow depth measurements. Tide measurements were incorporated into the datasets analyzed in Reefmaster, using measurements from the Tuktoyaktuk Tide gauge [36]. The cleaned bathymetric data were then exported as comma separated values (CSV) files for further analysis in ArcGIS Pro 3.1 (Figure

2) [50]. Interpolation of the dataset was completed in ArcGIS using Kriging with barriers to include the importance of the complicated geometry of the harbour and the presence of islands which impact bathymetry.

Though the use of consumer-grade sonars has many benefits, the quality of the bathymetric data is lower resolution than that collected with typical research methods. To provide some contextualization of the internal errors in the community bathymetric data, a GIS near analysis was completed to assess the agreement between points (Table 2). The depth measurements of the data points were compared to other points in the community datasets if those two points are within 0.1 m. This distance was chosen as it is expected that the natural topographic changes are unlikely to be significant within a 0.1 m range and it corresponds to an expected sonar beam footprint at shallow depths, although this may not be valid on very steep slopes. This analysis was completed for all points in the survey, and compared for the entire survey, as well as those within the same sonar track and between different tracks (Table 2). Those in different survey tracks are further divided into the same year or different years.

The average difference in the measurements of the near analysis was 0.16 m, with a standard deviation of 0.25 m. Based on the comparisons, those measurements that are taken within the same survey track are the most similar, although the maximum depth difference was 0.71 m. It is expected that the internal consistency would be the greatest for measurements within the same survey tracks as many of the potential factors adding to error of the measurements are the same. For example, the differences caused by the mounting of the sonar, including the sonar draft and the angle of the sonar, and potential issues with the tidal correction would not apply to measurements made on the same day and close in time. This analysis suggests that the mean within-track depth difference was 0.03 m (average difference across the surveys). The largest average difference in the near analysis was between datapoints collected in different years at an average of 0.36 m (Table 2), this may be due to differences in the draft of the boats, the angle of the sonar, speed of the boats, tidal corrections or changes in the seafloor. There is no systematic difference in the accuracy of the datapoints collected and analyzed in the near analysis based on the depth of the measurement. Further analysis could explore the potential to automatically correct the influence of vegetation or slope on the depth measurements to improve data accuracy as necessary for specific applications.

Data and Information Useability

Community leadership shaped where, when and how bathymetric data were collected, with sonar data collected by 5–7 community boat operators in Tuktoyaktuk and up to 14 in Aklavik. HTC meetings guided survey locations and timing, while the HTC-based data coordinator linked collection, ongoing quality assessment and identification of coverage gaps. In Tuktoyaktuk, sonar records collected during routine boating trips revealed coverage gaps that prompted eight coordinated surveys of harbour infrastructure, navigation channels and surrounding coastal waters, some lasting several days. By 2025, much of the harbour was considered sufficiently mapped for immediate community needs, and surveying shifted towards the Kittigaryuit region of the Tarium Niryutait Marine Protected Area, an important local harvesting area. Public meetings in March 2024, 2025 and April 2026 provided further direction on priorities outside the harbour. In Aklavik, all surveys were undertaken independently by local operators, focusing on navigation routes through the river network. These contrasting approaches allowed survey effort to respond to local priorities and changing information needs.

The resulting data were shared through C-MAP Genesis and Transport Canada's Enhanced Maritime Situational Awareness (EMSA) system, allowing locally collected bathymetry to be visualized alongside other marine information. Boat crews used shared maps to identify coverage gaps and consulted previous tracks when travelling through surveyed waterways, demonstrating practical use during the study period. However, the extent to which these products reduce navigation incidents, influence infrastructure decisions or inform policy remains to be evaluated. Continued collection across successive seasons also demonstrates operational continuity, although sustainability beyond individual funding arrangements requires longer-term assessment.

The program contributes to citizen science through community-operated collection of environmental sonar data while retaining the distinct governance of Inuvialuit-led monitoring. Experienced boat operators applied their knowledge of waterways, travel conditions and harvesting priorities to survey planning and data collection, while the HTCs retained authority over survey priorities and data sharing. The resulting bathymetric datasets were produced through community-led data collection, supported by researchers' assistance with sonar equipment, processing and analysis.

Community collected bathymetry

During its first 3 years, the sonar data collection program has acquired almost 2468 km of sonar data in areas of concern to the Tuktoyaktuk community and 17,360 km in the rivers and coastal regions of interest for Aklavik. The overall coverage of Tuktoyaktuk harbour is relatively extensive, though areas without coverage are still present and have been added to collection plans for subsequent years. The amount of data collected varied significantly from year to year (Figure 3), depending on the needs and evolving priorities of the community. For example, less data were collected in Tuktoyaktuk harbour in 2025, where current coverage was deemed sufficient except some areas of interest in recent change potential, and instead community focus was on mapping the bathymetry of the Kittigaryuit region of the Tarium Niryutait Marine Protected Area (TN MPA), an area that is used for whaling to the southwest.

When the early datasets were interrogated by community members certain key features detected became of particular interest. The resolution of the sonar data, collected by different vessels and crews over the different years, was sufficient to visualize subtle seafloor features such as persistent areas of relatively soft sediment (Figure 4 Top). As the tracks for these sonar passes are not directly coincident, there are some variations in the appearance of the deposits but the ability to monitor the overall extent and annual changes of subtle (little elevational difference) features is reflective of the relatively settled seafloor within the harbour. Other features of interest included linear features such as anchor drag marks from heavy vessels and the vital water pipe that crosses Tuktoyaktuk Harbour, and the nearshore remnants of failed coastal defences including the remains of rip-rap and tyres that had once been used to protect against erosion (Figure 4 Bottom). Such discoveries have allowed the community to consider the impact of legacy issues such as whether they may be supporting (if the rocks form new habitats) or threatening (if the tires release contaminants) the marine ecosystem.

The resulting information was integrated into community-oriented data-sharing platforms, including C-MAP Genesis and Transport Canada's Enhanced Maritime Situational Awareness (EMSA) system, providing mechanisms through which locally collected bathymetric information could be visualized alongside other marine information. Boat crews frequently checked which areas had not been surveyed

when working in primary areas and used past tracks to support safe navigation when travelling between them. The community map also enabled the research outcomes to be of genuine benefit for the wider communities using the waterways, an open access resource that they could use to plan safe passage.

The inclusion of community-collected bathymetry within EMSA extends the value of the monitoring program beyond the production of individual survey datasets by providing more current information from shallow and nearshore areas where conventional hydrographic coverage may be limited or outdated. These are also areas of particular importance to local travel, harvesting, harbour access and coastal infrastructure. The program therefore provides a mechanism through which observations collected in response to community priorities can also contribute to a broader maritime situational awareness framework. Importantly, this does not require communities to relinquish control of their original datasets; decisions regarding what information is shared, and with whom, remain with the respective Hunters and Trappers Committees. In this way, the program demonstrates how community-led monitoring can simultaneously support local decision-making and contribute relevant observations to wider regional marine information systems.

Comparison with external datasets and applications

In addition to assessing the internal accuracy and consistency of the community bathymetric data, it is helpful to compare its performance against an externally produced dataset using higher end systems. A comparison between the community bathymetric map and a 2014 multibeam survey collected from a research vessel (Figure 5). Whilst it should be noted that there is up to a decade of genuine potential change between the datasets, the analysis of persistent subtle features is supported by strong agreement in the overriding bathymetric patterns of deeper pockets and channels. The higher resolution of the multibeam data affords sharper definition to the features and potentially is able to detect smaller features that are either obscured in the coarser community data or have infilled in the intervening period between the surveys. However, the coverage of the community dataset is far superior, and the flexibility and cumulative benefits of being locally sourced are evident. The coverage is not just significantly greater than can practicably be achieved (in terms of cost, time windows available for a single visit and resources) through an external contract, but the shallow nearshore areas that cannot be accessed by larger vessels can be captured with a combination of shallow draft small boats and skilled local navigators.

The ability afforded by local experience, vessels, and watercraft, to provide bathymetric data that covers areas such as the shore slope and shallow river channels, which are typically inaccessible to survey vessels, is of crucial importance to the value of the data. Conventional surveys are usually limited to assuming a linear interpolation from the edge of the bathymetric data to the shoreline, which can be tens to hundreds of meters apart. This data gap has particularly important implications for modelling alongshore sediment transport, as nearshore bathymetry strongly influences wave transformation, nearshore circulation and resulting patterns of sediment transport [51], flooding risk to infrastructure [52], and wave interactions [53]. Whilst navigation safety was the primary driver behind the collection of community sonar data in these areas, the production of a more complete, relevant, and current map enables its use in wave modelling. A Simulating WAves Nearshore (SWAN) wave model was implemented using the locally collected bathymetry with peak wave period of 10s and wind from 337.5° (relative to North) at a speed of 20.3 kph. Simulations were conducted for various extreme scenarios, considering 1/100-year wave conditions (producing a significant wave height of 2.7 m) and sea level rise projections for a medium emissions scenario up to 2100 (equating to 1.05 m). Simulations were run for all previously available data (which included the 2014 multibeam survey and globally available General

Bathymetric Chart of the Oceans (GEBCO)) and then with the addition of the community dataset and comparing the differences in outcomes (Figure 6). There were no tangible differences with the professionally collected scientific datasets in offshore areas but the coverage achieved by the community data produced important increases in significant wave height along the exposed western coastal face of the community, potential reduction in wave height at the northern point of Tuktoyaktuk, and smaller but important increases in the eastern inner harbour area, where locals have already noted increasing erosion rates over recent years [54]. The model comparison illustrates the sensitivity of predicted wave heights to bathymetric coverage; assessing changes in predictive accuracy would require comparison with observed wave conditions.

Community-led bathymetric mapping supports climate adaptation by connecting locally identified information needs with data collection and analysis relevant to community decisions. In Tuktoyaktuk, HTC planning discussions and feedback at public meetings guided the selection of survey areas beyond the harbour. These exchanges supported program coordination and were not collected or analyzed as human-participant research data beyond the harbour. This demonstrated how community priorities and engagement shaped monitoring activities. Incorporating the resulting bathymetry into coastal wave modelling strengthened the information available for assessing coastal hazards. This provides a practical connection to sustainable development goals (particularly on climate resilience and adaptive capacity), while operator training and independent bathymetric surveying support the capacity-development objectives to support climate action. Demonstrating the subsequent use of these products in navigation, infrastructure or coastal-management decisions provides further evidence of their contribution to adaptation.

Conclusions

A number of critical factors have converged to enable a co-developed, community-operated crowd-sourced bathymetric monitoring program to deliver data that is scientifically useful, locally relevant, and more sustainable than conventional externally contracted surveys. These include a combination of strong local leadership and existing organizational structures, affordable, integrated commercial grade sonar systems, simplified semi-automatic processing and visualization of data made publicly available for viewing, skilled local boat owners engaged with the program, continuous remote and regular in-person support from the research team willing to work beyond conventional project-related funding constraints. Community-led bathymetric mapping can fill persistent spatial and temporal gaps in conventional Arctic hydrographic data, and those additional observations can improve coastal hazard assessment Key findings include:

1. Community-led sonar mapping is a viable method for generating usable bathymetric data.

Over 2022–2024, community operators using affordable (<$3,000 CAD) recreational-grade sonar systems produced over 400 km of overlapping bathymetric tracks in Tuktoyaktuk Harbour alone, achieving spatial coverage in nearshore, shallow, and hard-to-access areas that conventional research vessels cannot practically survey.

2. Data quality, while lower resolution than multibeam systems, is internally consistent and fit for many purposes.

The near-point analysis showed strong within-track consistency, with a mean depth difference of 0.03 m, compared with 0.36 m between years. These comparisons support the use of the data for identifying bathymetric patterns and areas warranting further investigation, while differences between years may reflect both survey uncertainty and genuine seafloor change. This indicates the data has the potential to be for pattern identification, and change detection, even without high-accuracy external GNSS.

3. The datasets have genuine scientific and applied utility beyond navigation.

Incorporating community-collected bathymetry into SWAN modelling altered predicted wave heights along exposed and erosion-prone shorelines, demonstrating the importance of nearshore data coverage for coastal hazard assessment.

4. The data revealed features of direct relevance to community and ecological concerns.

Repeat surveys identified soft-sediment deposits, anchor drag marks, infrastructure (e.g., a freshwater pipeline), and legacy coastal defense remnants (rip-rap and tires) washed offshore, findings with direct implications for habitat assessment, contaminant risk, and infrastructure monitoring.

5. Co-production through the Hunters and Trappers Committees (HTCs) was central to success.

Local leadership and ownership (rather than externally driven objectives) enabled sustained, low-cost, ad-hoc and structured data collection, with rapid data sharing enabled via an accessible, semi-processed public map. The alignment of research approaches with community priorities, capacity, and Indigenous and local knowledge (consistent with the National Inuit Strategy on Research framework) provided a scalable model balancing data sovereignty and accessibility.

6. Community needs shaped divergent but equally valid methodologies.

The coastal setting of Tuktoyaktuk required systematic, dense and often gridded harbour mapping to address infrastructure and erosion concerns, while riverine Aklavik prioritized route-marker tracking for navigation, demonstrating that a single rigid protocol would not suit the diversity of Arctic community contexts, and that flexibility in method was itself a success factor.

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Data availability

For the purpose of open access, the authors have applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript (AAM) version arising from this submission. The bathymetric data generated through this research are owned by the Aklavik Hunters and Trappers Committee and the Tuktoyaktuk Hunters and Trappers Committee. Consistent with principles of Inuvialuit data sovereignty, ownership and decision-making authority over access, use, and sharing of these data remain with the respective Hunters and Trappers Committees. Derived products are made available for public viewing through C-MAP (www.genesismaps.com/socialmap) and the Enhanced Maritime Situational Awareness (EMSA) platform. Requests for sonar line by line data access should be directed to the respective Hunters and Trappers Committee and are subject to community approval and applicable data-governance protocols.

Competing interests

The authors declare no competing interests.

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Author contributions

R.L.: Writing – original draft; Writing – review & editing; Data curation; Formal analysis; Visualization. M.L.: Writing – original draft; Writing – review & editing. T.R.: Investigation; Project administration. M.G.: Investigation. D.K.: Investigation. C.G.: Investigation. J.D.S.: Investigation. R.M.: Investigation. J.M.: Analysis. D.W.: Conceptualization; Project administration; Supervision; Writing – original draft; Writing – review & editing.

Figure Captions

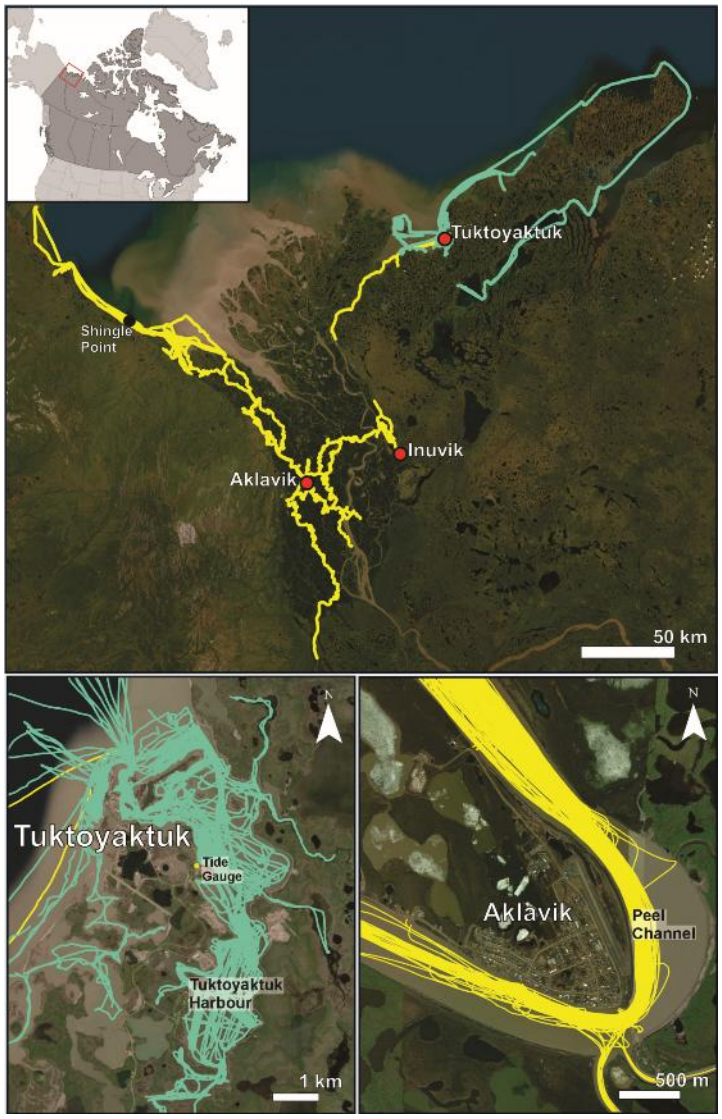


Figure 1: Study area map showing overall survey tracks of the bathymetry acquisition, with details insets of Tuktoyaktuk (lower left) and Aklavik (lower right).

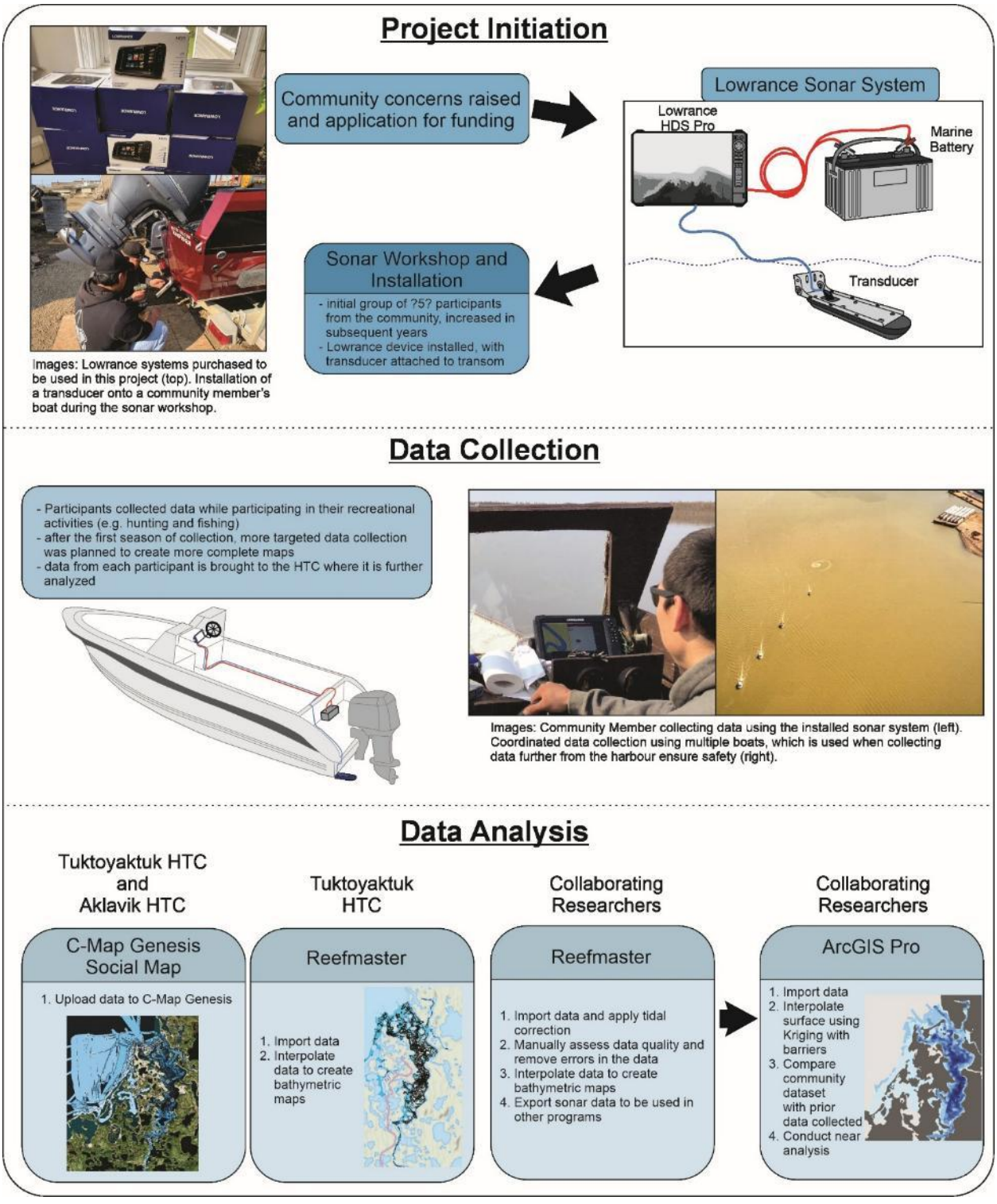


Figure 2: Detailed project schematic from installation, acquisition to data analysis.

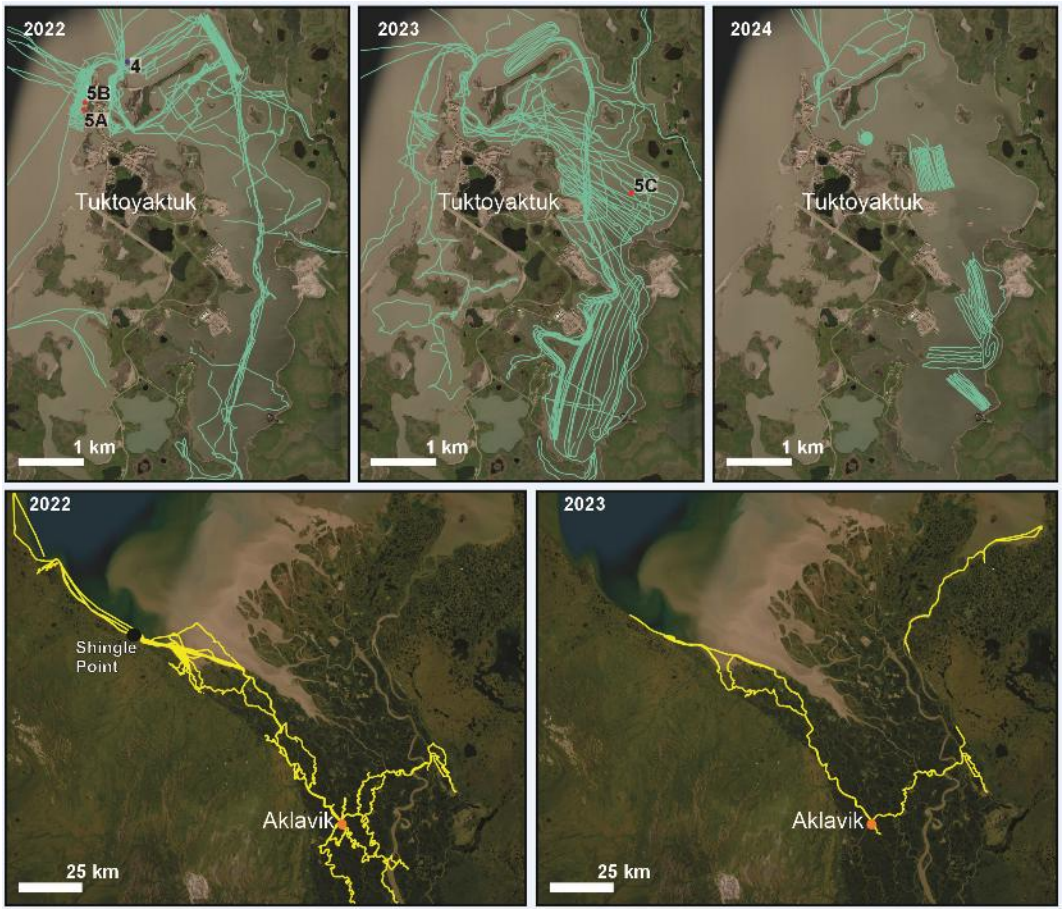


Figure 3: Scope of data acquisition between 2022 to 2024 for the Mackenzie Delta and Yukon coast and Tuktoyaktuk Harbour.

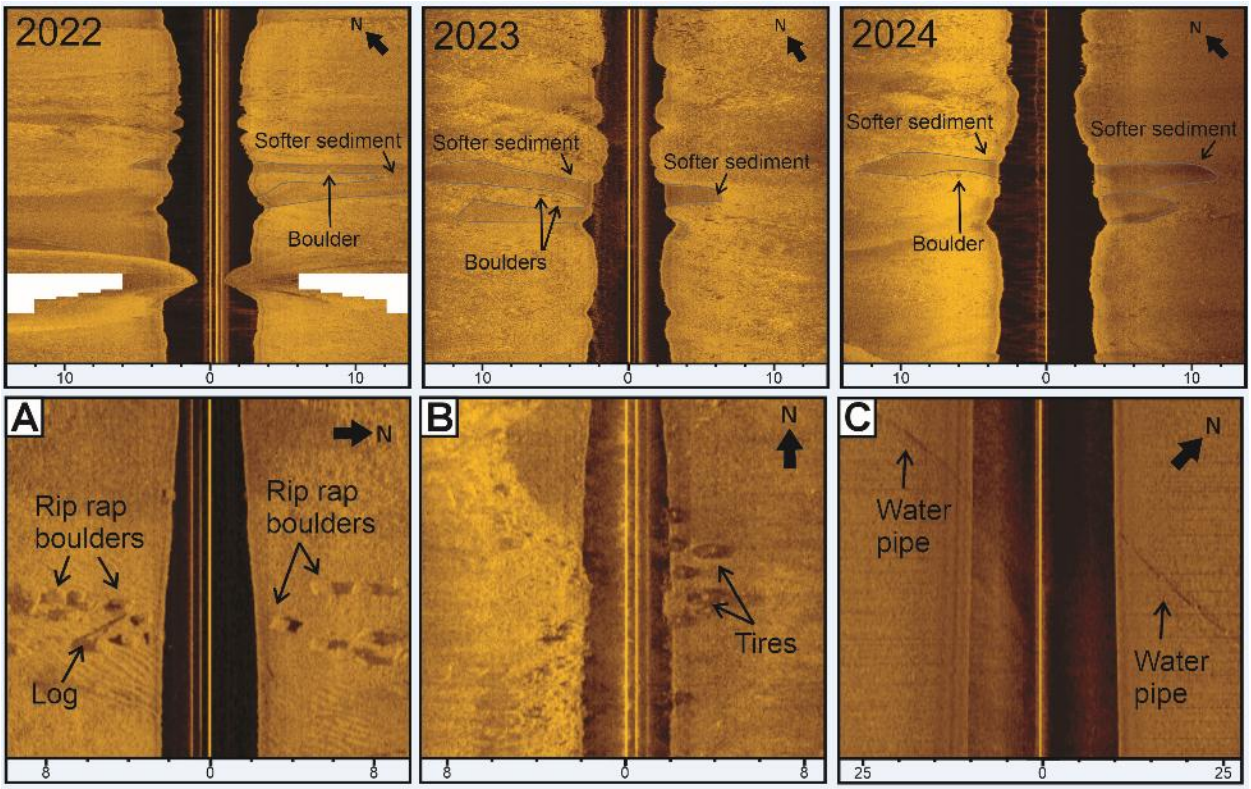


Figure 4: TOP: Multi-year (2022-2024) repeat surveys have been successful in detecting subtle seafloor difference such as localized areas of softer sediment seen here, which may have implications for marine life, and in subsequently monitoring changes over successive years. BOTTOM: Identification of linear features such as anchor drag marks, or the pipe connecting the community to it's freshwater drinking lake, and of legacy impacts like the migration of failed rip-rap or waste tire sea defenses.

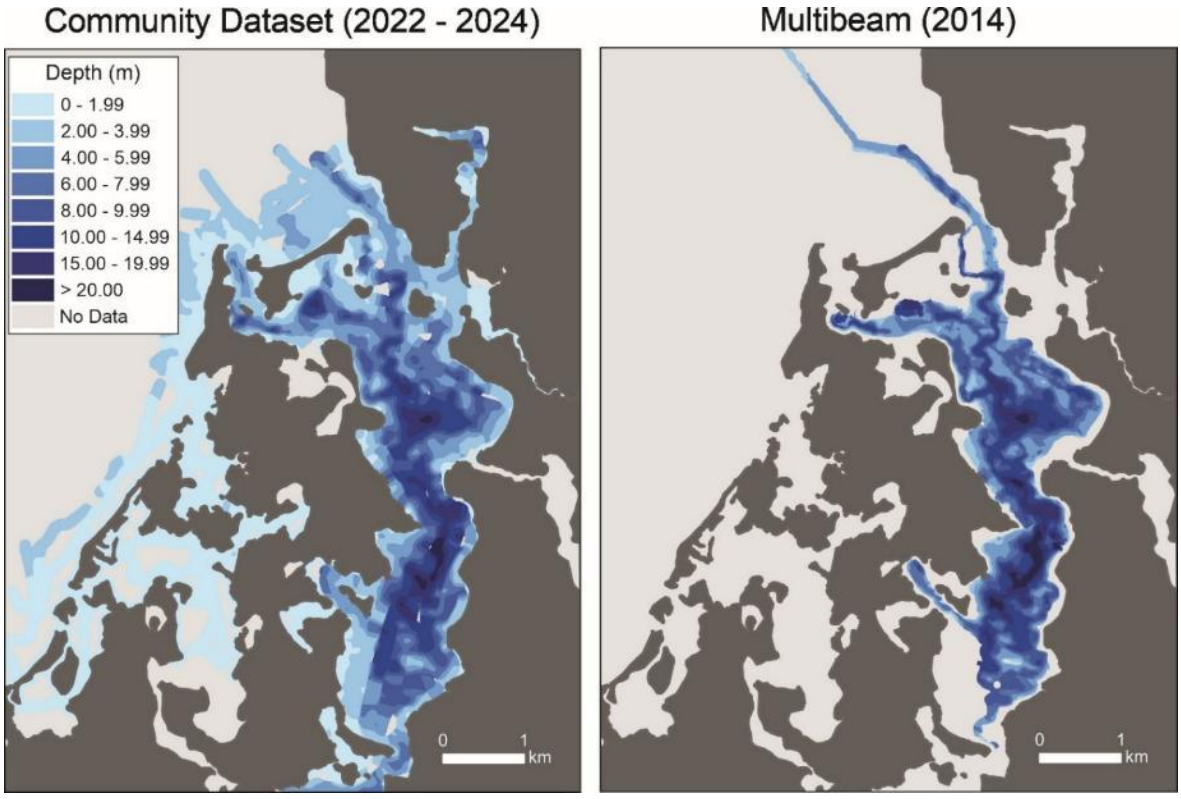


Figure 5: Comparison between community sonar data collected with low grade accessible systems versus a specific survey of the Tuktoyaktuk Harbour using a research vessel fitted with multibeam sonar.

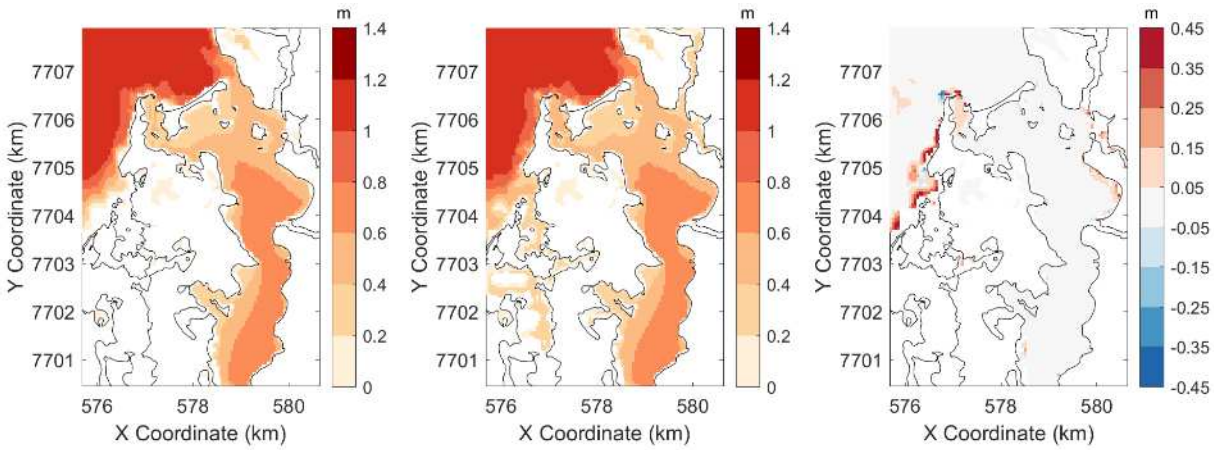


Figure 6: Comparison of SWAN significant wave height model outcomes in Tuktoyaktuk Harbour without (left) and then with community bathymetric data (middle) and the differences in the simulations (right).

Tables

Table 1: Summary of co-developed practices for good quality crowd-sourced bathymetric data collection with the considerations made in this survey program.

Guidance for crowd-sourced bathymetric data collection	Program Application
Bathymetric data collectors are experienced vessel operators and navigators	As the program was being led by community members. They are familiar with the coastal regions that are being surveyed, and have unique insights into the areas that are safely navigable and which areas would be the most advantageous for the community to receive data on.
Boaters are aware of the restrictions and impacts to local marine life of increased traffic and changing soundscape	The program is being led and guided by the Hunters and Trappers Committee this ensures that all operations adhere to the appropriate timing and locations of operations in and around marine life.
Ensure the equipment is appropriate for use and the limitations and practicalities are fully discussed	Workshops covered sonar operation, data collection guidelines (e.g., vessel speeds), and system limitations. Emerging issues and workarounds were shared through teams' existing communication networks, primarily social media.
The data are uploaded into a single repository. The ability for the data collector to visualise the data both out on the water.	The HTC holds its community's data and controls sharing with researchers and through C-MAP Genesis. Where timely updates benefit the community, automatic uploads within cellular range avoid transferring memory cards.
There is some level of data verification by knowledgeable users and compared with other available datasets to check data quality	Research collaborators assessed initial data quality, reported issues to HTCs, and prioritised comparisons with available bathymetric datasets. C-MAP Genesis filters errors before publication. External comparisons are recommended to assess general patterns and stable control features.
Data dissemination is viewed as an essential element of the workflow and utilises established structures for accessibility and timeliness	The program found CMAP genesis to be an effective method for wide sharing of data and updates through the social map. This makes it more accessible to the community and the wider public. In addition data was also shared through the EMSA platform for integration with other nautical aids.
Crowdsourced bathymetric data accepted into the host library included metadata and associated observations	Co-developed standards for field data capture included context and condition notes added to the bathymetry data files, team identifier tags for traceability and any images of screen data findings or issues.

**Best Practice phases (based on Stewart et al., 2020 and Calder et al., 2020), with consideration of the IHO Guidance on Crowdsourced Bathymetry and input from community survey teams.*

Table 2: Results of the near analysis conducted on the sonar datapoints which can be used to understand sources of error in the data collected for the Tuktoyaktuk region. The percent of values of the mean difference within +/- 0.15 m are recorded along row 1.

	All Datapoints	Comparison in same track	Comparison in different tracks		
			All	Same Year	Different Years
Mean difference in depth (m)	0.16 (67.7%)	0.03 (94.1%)	0.31 (38.1%)	0.29 (43.4%)	0.36 (28.6%)
Maximum difference in depth (m)	1.97	0.71	1.97	1.71	1.97
Minimum difference in depth (m)	0	0	0	0	0
Standard Deviation (m)	0.25	0.08	0.29	0.28	0.30
Number of Sample Pairs	1891	999	892	574	318