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BLINK AND YOU'LL MISS IT: EVALUATION OF A REDUCED- COMPLEXITY MODEL FOR ARCTIC DELTA MODELLING

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RÉSUMÉ

Kugluktuk, au Nunavut, est une communauté arctique située à l'embouchure de la rivière Coppermine qui fait face à une érosion côtière sévère, en particulier le long des îles du delta. Avec un cimetière historique situé près de l'escarpement de la plus grande île et des bâtiments au bord de la mer dans le village, l'érosion côtière représente un risque urgent et important pour la communauté.

Ce projet de recherche vise à mieux comprendre l'évolution du delta de la Coppermine au cours des prochaines décennies à l'aide d'un modèle à complexité réduite (MCR), ArcDelRCM. Ce type de modèle permet de modéliser à des échelles temporelles et spatiales plus grandes que ce qui serait possible avec des modèles hydrodynamiques grâce à une complexité de calcul réduit. Les MCR se concentrent souvent sur des processus à grande échelle, nécessitant des volumes de données importants pour reproduire avec précision les phénomènes observés sur le terrain ou produits par des modèles basés sur la physique. Entre 2021 et 2023, des données hydrodynamiques, bathymétriques, granulométriques et des photos saisonnières ont été collectées dans la région.

La recherche s'est concentrée sur le développement d'un nouvel processus d'utilisation du modèle pour adapter ArcDelRCM à être capable de simuler l'évolution à long terme des systèmes deltaïques matures. Des tendances globales des changements morphologiques prédit par le modèle correspondaient aux observations précédentes de terrain et les prédictions théoriques. La maturation graduelle des coulées («thalwegs») a créé des incisions dans le lit, en particulier le long des rives. Le modèle a été très sensible aux changements dans la résolution temporelle et spatiale, cependant, plusieurs variations de ces paramètres ont convergé pour produire l'expansion de la plateforme deltaïque submergée vers la limite du domaine de modélisation à long terme (c.-à-d. 300 ans).

ArcDelRCM a souffert des problèmes de stabilité non résolus aux résolutions spatiales plus fines, limitant son utilité dans son état courant d'agir comme modèle prédictif pour des changements morphologiques précises dans des deltas établis. Le modèle a réussi à simuler le delta à des résolutions spatiales moins fines avec un temps de calcul beaucoup plus bas que possible avec des modèles hydrodynamiques complexes, indiquant son utilité dans cette application de prédire des tendances globales du système.

Mots-clés : érosion côtière; modélisation; delta; rivière; arctique; modèle à complexité réduite; travail de terrain

ABSTRACT

Kugluktuk, Nunavut is an Arctic community built at the Coppermine River's mouth which faces severely eroding coastlines, particularly along the deltaic islands. With a historical cemetery close to the bluff of the largest island and waterfront buildings on the mainland, coastal erosion presents a major risk to the community.

This research project aims to better understand the evolution of the Coppermine Delta over the coming decades using a reduced-complexity model (RCM), ArcDelRCM. This model type allows for modelling at larger temporal and spatial scales than might otherwise be possible with hydrodynamic models due to reduced computational complexity. RCMs often focus on large-scale processes, requiring substantial volumes of data to accurately reproduce phenomena as observed in the field or as produced by physics-based models. Between 2021 and 2023, hydrodynamic data, bathymetry, granulometric data and seasonal photographs were collected in the region.

The research focused on developing a novel model-use process to adapt ArcDelRCM to be able to simulate the long-term evolution of existing, mature deltaic systems. Overall trends of delta morphological changes predicted by the model were aligned with previous field observations from the study site, as well as theoretical predictions. The gradual maturation of thalwegs created sharp incision into the riverbed, particularly along the banks of the river. The model proved highly sensitive to modifications of spatial and temporal resolution, however, several variations of these parameters converged to produce an expansion of the deltaic underwater platform towards the edge of the model domain over the very long term (i.e., 300 years).

ArcDelRCM suffered from unresolved stability issues in the higher spatial resolution test cases, decreasing its usefulness in its current state as a predictive model for specific morphological changes in established deltas. The model successfully simulated the delta at coarse resolutions with much lower computation time than possible with complex hydrodynamic models, suggesting its usefulness in this application of predicting overall system trends.

Keywords: coastal erosion; modelling; delta; river; arctic; reduced complexity model; fieldwork

SYNTHÈSE

CLIGNOTEZ ET VOUS LE MANQUEREZ : L'ÉVALUATION D'UN MODÈLE À COMPLEXITÉ RÉDUITE POUR LA MODÉLISATION DES DELTAS ARCTIQUES

Introduction:

De grandes portions de l'Arctique canadien sont couvertes par du pergélisol (c'est-à-dire les sols qui ont été gelés sans interruption pendant au moins deux ans), ce qui protège contre l'érosion côtière en rendant le sol plus résistant à l'action des vagues contre les côtes (Ressources naturelles Canada, 1995). De plus, la glace de mer qui se forme pendant l'hiver peut réduire les taux d'érosion côtière en limitant l'action des vagues (Barnhart et al., 2014). Avec le réchauffement de l'Arctique à trois fois les taux de réchauffement ailleurs dans le monde, des taux élevés de fonte du pergélisol et de la glace de mer ont été observés. Par conséquent, l'Arctique canadien a vu des taux d'érosion de 0,5 m / an et jusqu'à 20 m/an dans certaines régions (Lantuit et al., 2013; Solomon, 2005).

Les deltas sont des dépôts de sédiment qui se forment où une rivière se joint à une autre masse d'eau qui coule moins vite. Les deltas en Arctique sont différents que ceux dans des climats plus tempérés par ce qu'ils contiennent du pergélisol, ce qui change les processus morphologiques qui se passent dans ces deltas. De plus, la glace de mer se forme autour d'un grand nombre des deltas en Arctique, conduisant au développement des rampes de sédiment qui se descend dans l'eau jusqu'à ~2 m, une caractéristique commune des deltas Arctiques. Lorsque l'épaisseur de la glace de mer flottant achève son plus épais vers la fin de l'hiver, il s'attache au fond, permettant le transfert efficace de chaleur entre l'air froid au-dessus de la glace de mer et les sols gelés du fond marin, conduisant aux augmentations dans l'étendue du pergélisol, ce qui soutient la poursuite du développement des rampes peu profondes (Reimnitz, 2002).

Les deltas sont particulièrement importants à la recherche Arctique en raison de leur fréquence et leur utilisation substantielle par des communautés Arctiques, notamment comme source alimentaire et pour le transport des marchandises. Plus que 2700 deltas d'au moins 500 m en diamètre ont été identifiés dans l'Arctique canadien (Bendixen et al., 2025). Les changements dans la morphologie de ces deltas peuvent avoir des impacts substantiels tant sur les communautés que sur les écosystèmes. Étant donné que les côtes près de ces communautés

subissent présentement des taux élevés d'érosion côtière, ce projet les aidera à améliorer leur résilience aux changements climatiques rapides.

Problématique:

Historiquement, la modélisation a été réalisée en utilisant des modèles complexes basés sur la physique qui résout les équations théoriques pour le transport des sédiments et la dynamique des fluides. Ceci nécessite une variété des sources de données mesurées dans le terrain pour établir les conditions initiales pour le modèle (Bokulich, 2013; Liang, Voller, et al., 2015). Les modèles basés sur la physique simplifient les observations à grande échelle aux processus élémentaux qui peuvent être décrits par ces équations théoriques, ce qui peut mener à l'incapacité de reproduire des observations vues dans le terrain quand les phénomènes se produisent en raison de l'interaction entre ces processus aux échelles différentes (Werner, 1999). La charge de calcul de ces modèles fait que les prédictions à l'échelle décennale est difficile, ce qui suggère l'utilité potentielle des modèles moins complexe (et donc, avec moins de charge de calcul) à faire les simulations sur des échelles temporelles ou spatiales plus grandes.

Objectives:

Ce projet de recherche vise à incorporer le travail de terrain et la modélisation numérique pour avancer notre compréhension de la modélisation à complexité réduite (MCR) des deltas Arctiques. La partie de terrain contribuera à la petite base de données qui existe dans l'Arctique canadien, concentré sur les processus d'érosion et l'hydraulique de la région autour de Kugluktuk, Nunavut. La modélisation déterminera la faisabilité d'appliquer ArcDeIRCM aux deltas existants pour la modélisation à l'échelle décennale, ce qui améliorera notre compréhension de l'utilité des MCR comparés aux modèles basés sur la physique. Cette partie comprendra la modification du modèle pour permettre l'importation des données bathymétriques et une analyse des résultats générés par le modèle en utilisant les tendances observées lors de travaux sur le terrain précédents et des données de télédétection.

Méthodologie:

Cette recherche se concentre sur le delta Coppermine, à l'embouchure de la rivière Coppermine en Kugluktuk, Nunavut, dans le coin sud-ouest du golfe du Couronnement, un golfe

peu profond dans l'archipel Arctique Canadien. Kugluktuk est une communauté Inuit d'environ 1400 personnes (Statistique Canada, 2023). Le delta Coppermine contient deux îles deltaïques (**Figure 4**), dont le plus grand, Elogikhivik (dans ce rapport, «Graveyard Island»), possède un cimetière historique 20 m du bord de l'escarpement en érosion. Plusieurs types de côte existent dans la région (**Figure 5**), principalement le sédiment non consolidé avec des plages sableuses et des escarpements abrupts de 1–3 mètres en hauteur (Tanguy et al., 2024). Historiquement, la région avait le pergélisol continu faible/modérée, dont 90 % – 100 % du sol est le pergélisol (The National Atlas of Canada, 1995). Pendant la période estivale sans glace, la station hydrométrique la plus proche—102 km à mont du domaine de modélisation—a mesurée des débits d'environ $250\text{--}500\text{ m}^3\cdot\text{s}^{-1}$, avec des pics de $1000\text{--}2000\text{ m}^3\cdot\text{s}^{-1}$ pendant la période du dégel printanier (**Figure 7**) (National Hydrological Service, 2025). Les marées sont typiquement de 25-35 cm (Canadian Hydrographic Service, 1982). La plupart des vagues au large ont une hauteur significative de 0–0,8 m venant de plusieurs directions entre le nord et l'est. Les vagues plus grandes (c'est-à-dire $H_0 > 0.4\text{ m}$) viennent presque uniquement de la direction ENE ($67,5^\circ$), ce qui correspond au fetch maximum possible dans le golfe du Couronnement (Binette et al., 2024).

Des chercheurs et des chercheuses ont visité Kugluktuk pour des projets similaires à celui-ci depuis 2021 pour collecter des données telles que les profils de plage GNSS, la bathymétrie, le débit, le niveau d'eau, les données de vagues, les profils thermiques du sédiment, la topographie de la région, et plus encore. La carte bathymétrique utilisée dans ce projet est une combinaison des données sonar à faisceau unique (2021-2022), des profils de plage GNSS (2022), de la topographie et bathymétrie dérivée à partir des images satellites, et des données bathymétriques non navigationnelles. Cette diversité des sources de données ont permis d'obtenir les données bathymétriques de la plus haute qualité possible, et chacune d'entre elles ont offert une disponibilité spatiale différente (**Figure 8**).

ArcDelRCM utilise une maille des carrés uniformes sur l'ensemble du domaine de modélisation. Ce domaine a été choisi d'être carré dans tous les simulations (c'est-à-dire, les dimensions x et y sont identiques; $N_x = N_y$). La première colonne du domaine forme un mur imperméable et toutes les autres cellules utilisent une profondeur de bassin défini par l'utilisateur (h_B) à l'initialisation du modèle, créant un bassin vide. Dans le centre du mur ($\frac{N_y}{2}$) est une ouverture qui permet l'eau d'entrer dans le domaine en versant dans le bassin (**Figure 11**). Le modèle incorpore des processus du transport du sédiment, la couverture de glace annuelle et les effets thermiques sur le pergélisol.

Résultats:

ArcDelRCM a été exécuté avec une diversité des paramètres pour tester sa réponse aux variations qui pourraient se produire dans le milieu naturel. La taille du maillage (la résolution spatiale), le pas de temps (la résolution temporelle), le flux d'eau entrant dans le domaine de modélisation et le nombre de jours par année-modèle ont été variés dans 9 simulations.

Une analyse de la sensibilité du maillage a été effectuée, présentée dans les cas C1-C5, avec des résolutions spatiales de 50–160 m et des pas de temps correspondants de 7–75 heures. Les tendances géomorphologiques ont été similaires entre ces cas, mais l'inspection d'une région ou l'autre révèle des différences importantes aux petite-échelles. Généralement, les cas de haute résolution (C1 et C2) ont eu des taux d'expansion du delta similaire aux autres cas, mais ils ont crû plus longtemps vers la limite ouest du domaine avant d'arrêter à croître (**Figure 16**).

Dans le cas A1, des processus de l'érosion et de déposition graduelle se présentent, en particulier proche à l'ouverture dans le mur imperméable (**Figure 21**). L'étendue et la profondeur de la glace maximum sont au début de chaque année modélisée (à la fin de l'hiver), suivi par une période de fonte. Lorsque la glace a fondu rapidement, une augmentation correspondante du débit a souvent été observée (**Figure 23**). Dans plusieurs instances (par exemple, cas B1, **Figure 25**), des événements rapides de déposition se sont passés dans les premières deux années, ce qui a efficacement coupé l'accès à ces régions pour l'eau pour le reste de la simulation. ArcDelRCM a fortement accentué les régions d'hétérogénéité dans des données bathymétriques, menant de profondes incisions dans le lit de la rivière. Ce phénomène a été reproduit dans plusieurs cas avec des variations dans la résolution spatiale, la résolution temporelle et l'échelle de temps. De plus, le modèle a souvent dirigé l'eau directement adjacent aux rives de la rivière Coppermine comme le montre la **Figure 18**.

Sur de longues échelles de temps, ArcDelRCM a prédit une croissance de la taille de la delta Coppermine. Le taux d'expansion a été dépendant des paramètres initiaux de la simulation. Cette expansion deltaïque est reproduite à plusieurs échelles spatiales, en particulier le dépôt des sédiments à l'ouest de Graveyard Island, où ArcDelRCM prédit l'érosion du lit de la rivière menant au développement d'un canal qui permet le transport efficace de sédiment hors du plateau submergé qui est présent dans cette région. Aux échelles spatiales présentées dans cette étude, les sorties du modèle n'indiquent pas de l'érosion substantielle de la côte ouest de Graveyard Island, ce qui concorde avec des observations à partir de l'imagerie aérienne historique (**Binette et al., 2024**).

Erreurs dans les strates sédimentaires:

L'importation des données bathymétriques a causé des erreurs avec les strates de sédiment dans le modèle. ArcDelRCM a mal calculé l'élévation du lit de la rivière et l'élévation du substrat rocheux à plusieurs emplacements dans le domaine de modélisation. L'opération du modèle avec ces erreurs a entraîné la propagation des erreurs aux cellules à proximité en quantités croissantes. Une région des erreurs des strates de sédiment a causé une charge de calcul importante en raison de la nécessité de construire assez des couches de sédiment en dessous de chaque cellule pour obtenir l'élévation du lit enregistré, ce qui a augmenté considérablement le temps de calcul et la taille des fichiers de sortie du modèle.

Conclusions:

Cette étude a investigué la viabilité d'ArcDelRCM comme option alternative aux modèles complexes basés sur la physique pour la modélisation des deltas Arctiques. Le modèle a été conçu pour simuler la création et l'évolution des deltas, et il incorpore plusieurs processus spécifiques à l'Arctique qui améliorent sa précision, tout en conservant l'objectif d'avoir une faible charge de calcul. Cette recherche révèle que la modification d'ArcDelRCM pour qu'il puisse servir comme modèle prédictif pour les deltas établis n'est pas présentement possible.

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1 INTRODUCTION

1.1 Context

1.1.1 Global view of the Arctic

The Canadian Arctic accounts for 70 % of Canada's coastline while being sparsely populated by small hamlets amounting to 70 000 people, approximately 1 % of Canada's coastal population. The winter season brings sea ice across much of the region, which has strong economic impacts in terms of transportation and resource access, and physical impacts on the coastline. Many communities rely on natural resources which require coastal access for subsistence purposes (Lemmen et al., 2016). Statistics Canada's 2001 *Aboriginal Peoples Survey* found that 69 % of individuals in the Canadian Arctic reported fishing in the previous 12 months, and 59 % had hunted waterfowl (Poppel et al., 2007). The vast majority of Arctic communities are only accessible by air and by water in the ice-free season, with rapidly changing climatic conditions impacting this accessibility. In addition, these coastal communities often have poor housing conditions, health services, food security, and water quality when compared to the rest of the country, providing more challenges to adapt to changes in the local environment (Lemmen et al., 2016).

62 % of the Arctic Canadian coast is made of erodible unlithified (i.e., non-rocky) material, particularly along the shores of Hudson's Bay and the western portion of the Arctic, where ground ice is common. During the last ice age, large portions of land were covered by ice sheets thousands of metres thick, which caused a depression in the ground below. With these ice sheets now having melted, many regions have experienced uplifting of the land, called isostatic rebound, resulting in various raised coastal geomorphic features up to 200 m above current relative sea level (Lemmen et al., 2016).

1.1.2 Permafrost and frozen ground

Large portions of the Canadian Arctic are covered by permafrost soils, which are defined in Canada as ground material that is continuously below 0°C for a minimum of two years (Harris et al., 1988). Grounds which are below 0°C but do not meet this uninterrupted freeze requirement are simply considered frozen ground. The distribution of permafrost in the Arctic can be sporadic or discontinuous (i.e., it occurs intermittently, with volumes of permafrost adjacent to permafrost-

free ground) or continuous, with an amount-frozen gradient serving as the boundary between these regimes (The National Atlas of Canada, 1995).

Permafrost can provide erosion protection to the coastline as waters contained within the pore space of soils, when continuously frozen, provide the soil with much greater stability, which renders the soil more resistant to wave action on the shoreline. Arctic thermal erosion processes can be grouped into two major categories, thermal denudation and thermal abrasion. Heat can enter the coastline by direct solar insolation, atmospheric heat, and water contact, where warmer temperatures are associated with greater erosion rates. Air temperatures are a deciding factor in permafrost establishment and maintenance, where warm summers and winters may thaw existing permafrost. This frozen ground results in decreased soil stability during the annual thawing season while also causing soil volume decreases during this period, resulting in greater erosion rates (Lemmen et al., 2016). Thawing permafrost also leads to gravitational impacts on the landscape—thermal denudation—where gravitational forces may lead to gradual events like land subsidence (i.e., a lowering of the land) or sudden events like landslides or retrogressive thaw slumps (Overduin et al., 2014). These slumps are C-shaped depressions in the landscape where the rate of thaw of a section of ground has exceeded the rate of erosion of a coastal bluff, leading to a mudflow towards the coastline from this thawed section of ground (**Figure 1**) (Lantuit & Pollard, 2008). The melting of ground ice supplements other erosive forces by increasing soil saturation along the coastline—permitting gelifluction—and transporting material to the coastline from further inland through streamflow (Günther et al., 2013). Short storm events and their respective surges can modify the coastline by several metres. The sudden draining of lakes or permafrost-related events, such as retrogressive thaw slumps, can change the coastline position by tens of metres in a single event. This results in short-term studies observing extreme shoreline retreat rates, while long-term studies average out these events and show lower mean annual rates (Ogorodov et al., 2020).

Thermal abrasion refers to the erosion of sediment by wave action, which can lead to the undercutting of bluffs in ice-rich coastlines, causing a unique form of discontinuous erosion called block failure (Overduin et al., 2014). This results in discrete events where the coastline may retreat by several metres rather than continuously over the course of several months. Ice wedges which protrude downward from the surface into the soil act as failure planes where large blocks of sediment ultimately separate from the surrounding soil (**Figure 2**), forming a large block of partially submerged frozen sediment that can then be melted through convective heat transfer from the water while being mechanically eroded from all sides by waves (**Figure 3**) (Jones et al.,

2018; Ravens et al., 2017). Once eroded, this allows for sediment to be transported away from the initial location of the block of permafrost (Nielsen et al., 2022). In non-bluff environments, the erosive energy transfer occurs between the waves and a sloped beach where the near-shore bathymetry determines the wave breaking type and breaking height while also being the determining factor of the amount of energy that is transferred into erosion from these waves (Nativí-Merchán et al., 2021). In highly erosive environments with large volumes of sediment transport, the depth of the active layer may ultimately impact the erodibility of a certain section of these beach coastlines should the non-frozen sediment be transported away and leave bare the frozen layer, which is much less easily eroded (Maslakov & Kraev, 2016).



Figure 1. A retrogressive thaw slump near Holmes Creek, Alaska. (*Photo credit: Trevor Lantz*)

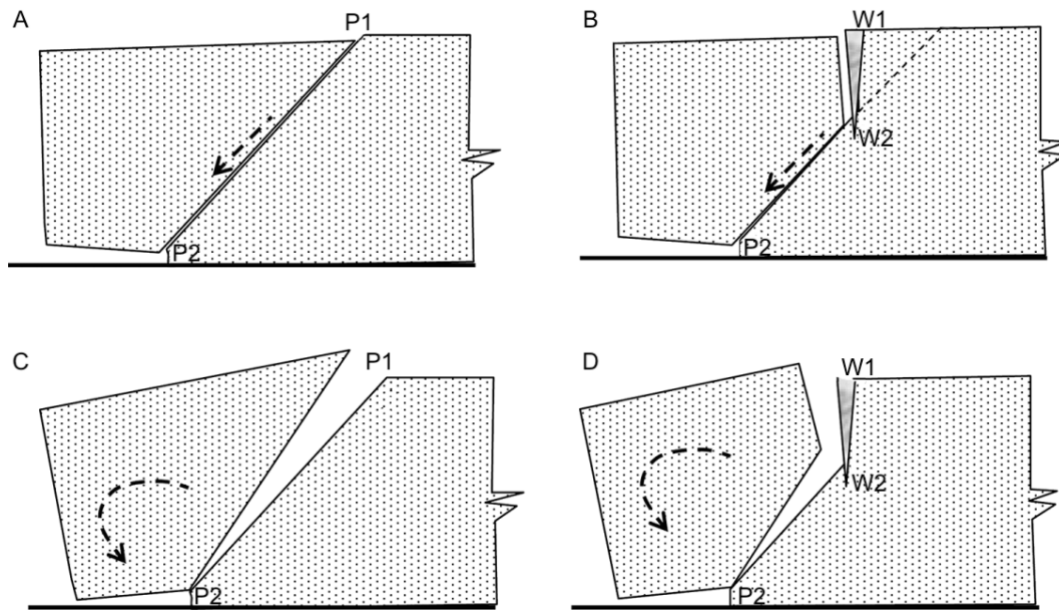


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Figure 3. An eroded block of permafrost along the Arctic Ocean coastline of Alaska. The right-hand side depicts a block of permafrost that has fallen into the ocean and can thus be acted upon by several thermal and physical processes. The coastline behind the block shows the severe undercutting by waves that leads to this block-type failure. *(Photo credit: U.S. Geological Survey)*

In non-ice-rich Arctic beach coastlines, the erosional processes that occur are mechanically more similar to those in temperate climates. The primary source of beach erosion is often wind-generated waves, where energy is transferred from the wind (which generates the waves) to the coastal environment, where it can do work by mobilising sediment. The total water level at any point is important in this process, where the presence of water at higher points along a beach or bluff allow for the other gravitational (i.e., collapsing), mechanical (i.e., wave scouring), or thermal (i.e., melting) processes to contribute to the erosion of the shoreline. Importantly, the bathymetric profile in the near-shore environment is implicated in the maturation of waves, which in turn impacts the location and severity of the erosion they impart on the coastline (Binette et al., 2024). Generally, coastal erosional processes transport sediment away from the shoreline of a given area, and can continually transport sediment offshore or laterally to neighbouring regions (Komar & Moore, 2018). The size of sediment in coastal environments also plays an important role, where regions with finer sediments (e.g., sandy loam, gravel, sands) have shown higher erosion rates than regions with larger sediments (e.g., cobble) (Ogorodov et al., 2020).

1.1.3 Sea ice

The presence of sea ice has a dramatic impact on the erosion potential of a region where, when intact, it provides substantial erosional protection to the coast by damping surface waves (Overeem et al., 2011). In addition, sea ice reduces the ability of wind to generate waves by reducing a parameter known as fetch, the distance wind is able to act without interruption across a body of water (Nielsen et al., 2020). This wind moving across the water surface experiences a non-zero coefficient of kinetic friction, causing the water to gain energy in the form of surface waves. With a longer fetch—a condition experienced in the summer with reduced sea ice cover—greater energy waves can be formed. The presence of sea ice directly frozen to a shoreline can reduce the rate of wave-based erosion.

These factors have resulted in many Arctic coastal erosion studies not considering the winter months when “open water” conditions are non-existent (Chan et al., 2023; Jones et al., 2018). The threshold value for what is considered “open water” is not a clearly established value, however, it ranges from 15 to 50 % sea ice cover, and the length of the open water season has been suggested by Overeem et al. (2011) as a first-order representative estimator for coastal erosion. The amount of open water time throughout the year for bays is less than that of non-enclosed coastal regions, resulting in a lowered ability for wave erosion of the coastline in these bays (Ogorodov et al., 2020). Barnhart et al. (2014) concluded that the duration of the open water

season explained coastal changes more than storm set up or wave heights in the Arctic, supporting the validity of the exclusion of the winter season in modelling.

1.1.4 Water level

The water level of a water body at a given moment is comprised of several components, each contributing to create the observed level, often known as the total water level. The mean water level represents a base elevation to which tides, atmospheric pressure, wind setup and wave setup can all add to or subtract from. Low atmospheric pressure conditions also result in higher water levels, which exposes the coastline at higher elevations to the processes of thermal denudation from water-based heat and thermal abrasion from wave action. Onshore winds cause the water to be pushed towards the shoreline, accumulating into a higher water level (wind setup). A given coastline will have oscillating water levels with wave runup and wave rundown as the water edge advances or recedes based on the phase of the wave. Wave runup is the observation of higher water levels, which exposes more vertical coastline to erosional forces. As waves approach the shoreline, they interact with the seabed in a process known as shoaling, where they increase in height and may eventually break (i.e., collapse), transferring some of the wave energy into erosional forces.

1.1.5 Sediment

The material of the coastline has an impact on the erosion process; when a coastal bluff is made of coarsely grained material, the material is harder to transport after removal from the bluff, rather, it is able to accumulate at the foot of the bluff, providing protection from further erosion (Jones et al., 2018). The presence of smaller sediment on the beach in a given region can indicate a lower-energy environment, which experiences less erosional forces (Nativí-Merchán et al., 2021). Rivers are able to provide sediment discharge to a coastline which can be much greater or smaller than the contribution of eroded coastal sediments to the total sediment flux of the region (Nielsen et al., 2022). It is thus important to monitor the sediment load of rivers in relevant areas to determine their importance in modelling.

Arctic deltas often have long ramp-shaped beds that slowly descend into the water until several metres below the surface, extending up to tens of kilometres into the water body. This results in very shallow-sloped bathymetry, greatly diffusing wave energy before reaching the coastline. This provides notable erosional protection to the delta and its surrounding coast (Chan et al., 2023). In the winter, sea ice can freeze the entire water column above these ramp features,

creating bed-fast ice, which protects against topographical changes throughout the season. Results from a modelling study in the Pearl River Delta (China) indicated that small islands in the delta were nuclei for deposition, resulting in skirts of deposition around the islands and troughs of deeper water between these landmasses (Wei & Wu, 2014).

1.1.6 Deltas

Deltas are the sediment deposits that form at the mouth of a river where it joins a slower-moving body of water. The decrease of water velocity, which occurs at the mouth of the river, results in a lowered ability to maintain sediment particles in suspension (floating throughout the vertical water column) or entrainment (sediment moving along the riverbed), resulting in the sediment falling out of suspension to be deposited on the riverbed, and decreased entrainment rates. Over time, this creates a notable region of accumulated sediment, forming the landform known as deltas (Seybold et al., 2007).

Deltas are often classified into three distinct categories based on the primary driver of their development: river/fluvial-dominated, wave-dominated, and tide-dominated. River-dominated deltas are characterised by substantial deposition of sediment with minimal post-deposition sediment transport where sand bars form at the mouth of the delta, bifurcating flow, and sediment continues to be deposited around the sand bar, decreasing the cross-sectional area available for water to flow (Galloway, 1975; Overeem et al., 2022). When the river ultimately overtops the relatively ever-shrinking banks, it is able to erode and deposit new channels, repeating the process to achieve the bird-foot morphology commonly seen with this type of delta. Wave-dominated deltas involve important redistribution of sediment by wave energy, transporting sediment away from the mouth of the delta and limiting the river's ability to deposit sediment into the sandbars, which would impact flow (Nienhuis et al., 2015). This results in these deltas often having fewer distributaries than their river-driven counterparts, with substantial sediment deposits on either side of the main channel in the form of beaches or dunes. The strong tidal currents seen in tide-dominated deltas transport sediment along the length of the delta, increasing its width and allowing for the formation of deltaic islands (Nienhuis et al., 2018).

Arctic deltas are distinctly different from these traditional categories for deltas in temperate climates. They generally have lower sediment fluxes than temperate deltas, can be influenced by isostatic rebound following a deglaciation period, and are impacted by the presence of ice many months of the year. Springtime upstream melting can lead to ice jams, which attempt to restrict the flow of water downstream, leading to increased water levels, bank overtopping, and massive

flooding of the surrounding area. This results in a substantial portion of the river's sediment to be deposited on the nearby landscape (Overeem et al., 2022).

Further, Arctic deltas' morphology are fundamentally different from those in more temperate climates given the formation of winter sea ice which leads to the development of ~2 m sediment ramps, which are characteristic of Arctic deltas. As the depth of this floating sea ice reaches its maximum in late winter, it comes into contact with the river/delta bed below, creating bottom-fast ice. This allows for efficient heat transfer between the cold air above the sea ice and the frozen soils of the delta bed, leading to increases in permafrost extent which support the further development of the shallow ramp feature (Reimnitz, 2002).

1.1.7 Climate change

With the Arctic warming at approximately three times the global rate, high rates of permafrost thaw and sea ice cover loss have been observed. As mentioned in section 1.1.2, Arctic coastal erosion is heavily influenced by thermal processes. With projected climate changes over the coming decades, mean coastal erosion rates are expected to continue to increase, while high erosion rates of 20 m·y⁻¹ may become more common (Lantuit et al., 2013; Nielsen et al., 2022; Solomon, 2005). These are increased rates when compared to more temperate regions due to the combined stress of mechanical and thermal (such as freeze-thaw cycles) erosional processes, and can be partially attributed to the further melting of permafrost due to warming air and water temperatures. Under different Intergovernmental Panel on Climate Change (IPCC) Shared Socioeconomic Pathways (SSPs), the yearly daily positive degrees—a measure of the potential of melting of the permafrost—and significant wave heights may increase by 15 % – 100 % by the end of the century (Nielsen et al., 2022).

Decreases in sea ice area resulted in increased significant wave heights in the Canadian Arctic Archipelago by 0.2 % – 0.3 % per year in the late 20th and early 21st century due to the greater fetch length provided by this increase in open-water conditions throughout the year (Casas-Prat & Wang, 2020). These results are in agreement with those found by Ogorodov et al. (2020) in their study of the Russian Arctic, which found that these longer fetch lengths resulted in greater overall energy able to act on the coast.

Warming climatic conditions have led to thinner sea ice conditions over decreased surface areas, which in 2017 caused a low-pressure zone over the Barents Sea, which has historically been a high-pressure zone in the winter. Combined with the penetration of North Atlantic cyclones

into the Arctic Ocean, this first-ever drastic pressure change resulted in a reversal of wind directions at the ocean surface, an anomaly whose occurrence will become more frequent with warming climatic conditions (Moore et al., 2018). Strong projected decreases in sea level pressure of the Beaufort Sea in autumn are predicted to also contribute to this change of wind directions in the region as well as a diminution of offshore wind speeds in the East Siberian Sea, impacting the ability of these winds to generate surface waves (Koenigk et al., 2015). These examples of sudden environmental phenomena shifts are indicative of the types of changes that continue to occur with current climatic changes and are not restricted to any given geographical area.

Ogorodov et al. (2020) found that future changes in thermal conditions alone will dramatically increase coastal erosion of frozen regions, without any influence from this increased energy available for mechanical erosion. The influence of warming climatic conditions on Arctic coastal erosion rates indicates the severity of changes that can be expected by the end of the century, given the 8 % – 117 % increase of permafrost-melting conditions predicted by 2100 in the Arctic as a whole (Nielsen et al., 2022). Günther et al. (2015) found that for their study site in the Laptev Sea, increased mean summer temperatures of 1°C resulted in overall coastal erosion rate increases of 1.2 m/y.

1.2 Research objectives

This research seeks to advance our understanding of reduced-complexity long-term evolution modelling of Arctic deltas, allowing for improved ability to model these environments at large spatial and temporal scales. This will be achieved through the following objectives:

- Fieldwork: the collection of bathymetric, topographic, and hydraulic data are targeted using a variety of techniques best suited to each local region. The fieldwork conducted for this research will contribute to the geographical knowledge base of the region, specifically focused on the hydraulic and erosional processes near Kugluktuk, Nunavut.
- Model evaluation: determine the feasibility of applying ArcDelRCM to pre-existing Arctic deltas for modelling on the scale of several decades. This objective seeks to improve our overall understanding of reduced-complexity model (RCM) usefulness, particularly in comparison to more complex physics-based models.
 - Modification of ArcDelRCM to enable the import of existing bathymetric data so the model may be used as a delta evolution and forecasting tool.

- Assess the quality of the model forecasts by comparing them to theoretically expected geomorphological changes and observed trends based in previous fieldwork and remotely sensed imagery.

1.3 Novelty

The ArcDelRCM model has never been applied to a Canadian delta, consequently, this research will contribute to the scientific community's understanding of the Canadian Arctic as a whole, as similarities exist across the entire region. This project thus addresses several current problems in the field: (1) there are few studies on coastal erosion in Arctic environments (particularly in the Canadian Archipelago), resulting in relatively low data availability for studies of this kind, and (2) the long-term nature of delta evolution, which renders their study challenging. ArcDelRCM reduces the complexity of data collection and analysis compared to typical hydrodynamic processed-based models, permitting modelling to occur over larger spatial and temporal scales due to its reduced computational load (Splinter & Coco, 2021).

1.4 Scientific Contributions

Peer-reviewed presentations:

Canham, N., Binette, S., Coulombe, S., Noël, B., Akana, R., Didier, D., and Stolle, J. (2025, June 9). *Arctic delta evolution modeling of the Coppermine Delta using a reduced-complexity model* [Oral presentation – presenter]. Coastal Zone Canada 2025, Charlottetown.

Samuel, B., Akana, R., Didier, D., Coulombe, S., Jourdain-Bonneau, C., Noël, B., Roberge, B., **Canham, N.**, Buffin-Bélanger, T., Stolle, J. (2025, June 10). *Coastal geomorphological changes monitoring in Kugluktuk and the Coppermine River Delta, Nunavut* [Oral presentation – author]. Coastal Zone Canada 2025, Charlottetown.

Non-peer-reviewed presentations:

Canham, N., Didier, D., and Stolle, J. (2024). *Coastal permafrost erosion modelling of the Coppermine Delta using a reduced-complexity model* [Oral presentation – presenter]. Young Coastal Scientists and Engineers Conference – Americas, Quebec City

Canham, N., Lafosse, L., Binette, S., Didier, D., and Stolle, J. (2025). *Application of a new reduced-complexity Arctic delta evolution model to the Coppermine River delta* [Oral

presentation – presenter]. Graduate Research on Water Technology and Hydraulics (GROWTH) Symposium, Ottawa

Non-peer-reviewed articles:

Lafosse, L., Stolle, J., Binette, S., **Canham, N.**, Coulombe, S., and Didier, D. (2025). *Bluff erosion in an arctic delta: A case study of the Coppermine delta, Nunavut*. <https://doi.org/10.2139/ssrn.5537472>.

Lafosse, L., Stolle, J., Coulombe, S., Binette, S., **Canham, N.**, Akana, R., and Didier, D. (2025). Hydromorphological dynamics of Canadian arctic deltas : An hydrological model of the Coppermine delta. *Coastal Engineering Proceedings*, 38, 29. <https://doi.org/10.9753/icce.v38.papers.29>.

1.5 Scope

This research project's principal aim is to validate the use of ArcDelRCM in the Canadian Arctic context. This takes the form of developing methods to import existing bathymetric data into the model (i.e., inheritance), then operating the model over several decades to determine its viability as a forecasting model.

ArcDelRCM routes both sediment and water through a random-walk cellular routing scheme and allows for a simplified differentiation of grain sizes entering the model domain. Further, annual ice cover extent and thickness are modelled, where control over the period required to melt this ice serves as a proxy for air temperatures. ArcDelRCM importantly simulates permafrost, accounting for both an active layer and the reduced erodibility of these frozen soils. The model uses a homogeneous mesh of square cells, constant time steps, and constant sediment flux entering the model domain (although, the latter can be varied by running multiple simulations with different parameters, inheriting the model state from each successive simulation). The cellular routing scheme chosen for water movement is in contrast to the solving of the shallow water equations (i.e., the depth-integrated Navier-Stokes equations), a practice commonly seen in computationally complex physics-based models (Liang, Voller, et al., 2015).

Given the importance of bathymetry to both ArcDelRCM and the overall quantity of data available in the region around Kugluktuk, these bathymetric data serve as the principal known data that are used by the model (i.e., this study does not use measured air temperatures, variable water discharges, sediment fluxes, or water levels).

2 LITERATURE REVIEW

2.1 State-of-the-art

2.1.1 Mathematical descriptions of Arctic coastal erosion phenomena

2.1.1.1 Sediment

For a sediment particle to be mobilised within a water body, a force must be applied to it by the moving water. In a channel, as the water passes over the bed, it exerts a frictional force on the bed particles in the direction of the flow, called shear stress. With insufficient shear stress, the forces acting on the particle are not enough to dislodge it. It follows that greater amounts of stress (often generated with higher flow velocities) can mobilise the particle. This threshold is known as critical shear stress:

$$\tau_{cr} = \frac{\pi}{6} \cdot \eta \cdot g \cdot (\rho_s - \rho) \cdot D \cdot \tan \varphi \quad (2.1)$$

where ρ_s and ρ are the density of sediment and water, respectively; η is a packing coefficient related to the diameter of the particle (D); and φ is the angle of repose: the greatest angle at which an unpacked pile of material is stable (Trenhaile, 2016). A common use of this critical threshold is in determining the Shields parameter, a ratio of the entraining force versus the submerged weight of the particle:

$$\theta = \frac{\tau}{(\rho_s - \rho) \cdot g \cdot D} \quad (2.2)$$

In terms of the direct removal of sediment due to lateral flow (causing the retreat of a river bank or bluff), an equation for cohesive soils is commonly used (Mosselman, 1995):

$$\frac{\partial n_B}{\partial t} = E \cdot \left(\frac{\tau_w - \tau_{wc}}{\tau_{wc}} \right) \text{ for } \tau_w \geq \tau_{wc} \quad (2.3)$$

where $\frac{\partial n_B}{\partial t}$ is the rate of bank retreat, E is the erodibility coefficient, τ_w is flow shear stress exerted on the riverbank, and τ_{wc} is the critical shear stress; the threshold below which no erosion is able to occur. Erosion first occurs at the “toe” of the bank, increasing its slope and ultimately leading to more drastic bank failure. The material falling from further up the bank can amass at the toe, which sometimes provides erosional protection to the bank.

2.1.1.2 Permafrost

Permafrost was described by Dupeyrat et al. (2011) as a combination of ice and mineral particles, forming a frozen soil. The energy flows into this soil determine the thawing of permafrost, thus, it is important to be able to model this energy. The specific heat of a saturated permafrost, or a frozen soil with saturated pores, was described as

$$c_{p_{sat}} = \left(\frac{\omega}{1+\omega} \right) \cdot c_{p_{ice}} + \left(\frac{\omega}{1+\omega} \right) \cdot c_{p_{sediment}} \quad (2.4)$$

where ω is the mass-based ice content of the permafrost. Further, the latent heat is

$$L_{sat} = \left(\frac{\omega}{1+\omega} \right) \cdot L_{ice} \quad (2.5)$$

The thermal conductivity of the soil helps predict permafrost thaw rates and is impacted by several mechanical characteristics of the soil. An estimation can be calculated as

$$k_{sat} = k_{ice}^n \cdot k_s^{(1-n)} \quad (2.6)$$

where n is

$$n = \frac{1}{1 + \left(\frac{p_{ice}}{p_s \cdot \omega} \right)} \quad (2.7)$$

2.1.2 Types of models: ideological differences

Different types of models have been developed to represent the delta-forming process observed in nature. Delta evolution was traditionally studied using sediment records; however, this poses limitations in terms of spatial resolution and costliness (Galloway, 1975). Thus, complex computer models were developed to predict bathymetric changes, accounting for hydraulic forces and sediment fluxes in the delta.

Two-dimensional complex models aim to model the hydrodynamic processes in rivers in the x-y plane only, while the third dimension includes a vertical component in water flow modelling. 2D modelling uses a technique known as depth-averaging, where it is assumed that any flow in the vertical direction is relatively small when compared to the horizontal flow. Pressure can then be approximated as being only a function of water depth (i.e., hydrostatic), and the water velocity for each individual cell is given a single depth-averaged value. In this case, the 2D depth-averaged shallow water equations emerge from the 3D Reynolds-averaged Navier-Stokes equations, which are used to describe turbulent flows (Cea et al., 2007). In the case of 3D modelling, the vertical

component allows for processes which occur in the vertical direction—such as spiral flows—while being more computationally demanding and requiring more complex field campaigns to gather these data (Kasvi et al., 2015). A popular 2D model is TELEMAC-2D, which solves the continuity equation, x and y momentum equations, and a tracer equation (i.e., an equation used for transport of a passive scalar such as temperature) (EDF R&D, 2014; Warhaft, 2000). The XBeach model focuses more specifically on wave modelling, accounting for processes such as short-wave refraction and breaking, infragravity wave dissipation, and wave-induced setup (Deltares, 2015). The difference between these two models highlights the importance of case-specific model choice, where TELEMAC-2D can be directed to use the “TOMAWAC” component to model, for example, wave reflection and diffraction, but individual coupled components can be omitted to decrease computational load (EDF R&D, 2014). Many advanced models allow for parallel computing to decrease model runtimes, where the modelling domain is partitioned and each partition’s calculations are completed on a separate CPU core, or in the case of some models, hundreds of partitions on different GPU cores (Crespo et al., 2015; Deltares, 2025).

In direct opposition to these complex models are ones which are able to predict delta formation at a coarser scale, providing only estimates of shoreline positions, longitudinal profiles, and average profiles of the delta, and not any detail on the deltas’ interior morphology or channel networks (Parker et al., 2008). One-dimensional profiles are an example of a simple model which views sediment and water inputs forcing factors from the upstream side of a coastline, and coastal erosion processes which counter these to create a dynamic shoreline (Lorenzo-Trueba et al., 2013). These models often incorporate the observed phenomena or overall processes at work in a region rather than the elementary processes described in more complex models. This allows for faster computation of results but larger data requirements to validate when using these simplified models.

An additional creed is synthesist modelling of geomorphological processes, which describes processes on a larger scale while avoiding smaller details. Some argue these smaller details should only be considered in the context of describing small-scale processes, not combining several to describe observed large-scale processes, particularly as these may not have much of an overall impact on dynamics at the large-scale (Murray, 2003; Paola, 2001; Werner, 1999). Reduced-complexity models aim to simplify the diversity of data requirements and computational intensity of complex models without undermining the ability to predict observed phenomena, providing more detailed predictions of delta morphology than the spatially averaged models. RCMs bring their own challenges related to flow and sediment routing, and similar to complex

models, may struggle to reproduce real-world phenomena if certain physical principles—or especially, sufficient data—are not incorporated into the model (Liang, Voller, et al., 2015).

2.1.3 Existing RCMs

Modelling with reduced-complexity models has been approached with many different considerations, resulting in models with strengths in various areas. Since their development in the modern context (i.e., with the aim of having a reduced complexity, rather than rudimentary models in the past, which were the most complex possible at the time but simple by modern standards) remains relatively recent, a relatively small number of RCMs have been developed across a range of fields. Murray and Paola (1994) were among the first researchers to develop and use a reduced-complexity model within the geomorphology field. They developed an RCM for explaining the causal factors in braided rivers, a type of river where multiple channels evolve continuously while staying generally within the same overall channel width, forming a braid-like pattern. This style of model was preferable to more complex options, as it was unknown which of the many processes contributing to braided rivers were principal determinants of the ultimate morphology of the river (Murray & Paola, 1994). This simplified model allowed for more straightforward determination of the mechanisms which result in the braiding pattern formation, whereas more complex models (e.g., Delft3D) are better able to accurately reproduce the formation and development of rivers in higher levels of detail (Bokulich, 2013).

A reduced-complexity model for African rainfall erosivity was developed by Diodato et al. (2013) to simplify the analysis and estimation of rainfall when compared to a more traditional physics-based calculation founded on the principle of conservation of mass (USDA Agricultural Research Service, 2016). In contrast with many other RCMs, this model was able to function with lowered spatial and temporal resolution when compared to physical process-based models due to its assumption of homogeneous data values across the extent of the analysis (Diodato et al., 2013). From these results we can conclude that RCMs can be developed for situations where field data are of lower resolution or frequency than desired by making these value assumptions for certain variables. While the RCM may be able to provide rough estimations of the development of expected natural processes in a region, the lack of data greatly impacts the usefulness of the results at a local scale, meaning the distribution or patterns of the results are likely to be unreliable in this instance.

Abdelhady & Troy (2023) found that existing models were unable to accurately model shoreline movements as caused by water level variations in the Great Lakes; thus, they

developed a 1-dimensional RCM with the specific goal of predicting the impact of these very low-frequency fluctuations on the shoreline. This model incorporated only two mechanisms for this impact prediction: flooding and wave forcing. This simplified view resulted in reasonably accurate predictions (and in some cases, improvements) when compared to other models. In one instance, the model decreased error propagation with longer timescales due to the incorporation of the water level-based shoreline variations into the model, where previous models ultimately absorbed these impacts into other mechanisms (Abdelhady & Troy, 2023).

2.1.4 Simplification of real-world conditions for modelling

Modelling environmental variables can come with great complexity, particularly over long time periods where parameter values may systematically increase or decrease. Thus, it is important to make valid assumptions that result in simplifications of the model. For example, the Hamburg Shelf Ocean Model uses only shallow-water equations and does not incorporate wave forces as the authors of this model determined they only provide notable impacts outside of protected bays (Wei & Wu, 2014). The strategy employed by Ravens et al. (2017) to simplify their use of an Arctic-modified version of the XBeach model of geomorphic change was to hold the air and water temperature variables constant throughout the several-day timespan of the simulation.

Further simplifications, which provide computation speed benefits, can include choosing a larger time step and the binary classification of cell types. The latter was employed by Ravens et al. (2017) in their study where cells could be classified as dry/wet based on a chosen threshold value, thus not requiring the model to include the implications of a partially wetted cell in its calculations .

Models which account for natural physical processes have the advantage of simulating real-world conditions, albeit at a computational cost. Nielsen et al. (2022) used a temporal resolution of one year and assumed an equal contribution of mechanical and thermal factors to the overall erosion. The authors comment that simplified models such as theirs are required to be able to model the entire Arctic region due to current computational constraints, while more detailed models, which incorporate a greater number of environmental variables or operate at higher spatial resolution, are better suited for local analysis.

2.2 Research needs

Coastal erosion modelling provides a large computational challenge and has historically been limited by a lack of computational resources, resulting in little time for more advanced modelling to have been developed. Thus, the relative importance of different drivers of erosion is not well understood, particularly for the Arctic, as many models have been developed for temperate and tropical climates. This results in a lack of Arctic-specific features being included in erosion models. Additionally, minimal field research has been completed in the Canadian Arctic compared to those of Europe and Asia, resulting in a low data volume for the region being available to modellers. The principal research needs for the field are thus:

- Validation of existing reduced-complexity and Arctic models (such as ArcDelRCM).
- Determination of the relative importance of each driver of erosion. For example, thermal erosion, wave action, aeolian processes, and post-glacial isostatic rebound (i.e., land uplift).
- Collection of more data related to coastal erosion in the Canadian Arctic.
- Development of new models for different regions or geomorphological processes than are described by existing models.
 - Inclusion of delta-specific geomorphological features into models, such as ramp features for Arctic deltas.
 - Incorporation of sediment input, river water flow, and ocean processes into models.

3 METHODOLOGY

The site of this research is the Coppermine Delta, at the mouth of the Coppermine River in Kugluktuk, Nunavut. This lies in the south-west portion of the Coronation Gulf, a shallow body of water in the Canadian Arctic Archipelago. Kugluktuk is an Inuit hamlet of approximately 1400 people (Statistique Canada, 2023). A historical cemetery present on one of the deltaic islands is at risk of coastal erosion in the coming decades.

Other projects in the area include an environmental characterisation, where the social and community implications of coastal erosion are being researched, as well as a geomorphological characterisation and sediment transport analysis to monitor morphological changes in the river and delta and determine the driving forces behind the observed erosion of shorelines. Kugluktuk was selected for these research projects due to the specific community challenges that face the hamlet related to the presence and the importance of the cemetery, as well as the constant and rapid morphological changes of the riverbed, which impact navigation and other quotidian activities.

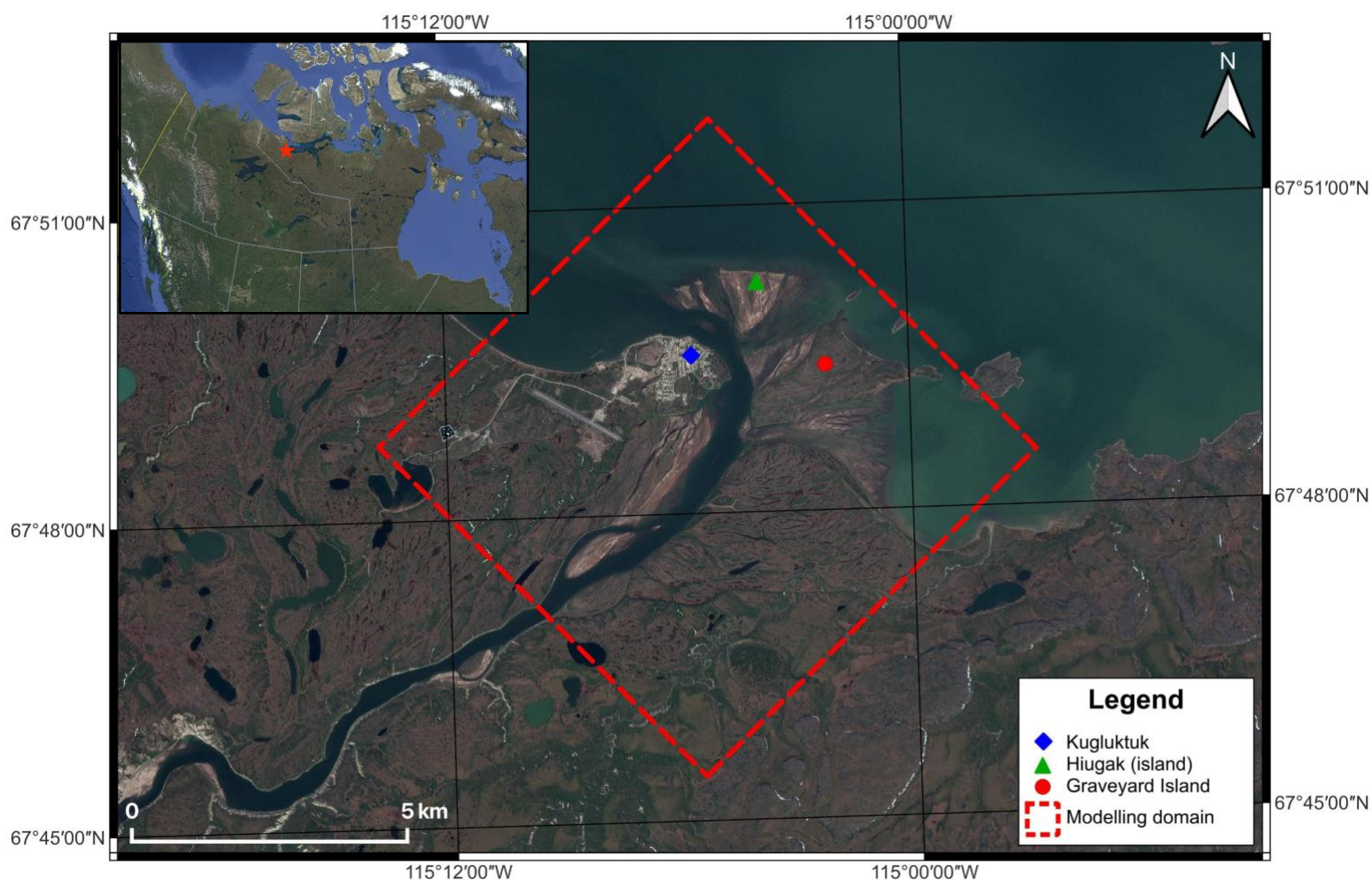


Figure 4. A satellite image of the study site, centred on Kugluktuk, Nunavut. The Coppermine River flows from the southwest corner of the image to the centre, where it culminates in the Coppermine Delta. The Coronation Gulf lies north of Kugluktuk. Individual study sites are upstream along the river (southwest of Kugluktuk), west of Kugluktuk along the shoreline of the Coronation Gulf, and directly east of Kugluktuk on the larger, triangular island named Graveyard Island and the smaller island further north, Hiugak (Binette et al., 2024). *Images courtesy of the European Union Space Programme, the U.S. Geological Survey, and Planet Labs (2025).*

3.1 Study site

The Coppermine delta contains two large deltaic islands, as seen in **Figure 4**. The larger of the two, named in this report as Graveyard Island (also known as Elogikhivik), is the site of the historical cemetery, which lies approximately 20 m from the eroding bluff edge. The smaller island, Hiugak, has low elevation across its entire area and low-slope beaches.

Kugluktuk is characterised by a variety of types of coastlines (**Figure 5**) which are mostly unconsolidated sediment with regions of beaches and steep bluffs ranging from approximately 1–3 metres in height (Tanguy et al., 2024). The reaches of the Coppermine River within the modelling domain are mostly made of recently (i.e., during the Holocene) terraced alluvial sediments, while the Coppermine Delt is made of marine deltaic sediments deposited during the Wisconsin glaciation (Geological Survey of Canada, 2015). The delta morphology seen today—with Graveyard Island as a notable feature—was formed principally over the last 3500 years after much higher sea levels in the preceding 6500 years (Binette et al., 2024). The region was historically considered to have continuous permafrost, thus 90 % – 100 % of the land area was underlain by permafrost, with approximately 10 % of the volume of the near-surface soil occupied by ground ice (The National Atlas of Canada, 1995). With sharply warming atmospheric trends in the Arctic over the last several decades, this region may fall into the discontinuous permafrost category and will continue to lose permafrost throughout this century, the impacts of which are already visible in images A and C of **Figure 5** (Nielsen et al., 2022).



Figure 5. The coastlines of Kugluktuk. (A) The south-west shoreline of Graveyard Island, showing 3 m tall sandy bluffs made of thawing permafrost. (B) The beach west of Kugluktuk, showing the 1-2 m sandy bluffs stabilised by the roots of the vegetation, which are exposed due to erosion. (C) The eastern bank of the Coppermine River approximately 3 km upstream of Graveyard Island, showing the ~15 m steep-sloped riverbanks with blocks of the surface layer falling as the permafrost thaws. (D) The rocky ~40 m western bank of the Coppermine River directly west from the southern tip of Graveyard Island.

The mean annual temperature from 1991–2020 was -9.7°C , with the daily means ranging from -27.0°C in February to 11.2°C in July (The Meteorological Service of Canada, 2025). Sea ice in the region forms in late October, and it breaks up around July 1st (The Atlas of Canada, 2009a, 2009b). This results in a relatively brief ice-free period where the greatest erosion by waves occurs. The daily mean temperature of Kugluktuk is below 0°C from October through May each year, with the average snowfall-free period being June 3 – September 17, providing a short thawing season where coastal erosion might be expected to occur (**Figure 6**) (The Meteorological Service of Canada, 2025).

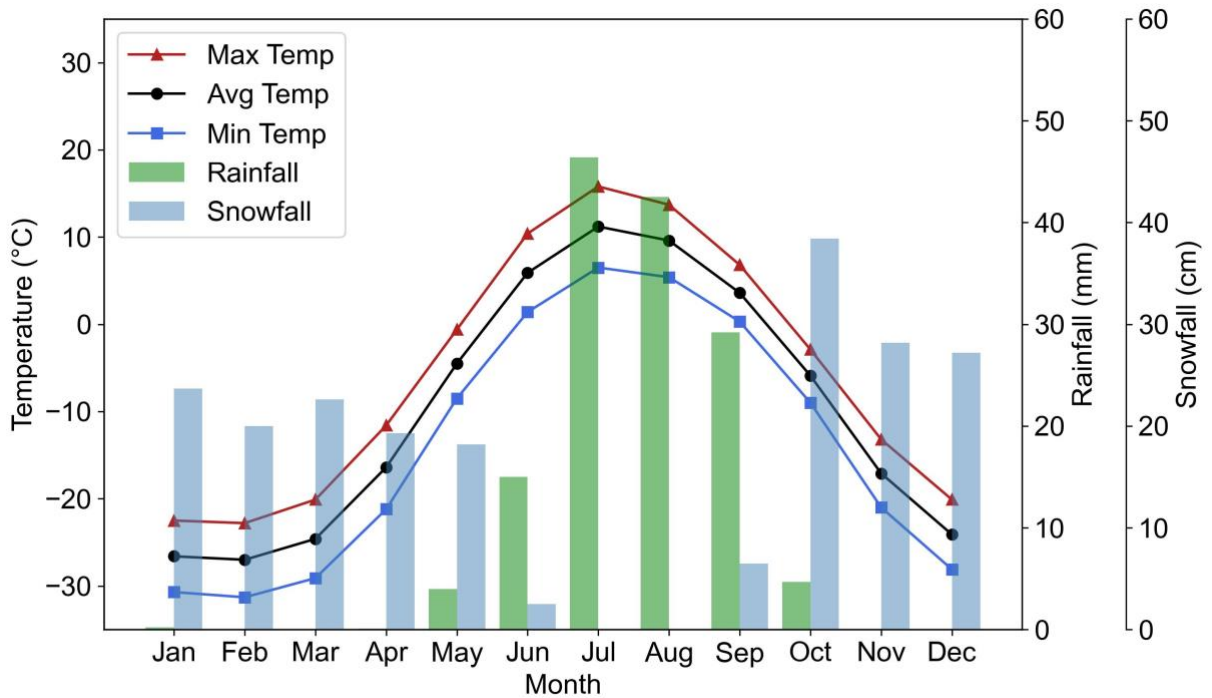


Figure 6. A climograph of Kugluktuk based on the 1991-2020 period (The Meteorological Service of Canada, 2025).

During the ice-free summer period, the nearest hydrometric data station—102 km upstream from the modelling domain—has measured typical discharges of approximately $250\text{--}500\text{ m}^3\cdot\text{s}^{-1}$, with peaks of $1000\text{--}2000\text{ m}^3\cdot\text{s}^{-1}$ during the spring-thaw period (**Figure 7**) (National Hydrological Service, 2025). The annual distribution of precipitation ranges from a 7.0 mm low in February to its July peak of 45.2 mm, with an annual mean of 233.1 mm during the 1991-2020 period, 142.0 mm as rain—mostly from June–September—and 206.5 cm as snow (The Meteorological Service of Canada, 2025). The tides in Kugluktuk are typically in the range of 25–35 cm (Canadian Hydrographic Service, 1982). The majority of offshore waves have significant wave heights of 0–

0.8 m coming from the North through East. The largest waves (i.e., $H_0 > 0.4$ m) come almost exclusively from the ENE (67.5°) direction, which corresponds with the maximum possible fetch within the Coronation Gulf (Binette et al., 2024).

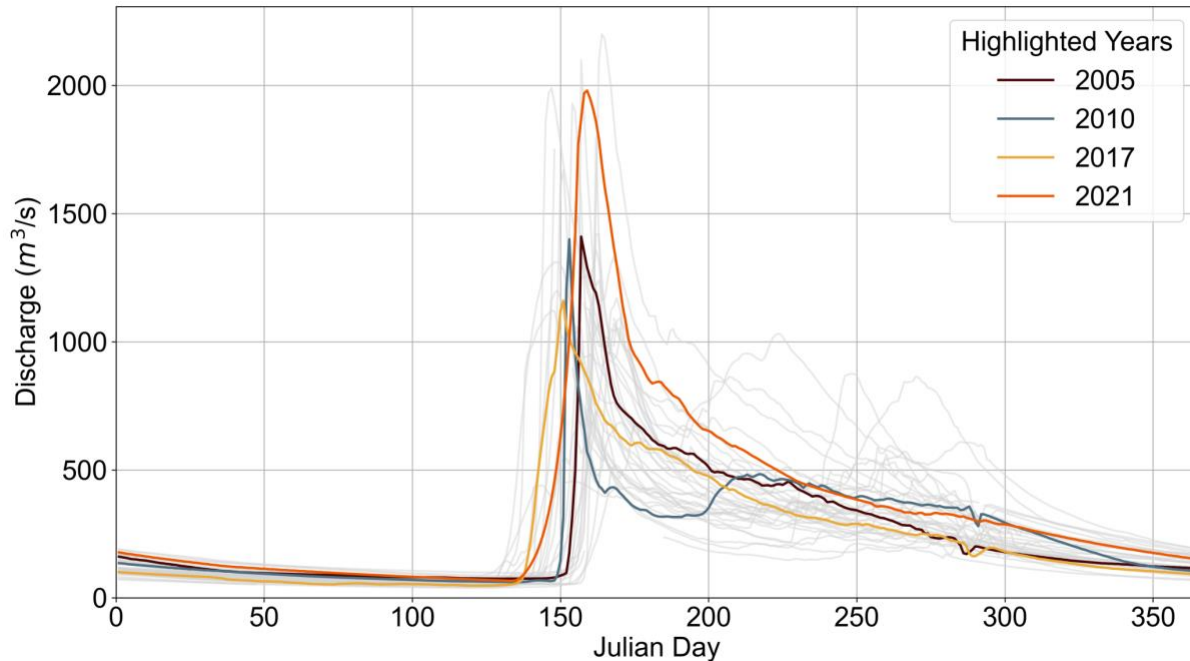


Figure 7. A hydrograph of the discharge for the Coppermine River at the National Hydrological Service’s hydrometric station on the Coppermine River above Copper Creek (ID: 10PC004) showing data from 1987–2003. Several years with continuous data throughout the year over the most recent two decades have been coloured, highlighting the interannual flow variability (National Hydrological Service, 2025).

Climate changes are expected to have a moderate impact on sea levels near Kugluktuk, with 10–30 cm drops by mid-century, and 30–60 cm drops by 2100, relative to 1986–2005 baselines (James et al., 2021). Under the International Panel on Climate Change’s (IPCC) Shared Socioeconomic Pathways (SSP) 4.5 scenario (moderate emissions) using a Coupled Model Intercomparison Project 6 model (CMIP6), mean annual temperatures are expected to increase by 4.3°C to 8.0°C by 2071–2100 (Environment and Climate Change Canada, 2025).

3.2 Field data sources

The bathymetric map used for this modelling project was a combination of various sources: single-beam sonar data (collected in 2022), GNSS beach profile surveys (collected in 2022),

satellite-derived bathymetry and topography (2022 images), and non-navigational bathymetric data.

The single-beam sonar bathymetry data were collected using a Hydroball® buoy, allowing for these data to be collected in the very shallow-water environment of the Coppermine River. The buoy was fixed and tugged behind a small personal watercraft at 7-8 km/h for a total of 45 h, resulting in line-geometry bathymetry coverage to the west of Kugluktuk, the mouth of the delta between Kugluktuk and Graveyard Island, and upstream reaches in the Coppermine River past the edge of the chosen modelling domain. The Hydroball® assumes a freshwater environment with a sound velocity of 1450 m/s. During the processing of these data, large portions of the dataset were removed due to poor data quality caused by phenomena such as poor GNSS connection and insufficient acoustic return due to complex bed material mixtures. The post-processing of the accepted data indicated that the majority of the accepted data had a vertical error of less than 40 cm.

The satellite-derived bathymetry (SDB) data were generated using two Sentinel-2 images, from 2022-08-01 and 2022-08-06. An ARCTUS model used to generate these data (<https://arctus.ca/>) was trained and validated on the Hydroball® point data, where 80 % of the 5545 point measurements were used for training and 20 % were used for validation. A comparison between the satellite-derived bathymetry and the Hydroball® data showed an R^2 value of 0.97 and an average error of 0.49 m. This bathymetry was tide-corrected using the Canadian Hydrographic Service's predictions for the Kugluktuk station (#06290). The non-navigational (NONNA) bathymetric data are produced by the Canadian Hydrographic Service using multi-beam sonar technology at both 10 m and 100 m resolutions in the CGVD2013 vertical datum, providing data west of Kugluktuk and north of Hiugak Island (Canadian Hydrographic Service, n.d.). Only data with elevations less than -3 m were used. These data lie largely outside of the chosen modelling domain (**Figure 8**). The use of satellite-derived bathymetry for a large portion of the modelling domain resulted in it acting as a background for other, finer data sources, where they were not available. In locations where field-based sources of bathymetry were challenging to acquire, such as the many shallow-water regions within the Coppermine River and any area of large spatial extent (i.e., offshore), the satellite-derived data offered a reasonable estimate of the bathymetry while offering full spatial coverage of the river and delta.

ArcticDEM satellite-derived topography data are produced jointly by the National Geospatial-Intelligence Agency (NGA) and the National Science Foundation (NSF) of the United States (University of Minnesota, n.d.). These data are a digital surface model of the Arctic regions,

produced using photogrammetry. The data were re-projected using the bicubic interpolation, then data below 0.5 m in CGVD2013 were excluded in order to preserve the importance of the high-quality GNSS beach profile surveys. The GNSS beach profile surveys were conducted in 2022 using Emlid© GNSS receivers, allowing for manual access to the coastline on both sides of the water line. These data were prioritised in the generation of the bathymetric map due to their precision and unique area coverage.

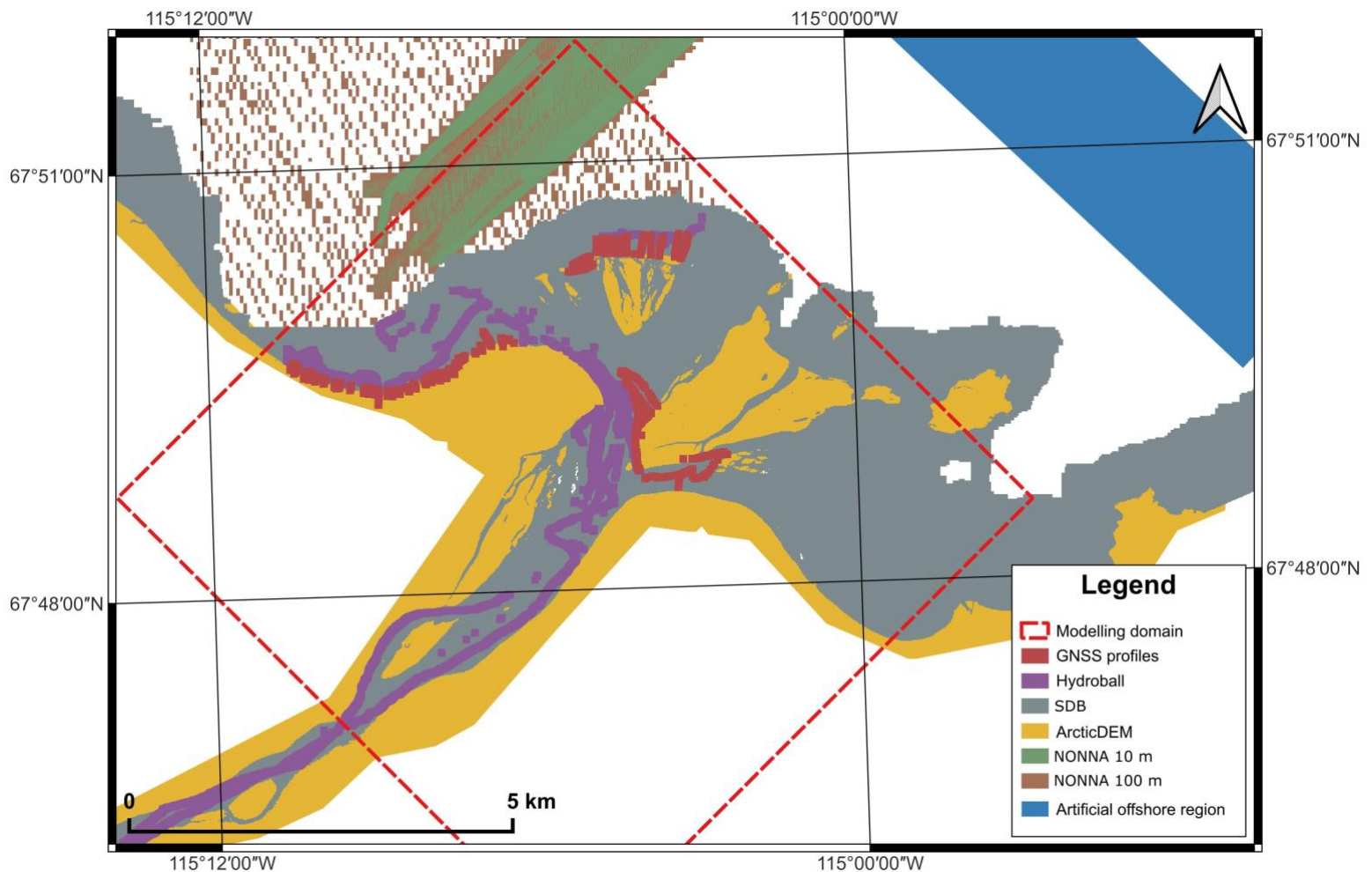


Figure 8. A map of the study site showing the extents of the various data sources used to produce the final interpolated bathymetry data. The modelling domain is outlined, highlighting the relative importance of the satellite-derived bathymetry, the single-beam sonar (Hydroball®) data, and the GNSS beach profiles when compared to the NONNA multi-beam sonar data, which lie at the seaward extremities of the modelling domain.

3.3 Bathymetric map creation

The bathymetric data north-east of Graveyard Island—which lies far offshore and in presumably deeper waters that are less impactful on the long-term delta evolution—were artificially generated by duplicating data from the north and north-west regions due to a complete lack of field data for this region. The modelled domain was selected to not extend into this artificial region. Only the most south-western reaches of the NONNA data lie strictly within the modelled domain, thus, with the small-kernel interpolation method chosen, these artificial regions ultimately had no impact on the bathymetric map (**Figure 8**).

All five of the data sources described in section 3.2 were used for creation of the bathymetric map. The various field data sources were combined and interpolated in two rounds, both using the k-3-nearest uniform neighbour method. The first round of interpolation was by region (i.e. river, delta mouth, west of mouth, east of mouth, and offshore), then a second round of interpolation was applied to the whole area, to smooth jagged differences between regions left after the first round. Multiple interpolation techniques were tested, with k-nearest uniform neighbour (with k=3) proving the most successful after overall statistical comparison between methods. This resulted in the production of a 4 m resolution bathymetric map of the entire region, from which the model domain was extracted (**Figure 9**).

Fixed field locations (i.e., installed instrument locations for other projects) were used for specific comparison between methods, indicating a maximum of 14 cm error after both rounds of interpolation with the k-3-nearest uniform neighbour method, when compared to the single-beam sonar (Hydroball®) and GNSS beach profiles.

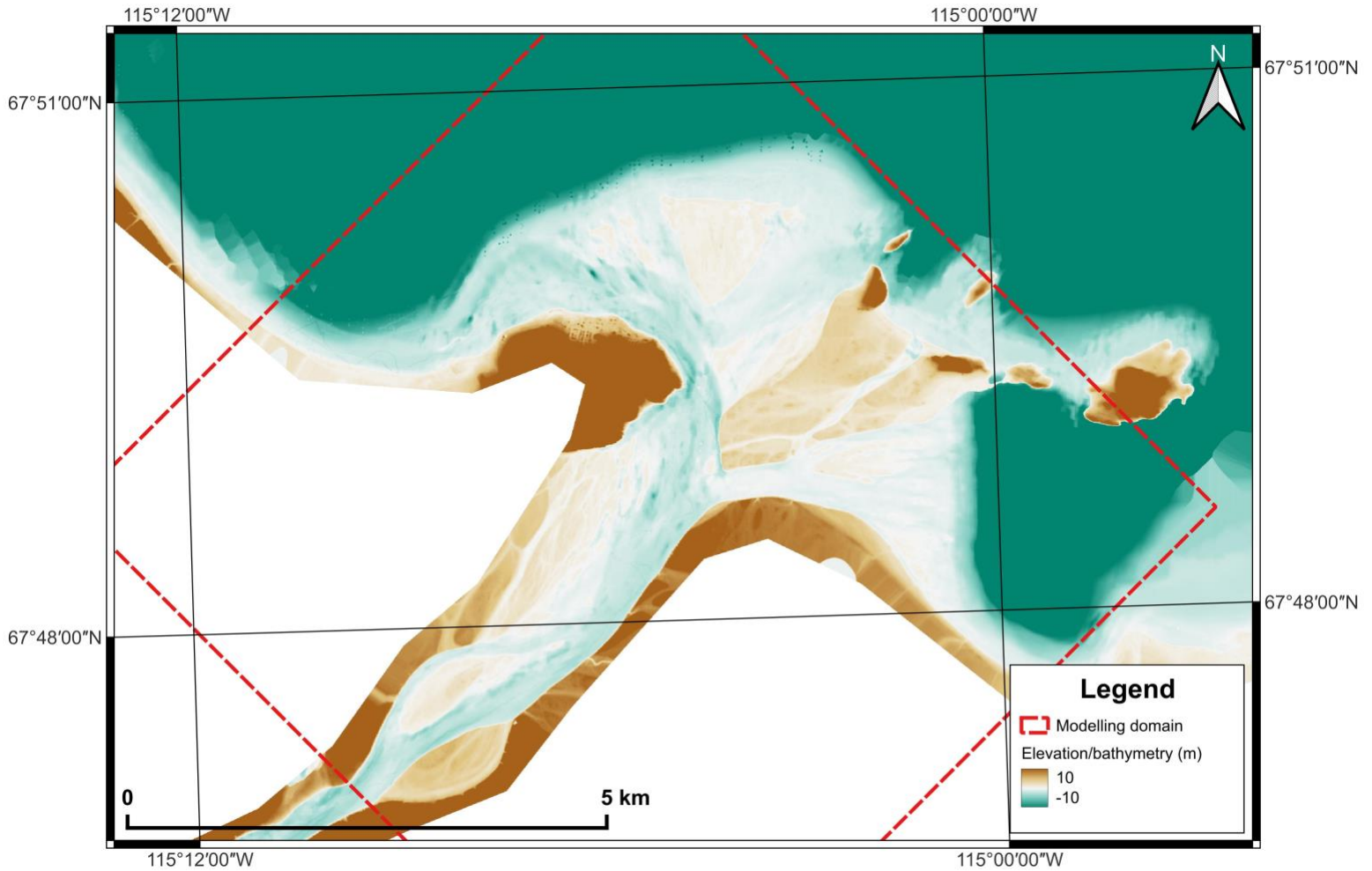


Figure 9. Bathymetric map generated by the interpolation of five different data sources (single-beam sonar (2022), GNSS beach profile surveys (2022), satellite-derived bathymetry and topography (2022), and non-navigational bathymetric data).

3.4 Model domain extraction

ArcDeIRCM is a model which does not treat bathymetric data as georeferenced, thus, the 4 m bathymetric map needed to be rotated in order to align the Coppermine River with the model inlet, which lies in the centre of the y-dimension at column $x=0$. The bathymetric map was thus sampled into a vector dataset (1 point at the centroid of each square pixel), rotated 45 degrees clockwise, and resampled to a raster with 4 m pixels aligned with the new x and y axes. The rotation of individual pixels within a rigid rectangular structure results in data holes, which were then filled using the inverse distance weighting interpolation method with a maximum distance of 3 pixels used to calculate the interpolated value (**Figure 10**).

Given that the on-land regions around Kugluktuk were generally not part of this dataset (with the exception of the near-shoreline environment), they were filled in with the value of 5.0 m so that the model could properly handle these regions. This value was chosen as it is sufficiently elevated as to flag these regions as not being covered by water, but not so high as to cause unnecessary computational load or unreasonable erosion patterns. This final interpolated bathymetric map was then clipped to the modelling domain (**Table 1**) and exported at several resolutions for modelling use using a bilinear resampling method (i.e., 2x2 kernel).

Table 1. The modelling domain in UTM Zone 11 N coordinates.

Easting (m)	Northing (m)
580580.6	7517042.0
586545.8	7523007.1
580580.6	7528972.3
574615.5	7523007.1

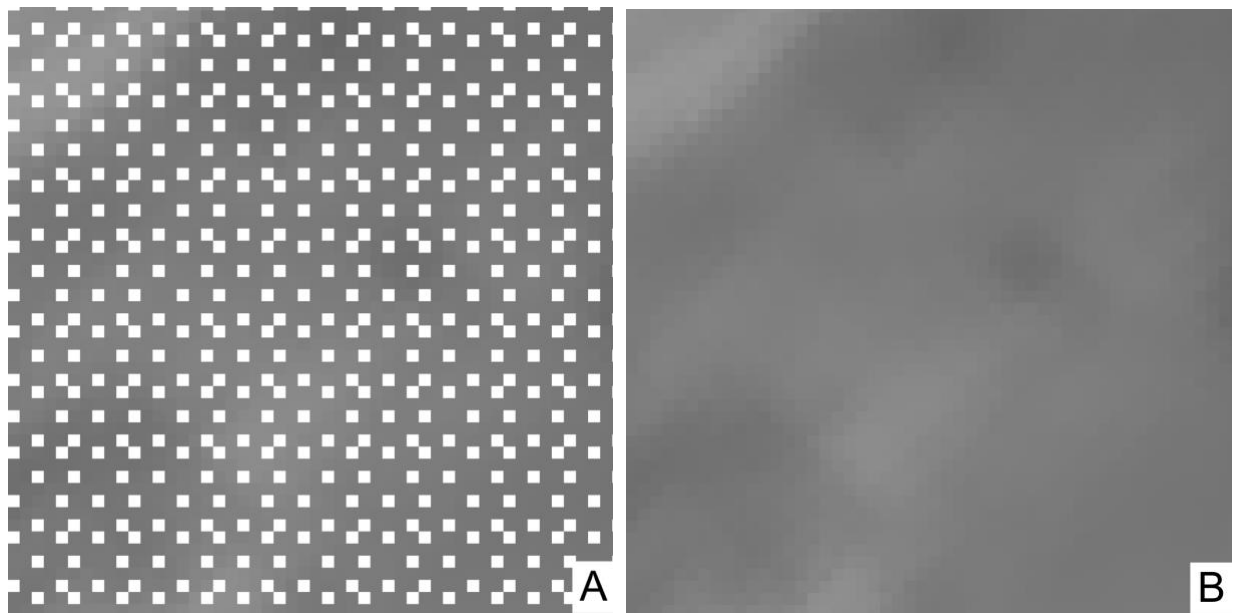


Figure 10. Sample patches of the bathymetry data at different stages of processing. (A) The rotated bathymetry with holes in the data; (B) the interpolated result using the inverse distance weighting (IDW) method to fill in data gaps.

3.5 ArcDelRCM

3.5.1 Development chronology

Liang, Voller, et al., (2015) developed DeltaRCM, a reduced complexity model which requires less computational intensity to operate when compared to a physics-based model as it treats water as discrete packets rather than using more advanced computational fluid dynamics while being able to recreate results with reasonable accuracy (Liang, Voller, et al., 2015). From this, Lauzon et al. (2019) developed DeltaRCM-Arctic, which notably included modifications to incorporate permafrost into the delta formation calculations. ArcDelRCM was then developed to be able to reproduce the ramp features in Arctic deltas, partially caused by the erosion protection provided to the bed by bed-fast ice in the winter (Chan et al., 2023).

3.5.2 ArcDelRCM major processes

ArcDelRCM uses a square cell-shaped mesh, uniform across the entire modelling domain. The model domain was chosen to be square in all simulations (i.e., the number of cells in both the x and y dimensions match, $N_x = N_y$, with square cells of size δc).

3.5.2.1 Domain inlet

The first column(s) of the model domain form an impermeable inlet wall, and all other columns of cells are set to a user-specified basin depth value (h_B) at model initialisation, creating an empty basin. In the centre of the inlet wall (i.e., $\frac{N_y}{2}$) is an opening in the wall to allow for an inlet to the modelling domain, with water pouring from the inlet into the basin (**Figure 11**). The width of the inlet (N_o) was calculated dynamically for each bathymetry resolution used, maintaining an opening similar to the Coppermine River's approximate 250 m width at the edge of the modelling domain. The water surface exiting the inlet is always at 0.0 m. The inlet can be set to a uniform depth (h_o) to approximate the river's depth, forming a slope or drop down to the basin depth. Further, an inlet flow speed (u_o , either a constant or a time series) can be set to represent the river's discharge at that location. These inlet cell depths are reset at each model time step to this value, allowing for erosion dynamics but ensuring that the total discharge entering the modelling domain remains a known value at each time step (Chan et al., 2023).

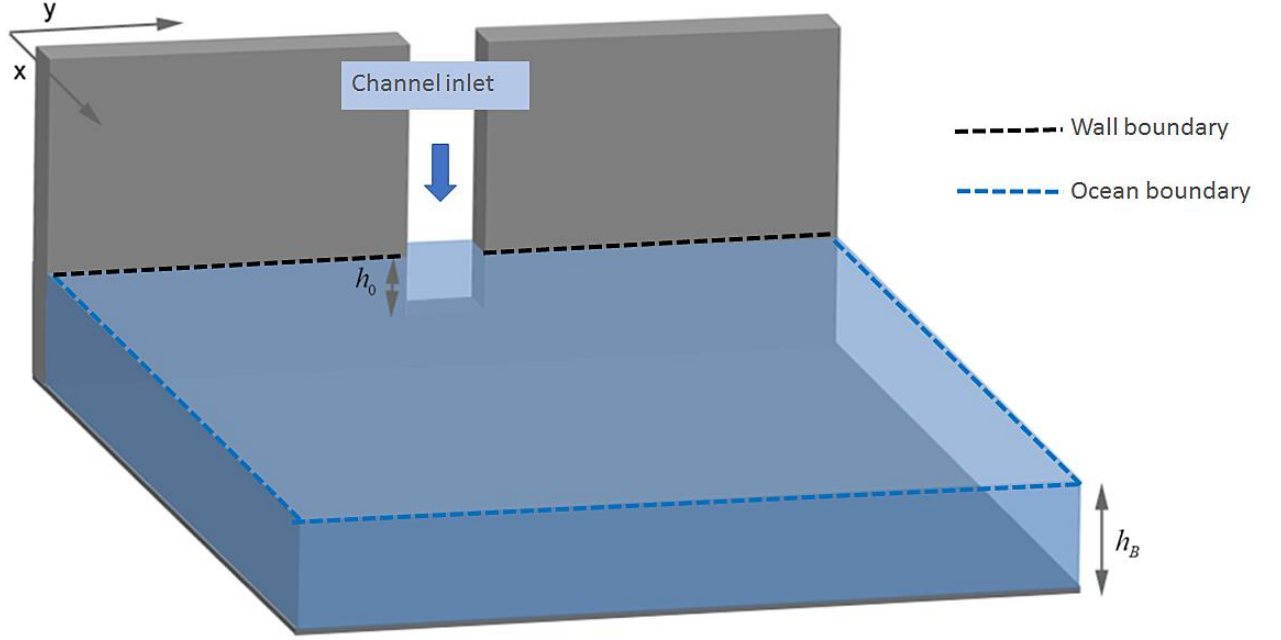


Figure 11. A diagram of the inlet channel of ArcDelRCM. The grey section is the impermeable wall that permits no water flow, with a break to allow water flow (where h_o represents the inlet channel depth) into the empty ocean basin (transparent blue section of depth h_B). The grey impermeable wall also extends underneath the ocean basin, preventing any erosion or water flow below this elevation. The edges of the basin are labelled with an ocean boundary, the spatial threshold where ArcDelRCM allows water to exit the modelling domain. Taken from Liang, Voller, et al. (2015).

3.5.2.2 Water flow

This discharge is divided into a number of individual packets (n_w) where each packet moves through the model domain using a weighted random-walk based on the combination of the water flow depth (emulating the water's inertia) and the water-surface gradient (i.e., the slope of the surface of the water, which emulates the downward force gravity has on the water) (Chan et al., 2023). The inertial contribution is calculated as:

$$w_{i,inertia} = (h_i - h_{i,ice}) \cdot \left(1 - \frac{h_{i,ice}}{h_i}\right) \cdot \frac{\text{maximum}(0, q_w \cdot d_i)}{\Delta_i} \quad (3.1)$$

where h_i is the water depth of a neighbouring cell and its ice depth, $h_{i,ice}$, which together produce the resistance to flow in that cell (Lauzon et al., 2019). d_i is a unit vector which points to this neighbouring cell, q_w is the unit vector for current discharge, and Δ_i is the distance between epicentres of the given cell and the neighbour.

The gravitational (i.e., water-surface gradient) contribution to the packet movement is calculated as:

$$w_{i,surface} = \text{maximum}(0, -\nabla H_i) \quad (3.2)$$

Thus, the water packet movement is determined by the combination of these individual contributions:

$$w = \gamma \cdot w_{surface} + (1 - \gamma) \cdot w_{inertia} \quad (3.3)$$

where γ is a “partitioning coefficient” set by the user to change the relative weight of each of the gravitational and inertial components, with the inertial component generally being far larger. This value was set to the midpoint of the range ($\gamma = 0.02 - 0.15$) for consistency across simulations as assessed by Chan et al. (2023) based on the initial works in making DeltaRCM (Liang, Geleynse, et al., 2015; Liang, Voller, et al., 2015). The water flow direction is calculated as the average direction of all water packets entering and exiting a cell at a given time step, the average taken multiple times to ensure stability.

Water depth is calculated as the difference between water surface height and the bed-elevation height (i.e., the top of the sediment column / riverbed). Cells which contain water that is less than 10 % of the inlet channel depth (h_0) are considered dry cells and are weighted accordingly during the flow calculations (weight of 0). On the other hand, dry cells which have neighbouring cells with higher water surface levels are wetted at the beginning of each time step with the average water surface height as the average water surface height of neighbouring wet cells (i.e., neighbouring dry cells are excluded from this calculation) (Chan et al., 2023).

3.5.2.3 Sediment

ArcDelRCM allows for a user-defined ratio of sand/mud in the water column, representing a bed load/suspended load ratio. Sediment is split into packets like the water packets and is transported throughout the model domain in a similar fashion. This sediment can accumulate or erode under each cell, resulting in a sediment column; a stack of layers of specified thickness (δz) in each cell representing the sand/mud ratio contained in each layer. The bottom of the sediment column is considered bedrock, or a non-erodible surface at the elevation of the user-defined basin depth ($-h_B$) unless a slope has been applied to the basin, in which case the bedrock elevation would follow the calculated values based on the slope parameters.

3.5.2.4 Ice cover

ArcDelRCM allows for a user-defined maximum ice thickness ($h_{ice,max}$) and initial upstream extent (f_{ice}) of ice cover. At the beginning of each model year, which takes place in springtime, the ice is at its greatest extent, reaching no further upstream than f_{ice} of the domain in the x-direction. The ice thickness at any given cell is limited to 99.99 % of the water depth to improve the stability of the model. Chan et al. (2023) added a feature to ArcDelRCM model called “bottom-fast ice protection”, which shields the bed from any erosion or deposition, preventing this narrow gap between the bed and the bottom of the ice from creating highly erosive, fast-flowing water. The ice is melted throughout the model year by the combination of two driving forces, atmospheric heat and discharge-based river heat flux.

$$\left(\frac{dh_{ice}}{dt}\right)_{atmospheric} = -a \frac{h_{ice,max}}{t_{melt}} \quad (3.4)$$

where t_{melt} is the time period required to melt the ice column due solely to atmospheric heating, and a is a coefficient which specifies the fraction of ice melting that occurs due to atmospheric heating (Chan et al., 2023).

$$\frac{dh_i}{dt} = -\frac{\rho_w c_p C_s u T}{\rho_i L_f} dt \quad (3.5)$$

where ρ_w is the density of water, c_p is the specific heat of water, C_s is a heat transfer coefficient of water, u is the water velocity, T is the difference between the water temperature and the ice melting temperature, ρ_i is the ice density, and L_f is the latent heat of fusion of water (Chan et al., 2023; Lauzon et al., 2019, supplemental; Searcy et al., 1996).

3.5.2.5 Permafrost

Each sediment layer in every cell is flagged as containing permafrost if their bed elevation remains below the assumed active layer depth of 0.5 m and has done so for a minimum of two years. If more than 75 % of the sediment layers in the sediment column are flagged as permafrost, or enough that would represent at least 75 % of the inlet channel depth, h_0 , then the entire sediment column in that layer is treated as having permafrost. This results in that cell being assigned an erodibility factor, E , designed to reduce the susceptibility of permafrost cells compared to non-permafrost cells.

A complete description of the inner workings of ArcDeIRCM and its parent models can be found in Chan et al. (2023), Lauzon et al. (2019), Liang, Geleynse, et al. (2015) and Liang, Voller, et al. (2015).

3.5.3 Implementation of ArcDeIRCM

Given the primary objective of this research was to determine ArcDeIRCM's usefulness as a predictive model, several model parameters were set to reasonable, identical values between iterations of the model, ensuring consistency across results (**Table 2**). The majority of values were left unchanged from the model code available from Chan et al. (2023) as of 2025.

Table 2. Parameter values held constant in all simulations.

Parameter	Description	Set value in all simulations
--	Random seed value	20200616230157
δc	Cell dimension	$\frac{8436}{N_x}$ m
δz	Stratigraphic layer thickness	0.05 m
N_0	Inlet channel width	$75 \cdot \frac{N_x}{2109}$ cells
N_{wall}	Inlet wall thickness	1 cell
n_w	Number of discharge packets	2000
n_s	Number of sediment packets	2000
$lastiterw$	Number of iterations in water packet release	5
f_{ice}	Upstream ice extent (as a fraction of delta length)	0.4
$h_{ice,max}$	Maximum ice thickness	3 m
E	Permafrost erodibility	0.95
$\dot{a}$	Atmospheric contribution to ice melting	1
$sedfraction$	Sediment fraction by water volume	0.001
f_{sand}	Fraction of sand (bed load)	0.5
f_{mud}	Fraction of mud (suspended)	0.5
h_0	Inlet channel depth	3 m
h_B	Basin depth	5 m
u_{muddep_coef}	Flow speed upper limit for mud deposition (coeff.)	0.3
u_{mudero_coef}	Flow speed lower limit for mud erosion (coeff.)	1.5
$u_{sandero_coef}$	Flow speed lower limit for sand erosion (coeff.)	1.05
α	Bed-elevation diffusive filtering scaling coefficient	0.1
β	Meyer-Peter & Müller exponent	3
γ	Partitioning coefficient	0.09
ε	Surface-elevation diffusion coefficient	0.1
ϖ	Underrelaxation coefficient	0.1
$backwater_method$	Method to use for backwater calculations	backwater_constslope
--	Ice-free model ramp up period	0
--	Days required to completely melt ice each year	10
--	All other parameters	default

3.5.3.1 Bathymetry data import

Given that ArcDelRCM is a delta evolution model designed to be run with an empty basin as initial conditions, a helper script was written to enable the effective import of bathymetry data into the model to allow for ArcDelRCM to be used in a predictive capacity. This script takes an initial (i.e., time step = 0) “save state” file (the output of the model used for inheritance, the continuation of modelling from any given time step at a later date), replaces the bed elevation data stored within the desired bathymetry data, re-calculates the water depth values for each cell, and builds up a sediment column of a specified height underneath each cell. During the initialisation of ArcDelRCM, each cell of the modelling domain is attributed a structure containing 3 vectors: “z”, “permaz”, and “strata”. These contain the sediment strata information necessary for the model to operate and are thus the injection point for the user-defined bathymetry data. The structure is defined as follows (**Figure 12**):

- z : a two-element vector containing the bedrock elevation and the bed-surface elevation
- permaz : a two-element vector containing the thickness of permafrost layers and the thaw depth
- strata : a vector containing objects of type Sediment{T}, one object per layer of sediment

Sediment{T} is itself a structure containing 3 variables, defined as follows:

- sandfrac : the fraction of sand in the layer (the sand : mud ratio)
- timeofdep : the time when this sediment layer was deposited in model years since the model initialisation
- frostysince : the time when the layer froze in model years since the model initialisation

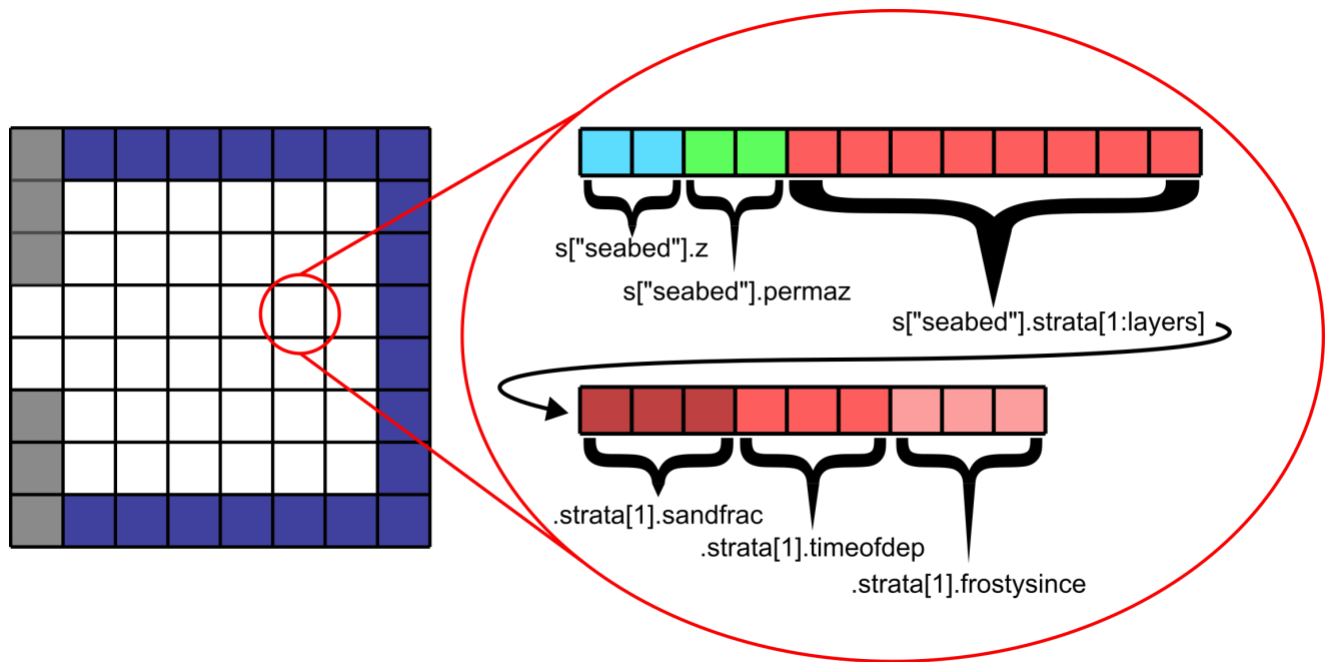


Figure 12. A visual representation of the sediment strata structure stored in each cell of the modelling domain, saved by ArcDelRCM in the “...savestate.jl” and optional “...strata.jl” file(s). The grey cells represent the inlet wall (either the first row or transposed to the first column), the outer blue cells the “ocean” or domain exit cells, and the white cells in the centre are those where the delta formation and modification occur.

The number of boxes attributed to each variable on the right-hand side of **Figure 12** are not necessarily representative of the true relative size of each variable, as this depends on the chosen cell within the modelling domain: the “strata” variable (`s[“seabed”][x,y].strata`) has a variable size depending on the number of layers of sediment present in the cell, and accounts for the vast majority of the model exports’ file size.

Of important note for the model results is the sand/mud ratio, which represents a simplified distribution of grain sizes and cohesiveness. This is expressed as the proportion of the total sediment volume that is sand, where 0 represents entirely mud and 1 represents entirely sand. A fraction of 0.8 was chosen in all cases for this built-up sediment, designed to represent the largely sandy soils of the region while minimizing the impacts of large amounts of cohesive sediment in the model. The thickness of sediment each “strata” vector (calculated as the stratigraphic layer thickness, δz , multiplied by the number of layers) accounts for the difference in elevation between the bedrock and the bed-surface of each cell, rounded to the nearest δz .

The “permaz” variable was not modified from the initialisation value to simplify this investigation, resulting in a permafrost layer thickness of 0 and a thaw depth of 0.5 (metres) in all

cases, which are values consistent with results obtained without the bathymetric data import after several model years. In the Sediment{T} structure, only the “sandfrac” was assigned a value (0.8). The “timeofdep” does not appear to impact model results and is used for record-keeping, thus, an arbitrary value representing ~4.5 minutes was assigned to all deposited sediment in all simulations. The “frostysince” variable is also used for record-keeping, however, it also serves to note if a layer of sediment has been unfrozen by storing a NaN value, which is what was assigned to all sediment during the bathymetry import. These are again values consistent with results obtained without the bathymetry data import after several model years.

The model was run on a desktop computer with an i7-3770K (3.5 GHz) CPU and 32 GB of DDR3 RAM. ArcDeIRCM writes the current frame outputs to a NetCDF file each time step the user chooses to record (default = every time step), which accounts for a large portion of the total model output file size in simulations with many time steps. Since the volume of data being written to this NetCDF file each time step is relatively small, disk speed is not an important factor on modern hardware. Thus, the model computation time is almost entirely a function of the CPU single-core speed if sufficient RAM is available to store the entire model domain’s sediment strata in memory (i.e., the “...savestate.jl” file). The use of swap/page file is not recommended due to drastically slower performance, since ArcDeIRCM requires access to all cells in the modelling domain at each time step, requiring the constant transfer of these data to and from an SSD/HDD. The model output file sizes are dependent on the resolution chosen and the number of time steps, which can be estimated as 100 000 cells per gigabyte of storage (with 5 metres of built-up sediment under each cell) for the sediment strata data and 400 time steps per gigabyte for the same 100 000 cells for the NetCDF model output data.

4 RESULTS

ArcDeIRCM was run with a variety of parameters (**Table 3**) to test its response to flow variations that might be expected in the natural environment, as well as changes in modelling parameters. For this section, several example test cases will be presented for comparison. **Table 3** shows the parameters which varied between these three test cases, while all other parameters were held constant (**Table 2**). The time steps in test cases A1, B1, B2, and B3 were chosen to keep a criterion ζ within the desirable range noted by Chan et al. (2023) to produce results not affected by numerical instability. This criterion is dependent on the sediment volume flux entering the model domain (ΔV_s), mesh spatial resolution (δc), and the basin depth (hB), and was $\zeta = 2.0$ for these test cases.

$$\zeta = \frac{\Delta V_s}{hB \cdot \delta c^2} \quad (4.1)$$

Table 3. The test cases presented in this study, with technical details about the model's operational requirements.

Test case	Resolution (m) [x, y]	Constant inlet flow speed (m/s)	Time step (s)	Length of simulation (model years)	Model runtime (hours)	Strata file size (MB)	NetCDF file size (MB)	Days per model year
A1	15	0.3	2 084	10	73	3 070	31 430	10
B1	25	0.3	23 148	25	6	1 100	2 500	10
B2	25	0.3	23 148	4.2	6	1 100	2 500	60
B3	25	1.0	6 944	25	22	5 800	8 280	10
C1	50	1.0	27 778	300	15	600	6 400	10
C2	80	1.0	66 666	300	2.5	230	1 000	10
C3	100	1.0	111 110	300	1.0	120	400	10
C4	120	1.0	201 666	300	0.5	76	151	10
C5	160	1.0	265 000	300	0.2	42	66	10

4.1 Mesh Sensitivity

A mesh sensitivity analysis was performed, presented in test cases C1–C5, with spatial resolution ranges of 50–160 m and corresponding time step ranges of 7–75 hours. The inlet flow

speed was increased for these simulations in order to encourage model stability at the coarser resolutions. The overall geomorphic trends are similar between test cases, but closer inspection of individual regions reveals notable differences at small scales. For example, test cases C1, C2 and C3 diverged notably by 20 years with the formation of a deep and narrow channel forming on the west side of the Coppermine River in C2, on the east side in C3, and near the inlet in the centre of the river in C1, but more closely followed the C2 morphology further downstream (**Figure 13**). Slight changes in the extent of the shallow delta ramp extent are visible, however, these differences between test cases are more evident at both the beginning and the end of the 300-year simulation.

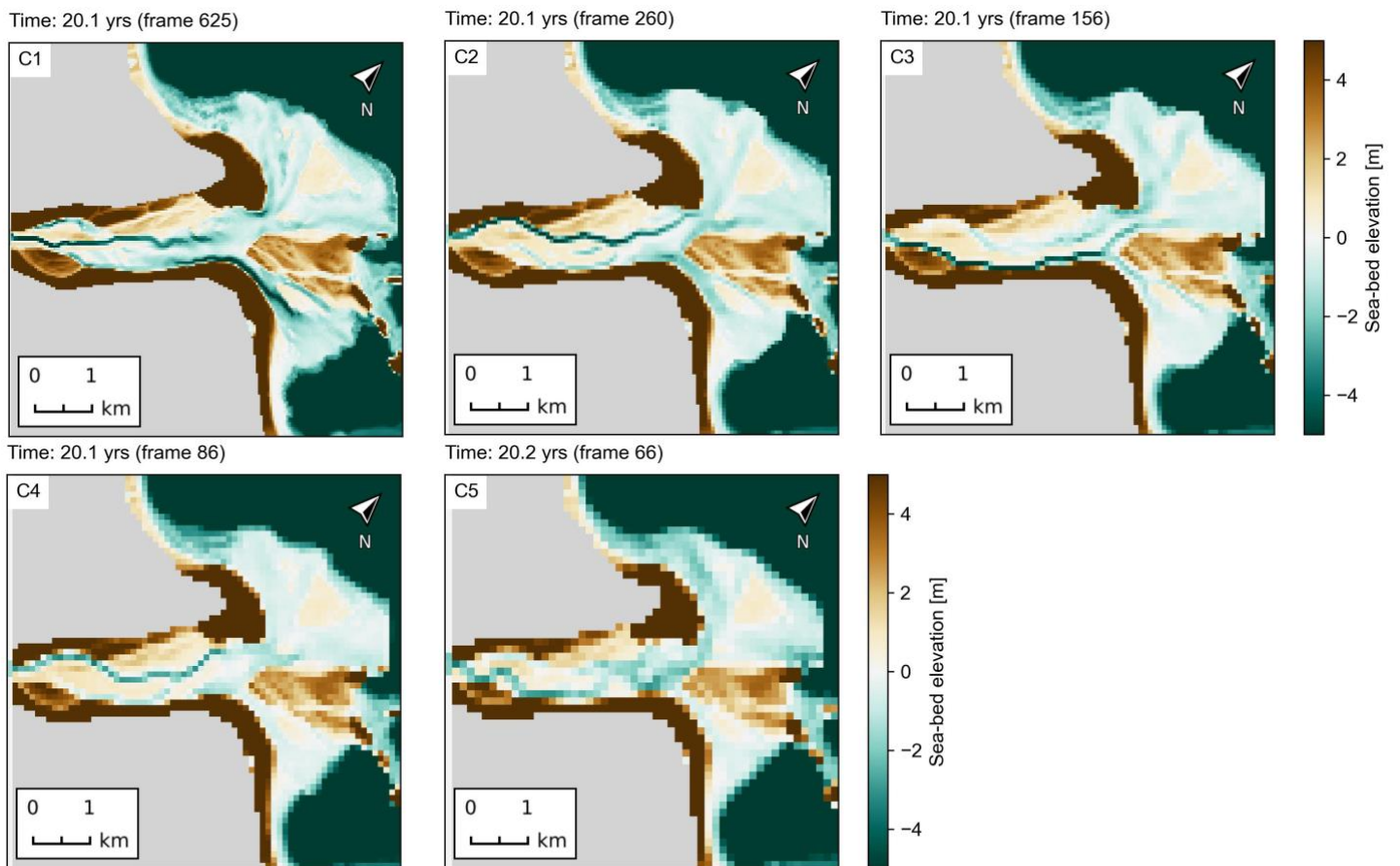


Figure 13. Mesh sensitivity test cases C1-C5 after 20 years.

In all cases except C5, the cessation of delta fan expansion is attributed to the formation of a principal channel along the west edge of Graveyard Island regardless of the route of a principal channel further upstream, while C5 maintained a principal channel to the east of Graveyard Island (**Figure 14**). These principal channels ultimately transported nearly all of the water and sediment

through the modelling domain, which supported the termination of delta fan expansion by starving these regions of potential drivers of geomorphic change (**Figure 15**).

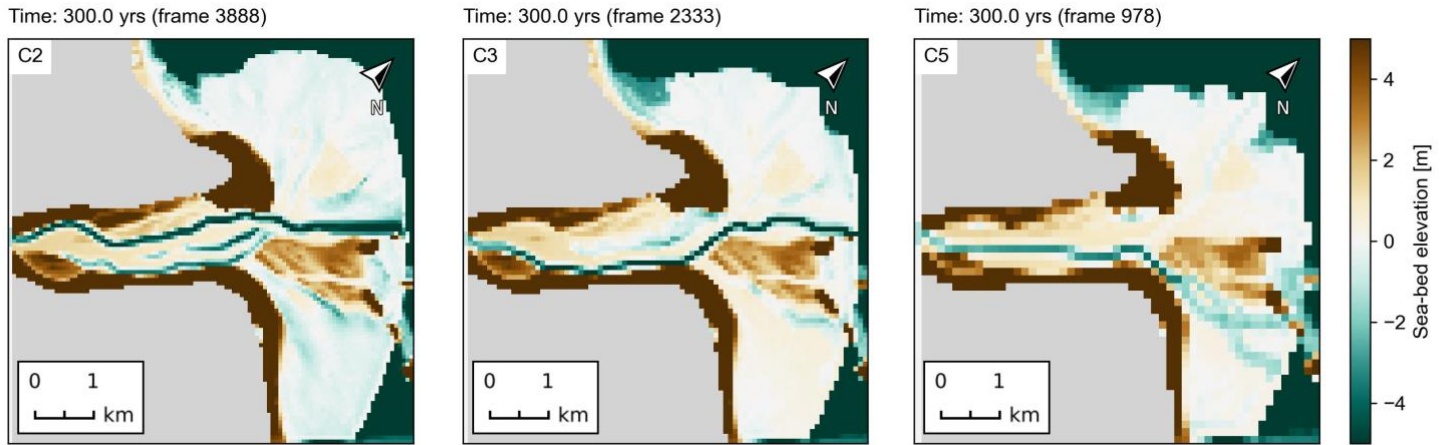


Figure 14. Plots exemplifying the formation of a principal channel west of Graveyard Island at the end of the simulation (test cases C2, C3, C5).

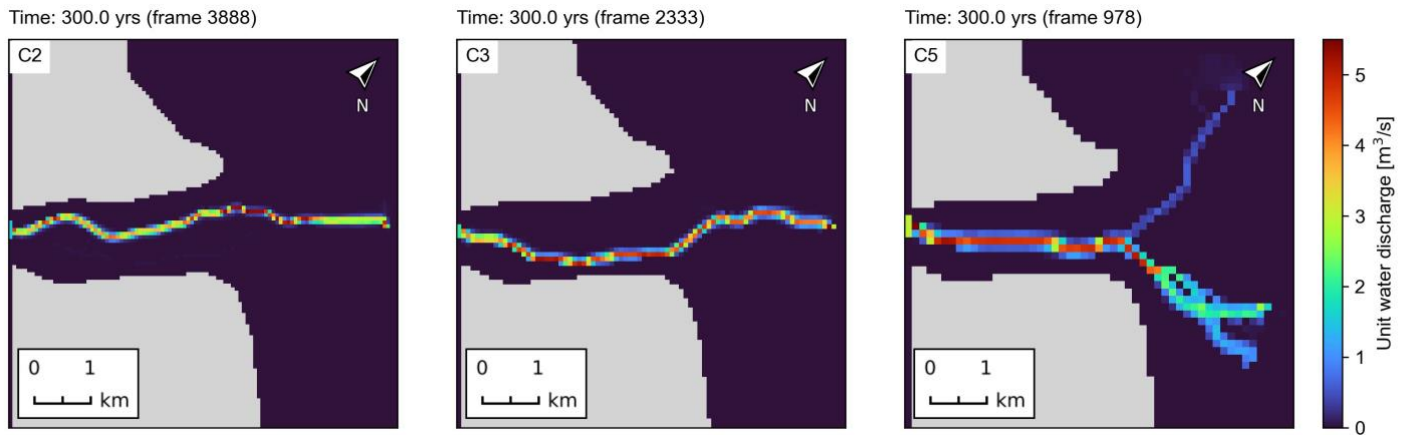


Figure 15. Plots showing the distribution of discharge throughout the model domain at the end of the 300-year simulation (test cases C2, C3, C5).

The total portion of the delta which lay below certain bathymetric thresholds is shown in **Figure 16**, showing that the higher-resolution test cases (i.e., C1 and C2) experienced similar rates of delta fan expansion as other cases, however, they expanded for a longer period of time towards the west edge of the modelling domain before ceasing expansion. Case C5 is the only example where the delta fan experienced practically no expansion until ~60 years, at which point it joined the other test cases in continual expansion for the following 150 years. The flat slope in all test cases after years 150-200 does not indicate that the deltas stopped expanding, rather,

that they had reached the edge of the non-ocean modelling domain on the east side of Graveyard Island, and sediment was thus carried out of the domain. **Figure 17** shows the change in area that lay below the same thresholds depicted in **Figure 16**, highlighting the variability in the rates of delta fan expansion between the different test cases. The delayed growth in case C5 when compared to all other test cases suggests that this very coarse 160 m resolution may not provide results consistent with other mesh resolutions; however, all other test cases show similar trends to one another, particularly in the rates of change of the shallow portion of the delta fan (i.e., -5 m threshold).

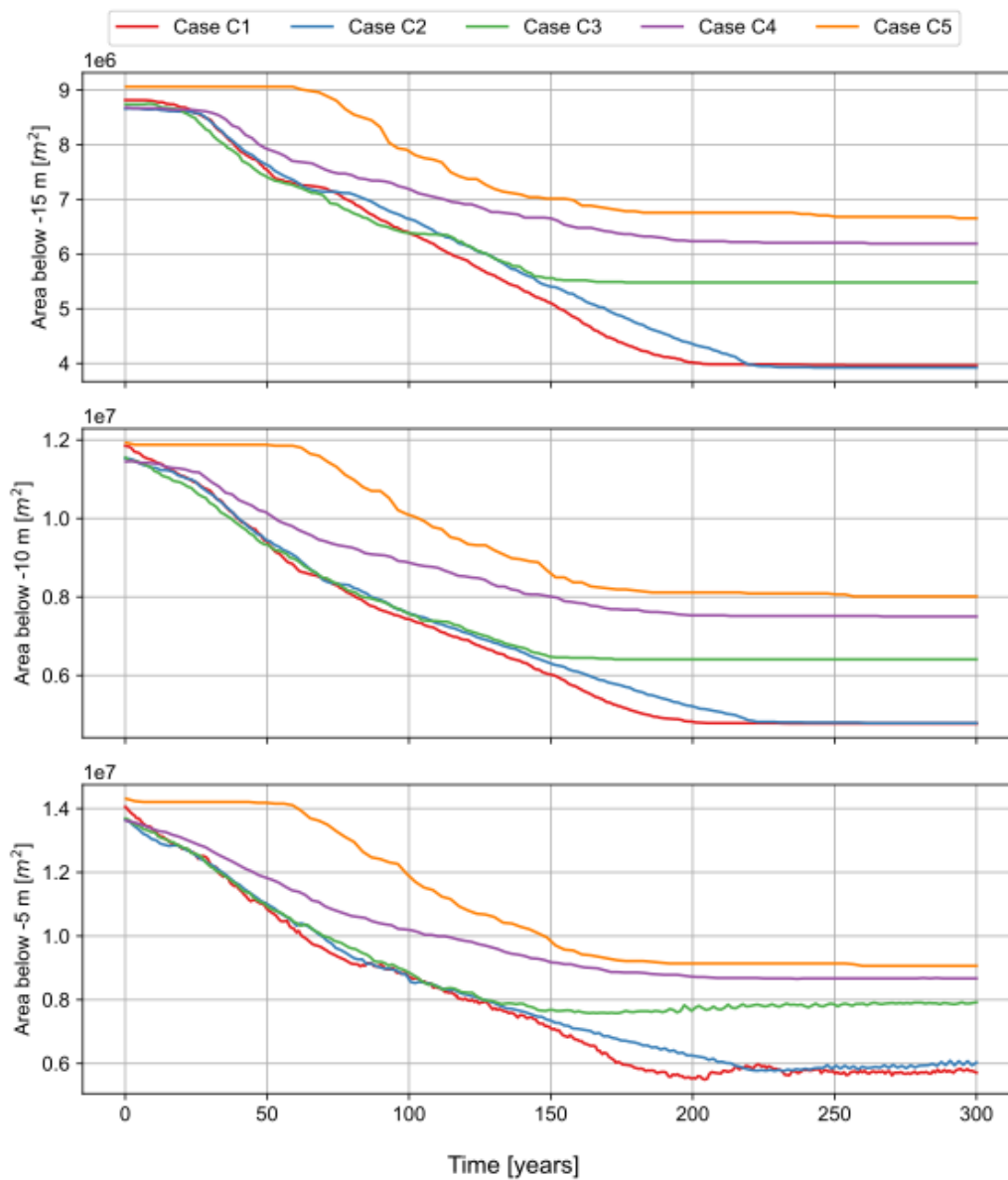


Figure 16. Plots showing the area within the model domain that lies below three elevation thresholds (-15 m, -10 m, -5 m) over time (test cases C1–C5).

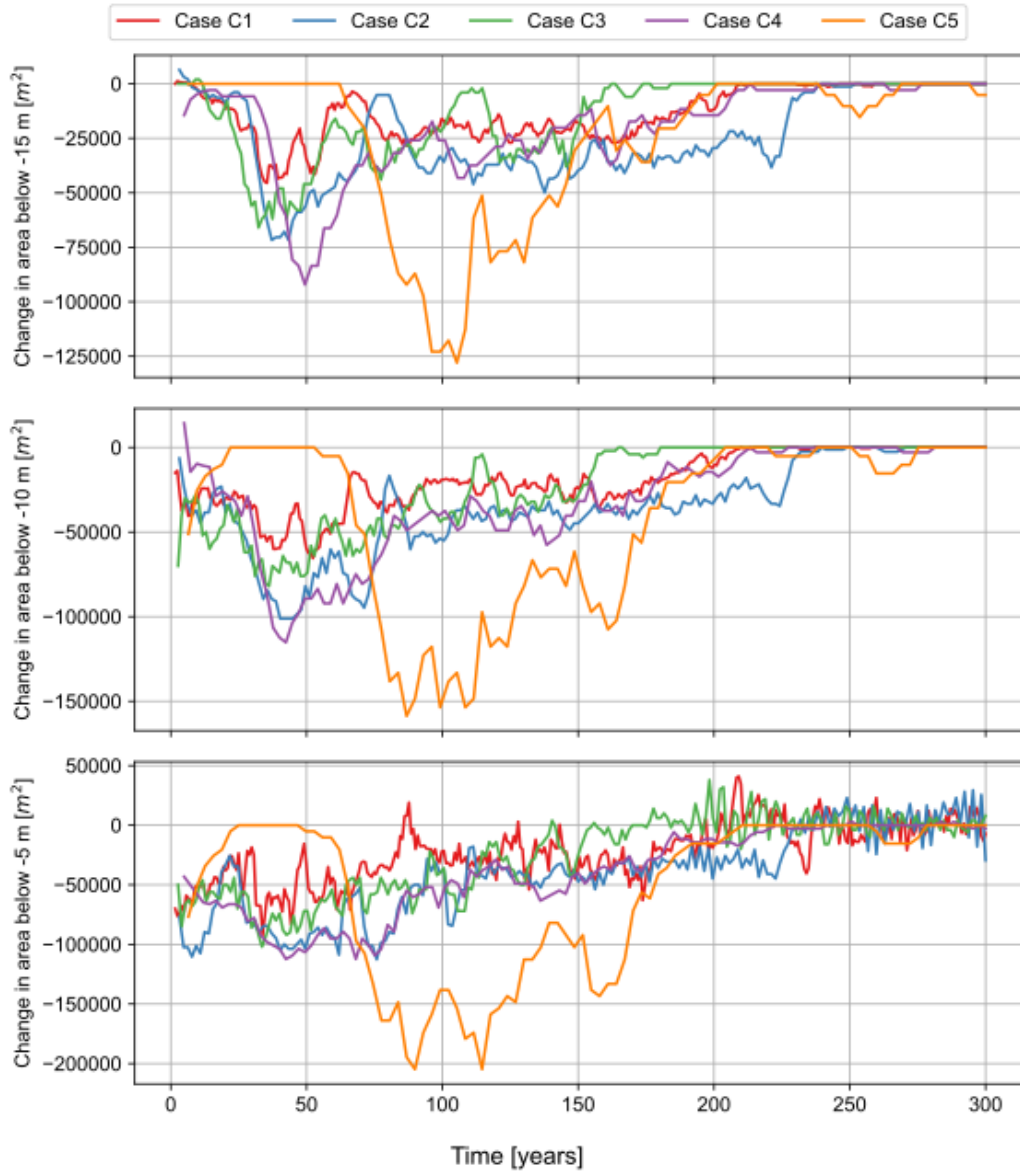


Figure 17. Plots showing the rates of change in area (smoothed with a 5-time step rolling average) within the model domain that lies below three elevation thresholds (-15 m, -10 m, -5 m) over time (i.e., deep-water loss rates) (test cases C1–C5).

4.2 Hydrodynamic Conditions

While test cases A1, B1, and B2 used a constant inlet flow speed of 0.3 m/s—corresponding with discharge estimations from the Coppermine River—all other test cases used an inlet flow speed of 1.0 m/s. A comparison can be made between cases B1 and B3, which used identical initial conditions except the inlet flow speed and a corresponding change in the time step size. This decreased deposition near the town of Kugluktuk in the case of the higher flow speed B3,

and decreased off-ramp sediment deposition east of Graveyard Island. These changes in the delta's behaviour were minor but represent a divergence after only 25 years.

Case B2 had identical initial conditions to case B1 except for a longer model year, containing 60 days rather than 10 days. The annual sea ice cover was set to melt over the same time period in each case, resulting in a 50-day ice-free period every year in test case B2, rather than immediately refreezing as in test case B1. This resulted in minor morphological changes within the Coppermine River, with the longer model year in B2 showing increased deposition throughout the width of the channel. Rapid erosion occurred along the western bank of the river causing a large proportion of the water flow to occur adjacent to this bank.

Similarly, other test cases (i.e., A1, B1) showed deep channel incision along both riverbanks, which corresponded with local increases in discharge, where a gradual change in the flow of water towards these incised channels occurred as the model progressed through multiple time steps. In general, the coarser resolution test cases (i.e., C-series) resulted in ArcDelRCM initially predicting water flow spread more evenly throughout the full river width. With finer spatial resolutions (e.g. A1), however, a lack of flow in large portions of the model domain existed from initialisation in both the riverine section and the delta. In all test cases, the lack of flow in portions of the expected river flow was accentuated as the simulation progressed, in alignment with the observed channel incision (**Figure 18**). The flow speed can be seen to exist in narrow channels after several model-years, in stark contrast to the model initialisation where a greater width of the Coppermine River can be seen to have substantial discharges.

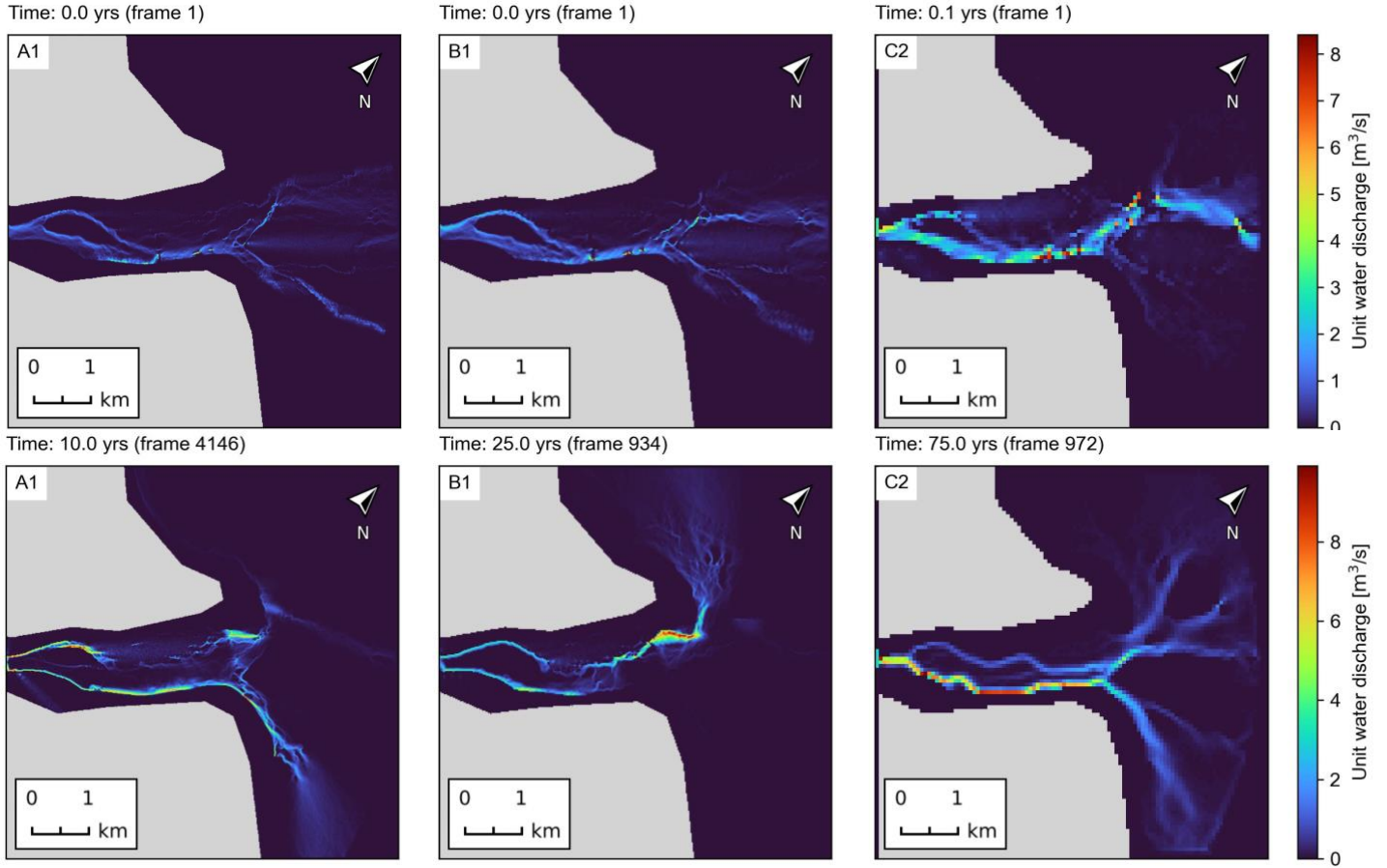


Figure 18. Test cases A1, B1, and C2, displaying the water discharge data. The top row of graphics shows the test cases at model initialisation and the bottom row at mature points in each simulation.

The flow speeds along the shorelines are not substantially different than those seen at model initialisation; however, this may only be due to a numerical limit set in ArcDelRCM for flow speeds: twice the average inlet flow speed (i.e., 2.0 m/s in this case). The tendency for water flow to occur along the shoreline is not a phenomenon which requires many model time steps to occur. As seen in **Figure 19**, the first time step of case A1 shows that while the inlet channel passes water relatively evenly throughout its width into the model domain, within 1 km downstream the flow rapidly coalesces to narrower channels, diverging when entering the mouth of Coppermine Delta. This heterogeneity is further accentuated as the simulation progresses. This split of the flows along either side of Graveyard Island also results in the majority of the discharge following the shoreline closely, with different test cases showing variation in the location of this shoreline-hugging behaviour.

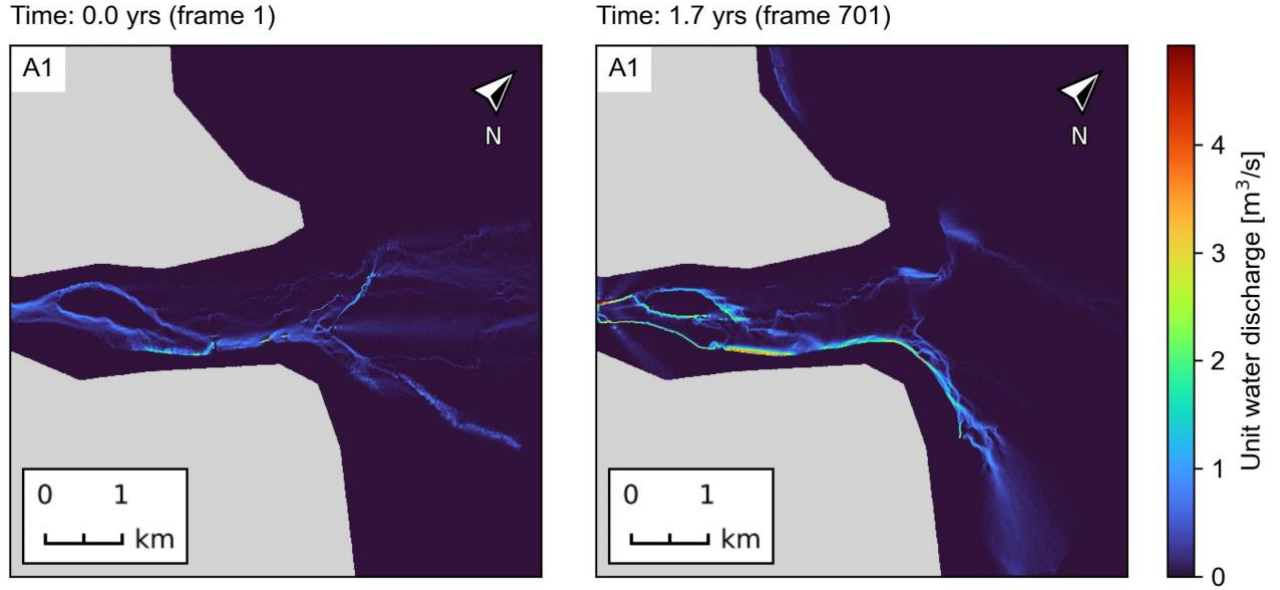


Figure 19. Test case A1, displaying the discharge data at model initialisation (left) and after 1.7 years (right).

The water levels predicted in each simulation follow expected trends based on the discharge data, with minor exceptions. **Figure 20** shows slight variations in the deltaic region in test case A1, which is consistent with the noted challenge of modelling low-slope environments like Arctic deltas. The lower-resolution test cases showed expected water levels with less sudden variations. The non-simulated ocean region is visible in the north and eastern corners of the domain in case C2.

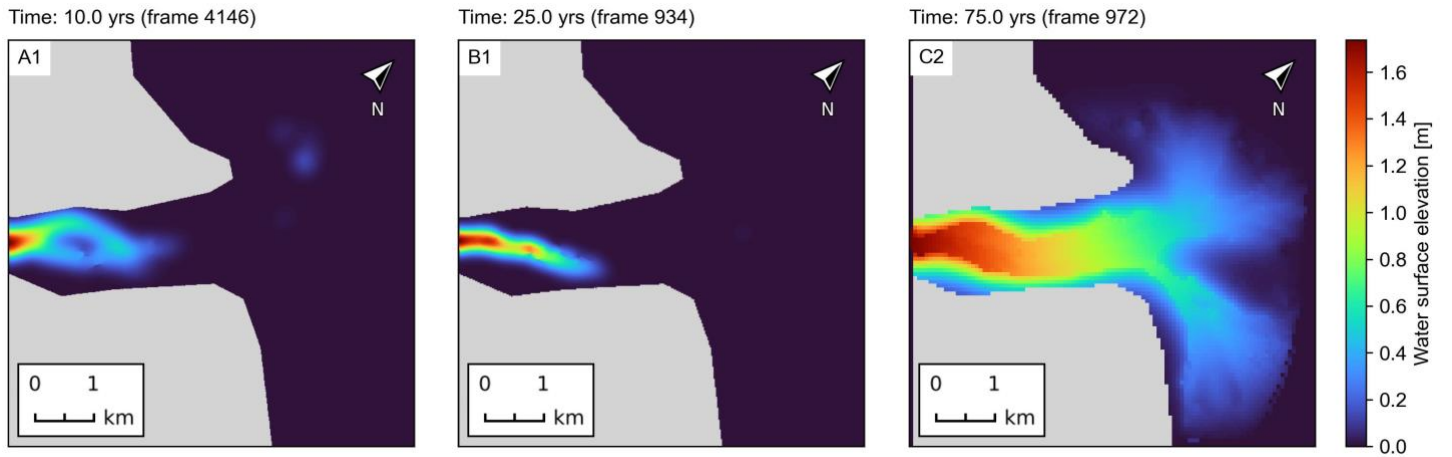


Figure 20. Test cases A1, B1, and C2, displaying water level data at mature points within each simulation.

4.3 Geomorphological Evolution

Several patterns present themselves in the outputs generated by ArcDelRCM. Processes of gradual erosion and deposition occur in test case A1, particularly in these locations near the inlet channel. **Figure 21** shows an example of a location where, in the fifth year after the simulation start, a year-long erosion event occurred, followed by several years of more gradual deposition, with corresponding changes in water depth and thus, discharge. This was not due to downstream ice cover changes impacting water flow, where a refreezing event is applied across the relevant portions of the model domain at the beginning of each year. This is a location further upstream than the maximum annual ice extent ($h_{i,max}$), and observations of the surrounding pixels revealed a temporary migration of the thalweg into that area, which was gradually filled in with sediment as the thalweg migrated away from the area. **Figure 22** shows a correlation between flow velocity increases and decreased water depth with a sudden deposition event at a nearby location occurring after year 6, highlighting the importance of both of these changes to overall discharge increases.

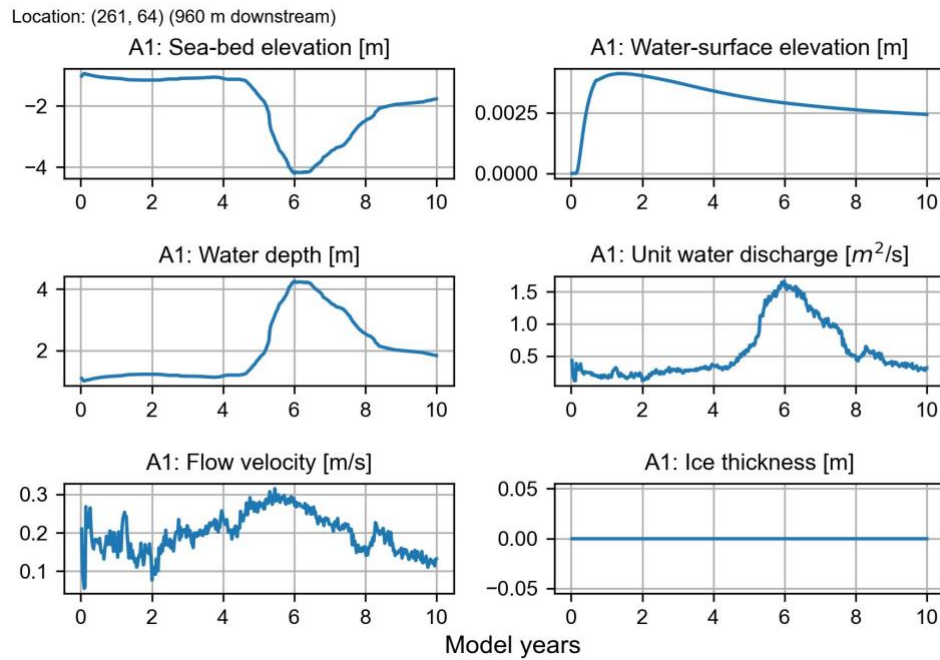


Figure 21. Test case A1 simulated values, at an upstream location near the west bank, west of a mid-channel bar, across 10 model years. The first ~6 hours are not displayed to enhance visibility. Top-left: sea-bed elevation, top-right: water-surface elevation, centre-left: water depth, centre-right: unit water discharge, bottom-left: flow velocity, bottom-right: ice thickness.

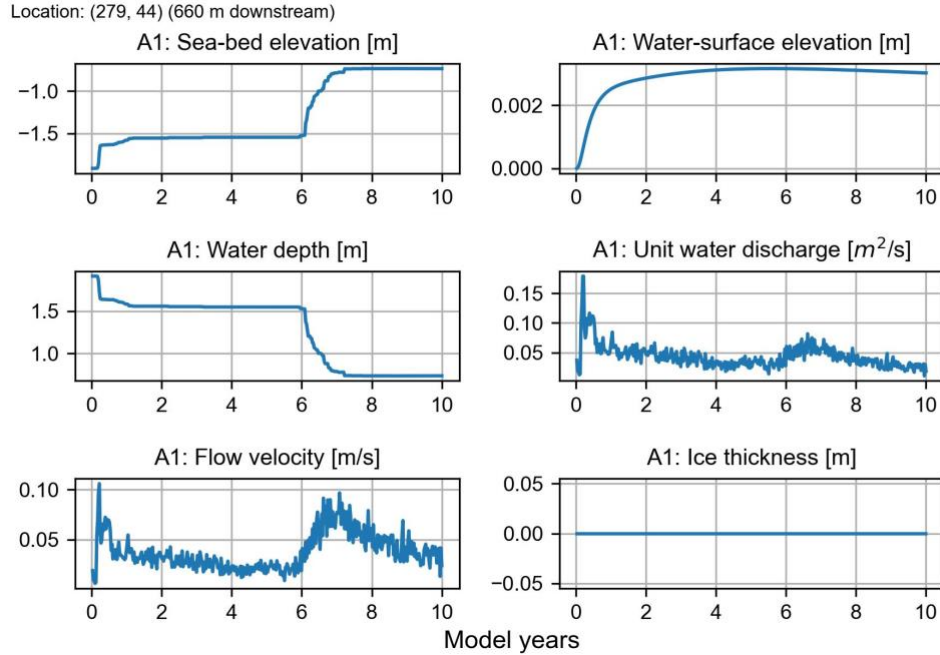


Figure 22. Test case A1 simulated values, at an upstream location in the centre of the river, east of the mid-channel bar. Annual ice cover does not reach this far upstream. The first ~6 hours are not displayed to enhance visibility. Top-left: sea-bed elevation, top-right: water-surface elevation, centre-left: water depth, centre-right: unit water discharge, bottom-left: flow velocity, bottom-right: ice thickness.

The beginning of each year saw maximum ice cover (greatest thickness and extent), followed by a melting period. As the ice rapidly melted, a corresponding increase in discharge was generally observed (**Figure 23**). The mesh sensitivity case C1 had a sufficiently long simulation period to allow for gradual expansion of the delta fan, beginning nearly 100 years after the initialisation. This allowed for observations of the change in ice cover thickness as sediment was deposited in the delta, ultimately raising the sea-bed elevation to the point where it approached the overall model water level, permitting minimal water depth and winter ice thickness (**Figure 24**).

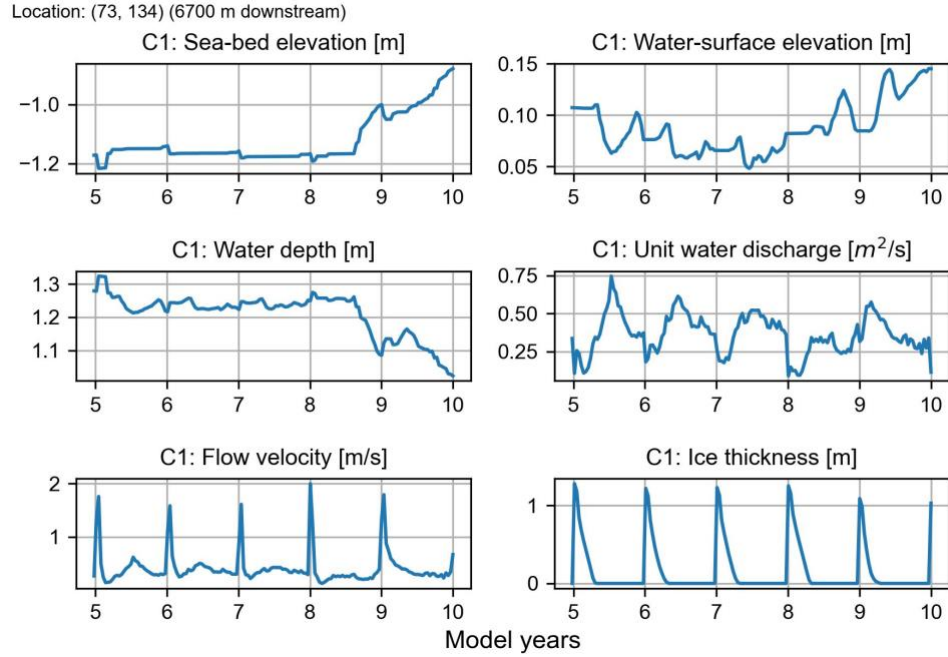


Figure 23. Test case C1 simulated values, at an offshore location approximately in the centre of the delta fan, between Graveyard Island and Hiugak Island. Annual ice cover reaches this region. Top-left: sea-bed elevation, top-right: water-surface elevation, centre-left: water depth, centre-right: unit water discharge, bottom-left: flow velocity, bottom-right: ice thickness.

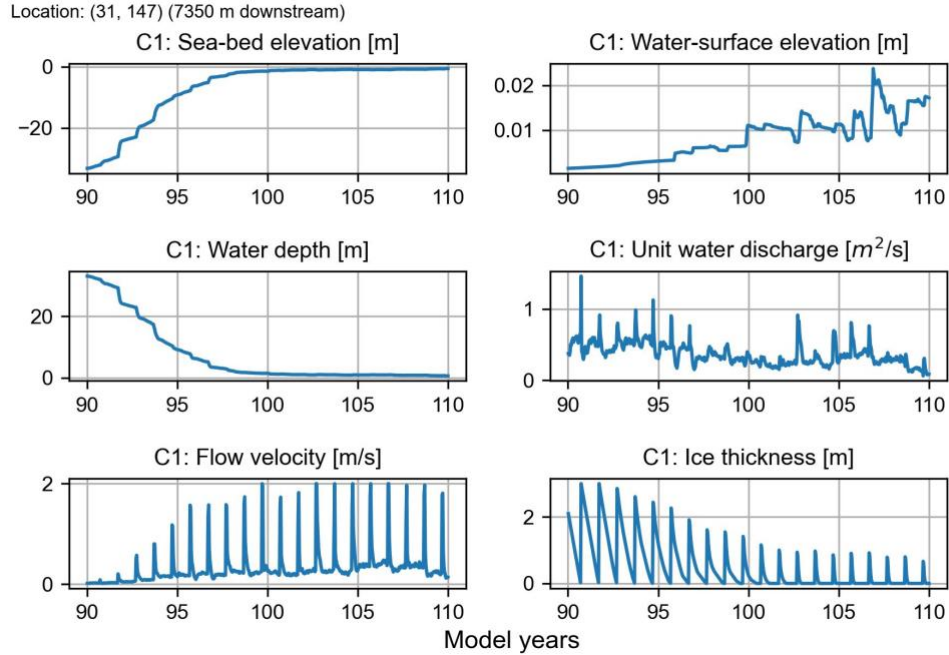


Figure 24. Test case C1 simulated values, at an offshore location just beyond the initial extent of the delta fan to the west of Hiugak Island. Top-left: sea-bed elevation, top-right: water-surface elevation, centre-left: water depth, centre-right: unit water discharge, bottom-left: flow velocity, bottom-right: ice thickness.

In some instances (e.g., case B1, **Figure 25**), rapid deposition events occurred within the first two years, which efficiently cut off water flow to these areas for the remainder of the simulation. In addition, **Figure 26** displays notable amounts of mixed material deposition in the centre of the river with complete erosion through the entire built-up sediment column (which was built to a 5 m depth during the bathymetric data import) along both riverbanks.

Location: (169, 30) (750 m downstream)

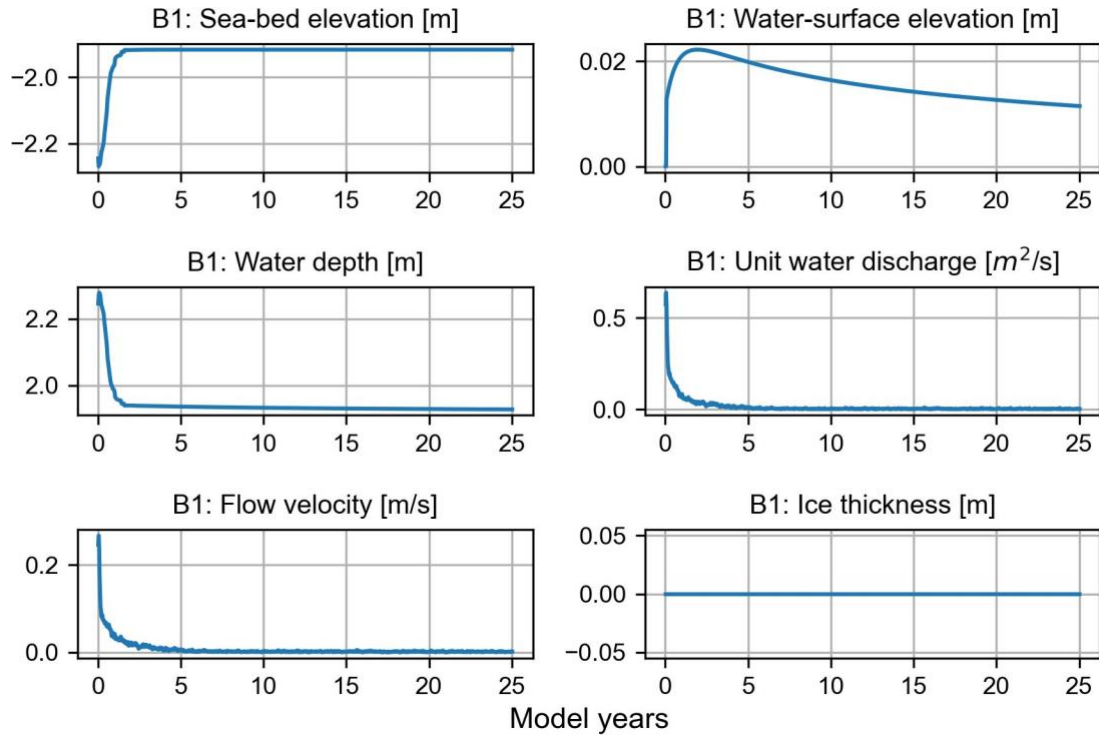


Figure 25. Test case B1 simulated values at an upstream, permanently ice-free location in the centre of the river. Top-left: sea-bed elevation, top-right: water-surface elevation, centre-left: water depth, centre-right: unit water discharge, bottom-left: flow velocity, bottom-right: ice thickness.

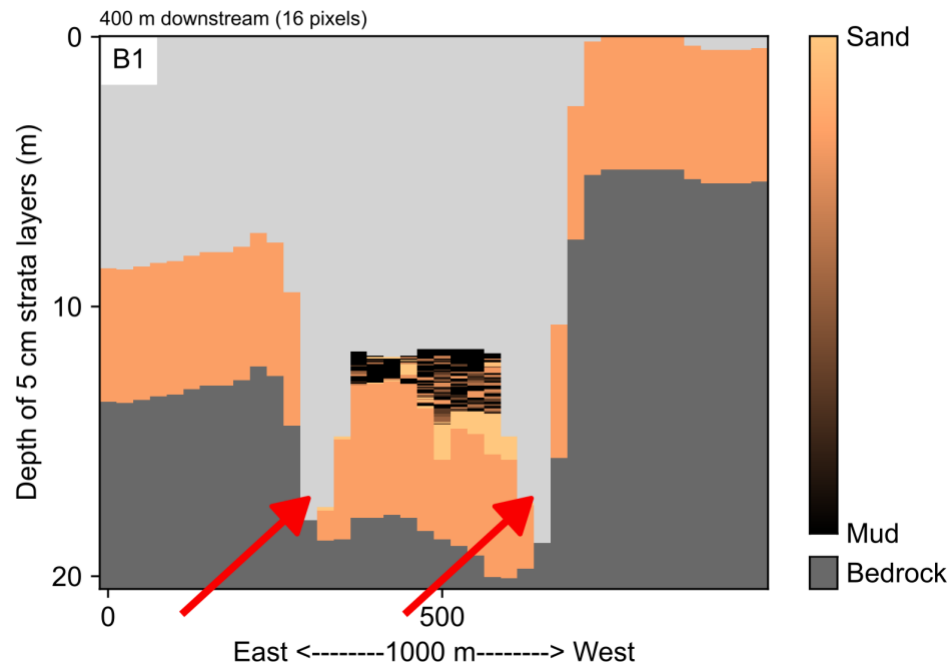


Figure 26. A cross section of the riverbed strata at a near-inlet channel location in test case B1, showing large amounts of both erosion (red arrows) and mixed material deposition (colour variations between the arrows, at the top of the sediment column).

ArcDeIRCM exhibited strong behaviour where slight heterogeneity in the bathymetric data was further accentuated, causing deep channel incision into the riverbed. This behaviour was consistent across variations in spatial resolution, time steps and timescales (**Figure 27**). The severity of the incision along the river edges in both cases A1 and B1 highlights the model's propensity for riverbank-adjacent channelization.

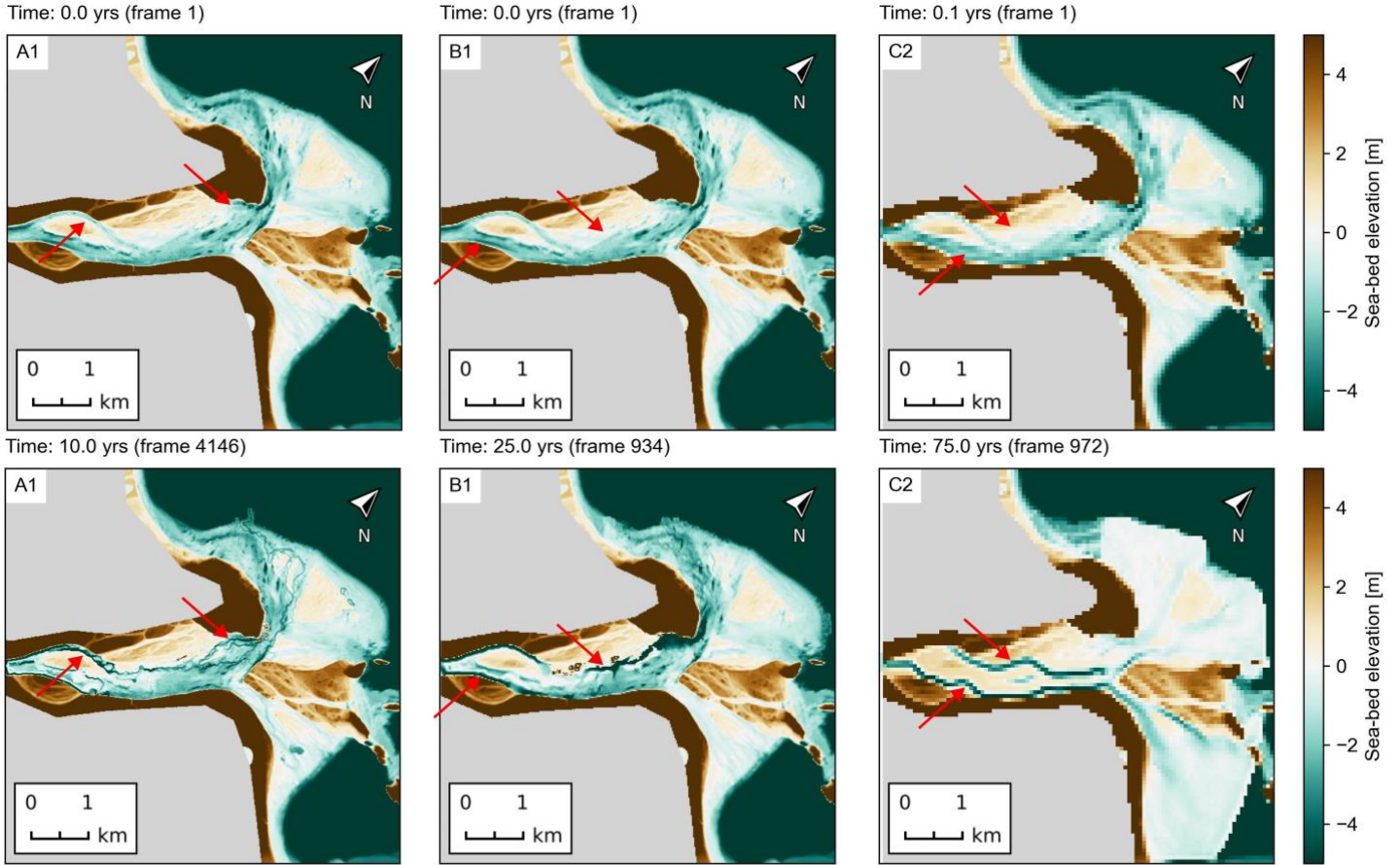


Figure 27. Test cases A1, B1, and C2, showcasing gradual channel incision (examples highlighted with red arrows) in the upstream riverine portion of the model domain. The top row of graphics shows the test cases at model initialisation and the bottom row at mature points in each simulation.

4.4 Long-term Delta Evolution

Over very long timescales, ArcDeIRCM forecasted a growth in the size of the Coppermine Delta, which can be defined as the infilling of the deeper ocean basin at the edge of the submerged delta fan, leading to its extension further offshore. The rate of delta expansion was dependent on the input parameters of the simulation. Using the C1–C5 test cases, delta fan expansion can be seen to have ceased by approximately the 200th year of simulation (**Figure 28**) in all cases. This is due to the delta having grown to the right edge (north-eastern edge) of the modelling domain at the displayed transect. In contrast, the different test cases exhibited maximal growth rates at differing times in the simulation as well as variability in their overall patterns of growth; test cases C1 and C2 exhibited repeated fluctuations in its growth rate throughout the simulation, while cases C3, C4, and C5 exhibited smoother changes in the delta growth rate.

Longitudinal transect 1700 m from western domain wall
 Depth threshold = -2.0 m

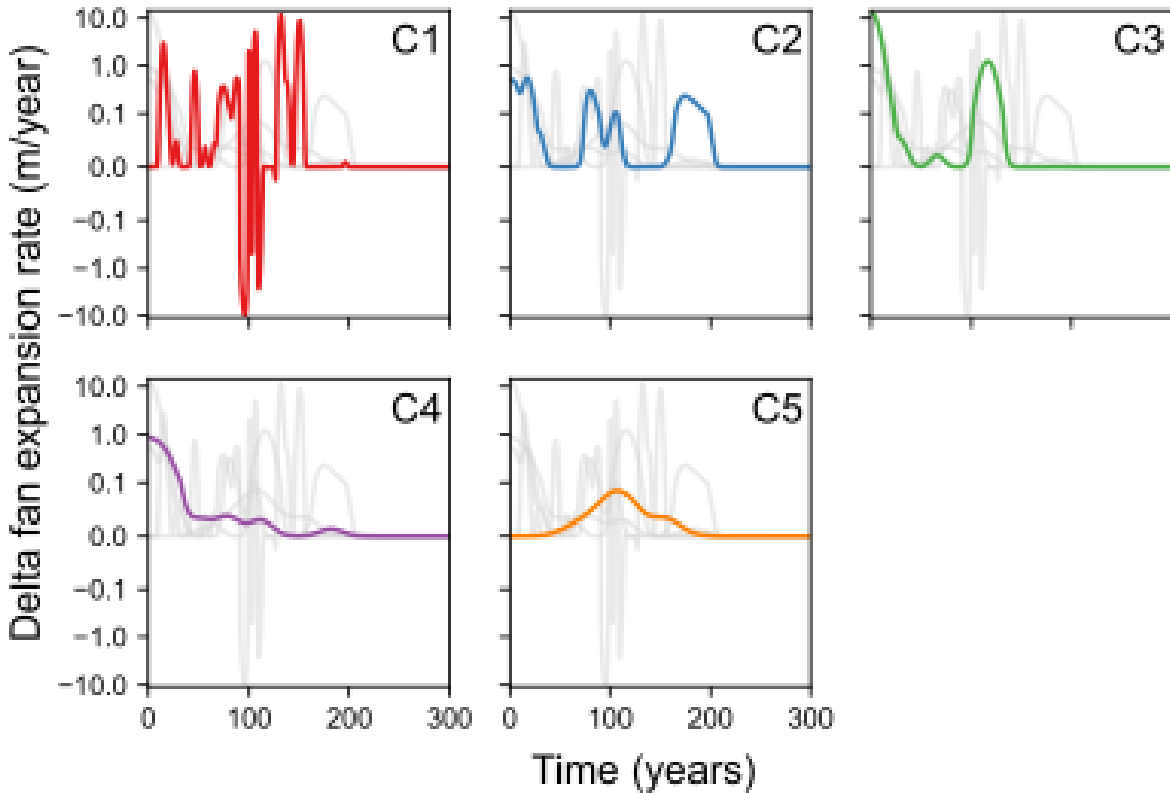


Figure 28. A plot showing the expansion rate of the delta over time for test cases C1–C5, with the edge of the delta fan defined as the cell at which the sea-bed elevation surpassed a threshold of -2.0 m. The coloured lines represent the test case highlighted in a given subplot, while the grey lines represent all other test cases.

This deltaic expansion is reproduced at several spatial scales, particularly the net sediment deposition west of Graveyard Island, where ArcDelRCM forecasts the erosion of the riverbed leading to the development of a channel, which enables efficient sediment transport off the shelf that exists in this region.

4.5 Sediment strata and bedrock malfunctions

The import of known bathymetry caused model errors, notably with the sediment column (**Figure 29**). The variable bedrock elevations are owed to the fact that the bathymetric data for the Coppermine River was imported with 10 m of sediment below it, allowing for a substantial amount of erosion to occur before the bedrock was reached without putting too much computational load on the model by avoiding regions with >30 m of built-up sediment. At this

location, depending on the river water level, the wetted area would extend from approximately $550 \text{ m} \lesssim x \lesssim 1400 \text{ m}$, bound by the riverbanks visible on either side. Landward of these banks, $x \lesssim 250 \text{ m}$ and $x \gtrsim 1800 \text{ m}$, the artificially generated topography values (5.0 m) are visible.

ArcDelRCM incorrectly calculated the riverbed surface elevation in a variety of locations throughout the modelling domain, both immediately following initialisation (time step=1) and after several time steps, depending on the initial model parameters. The bed-surface elevation was substantially modified in the positive direction in all cases, where continued operation of the model resulted in a propagation of these bedrock errors to nearby (although not necessarily directly adjacent) cells, in increasing amounts. For example, if at time step 20 cell (100,100) had its bed elevation modified from -15 m to 45 m, time step 23 might result in cell (105,100) having its bed elevation value modified from -14 m to 150 m, and time step 30 might result in cell (103,107) having its bed elevation value modified from -14 m to 750 m, and so on. This neighbourhood of bed elevation errors caused substantial computational load due to the need to build up layers of sediment underneath these inflated bed elevation values (in δz increments, or 0.05 m), drastically increasing computation time and model output file sizes. Similar errors occurred with bedrock elevation values, which are represented by the lowest index in the sediment column. These bedrock errors do not cause issues with memory or computation time, but they remain problematic for the validity of the model outputs; the modelled bathymetric change downstream of instability locations is greatly impacted by the region of instability. No bathymetric changes occurred downstream of the instability location depicted in **Figure 29** after it formed, which occurred after 0.4 model years (**Figure 30**).

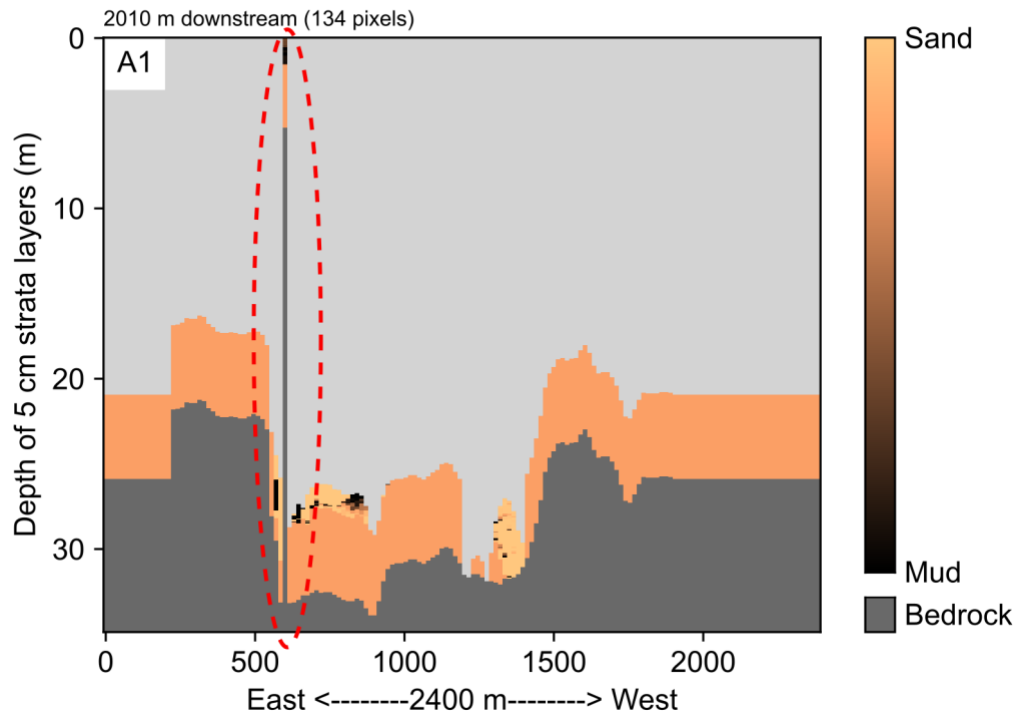


Figure 29. A width-limited cross-section diagram of the strata in test case A1 in the riverine section of the domain upstream from Kugluktuk, showing sediment layers stacked on top of a variable bedrock height. This example highlights a bedrock elevation malfunction, circled in red.

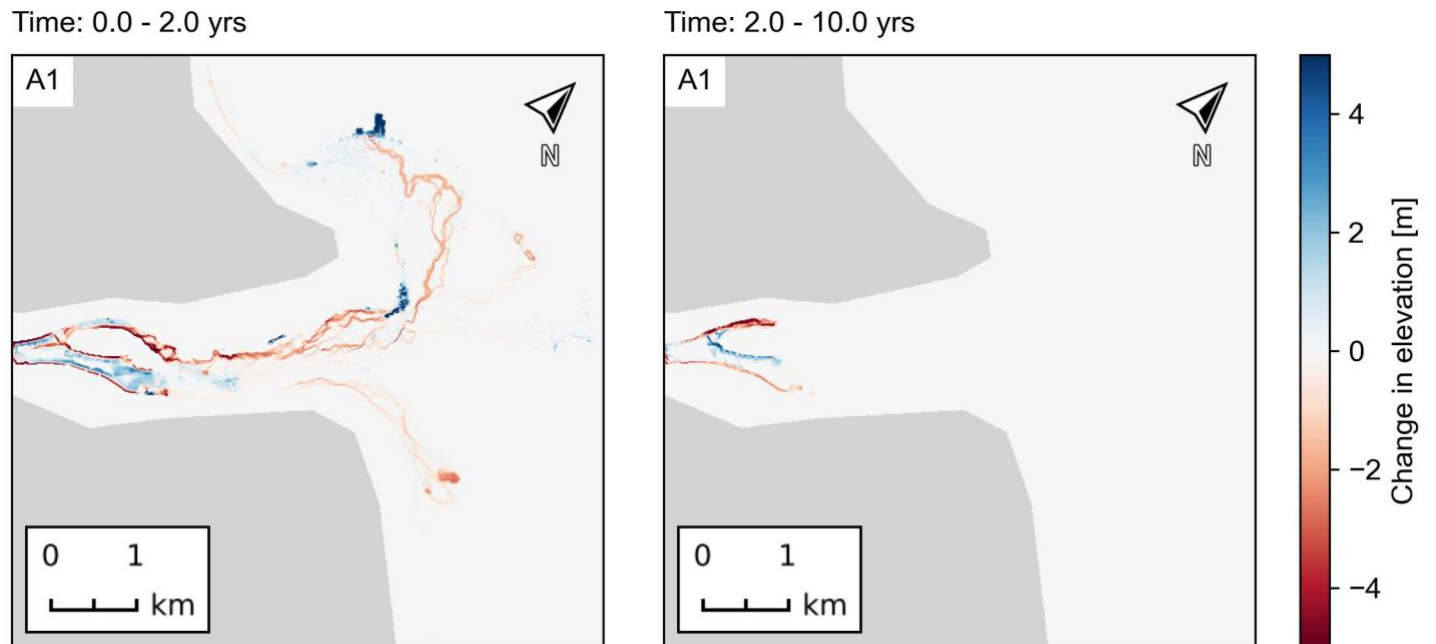


Figure 30. Test case A1, showing erosion (red) or deposition (blue) over time. The first two years are depicted in the graphic on the left, and the following eight in the graphic on the right.

5 DISCUSSION

5.1 Model set up

Each simulation used a 1:1 ratio of the model domain size to real-world dimensions, resulting in accurate spatial representation of water flow throughout the modelling domain. The flow routing scheme—which is mostly dependent on the surface water gradient due to the chosen partitioning coefficient value of $\gamma = 0.09$)—is greatly impacted by the distance between each cell; thus, a scaled representation would likely impact model results. In addition, horizontal scale changes would likely necessitate vertical scale changes to allow for the same morphological processes to occur. In testing, the use of full-size cells provided no computational benefit over scaled-down values; thus, the true delta size was used to maintain the quality of the results.

With large downstream delta expansion, the edge of the modelling domain can be reached, as is shown in **Figure 14**. ArcDelRCM reserves at least 1 cell around the entire border of the modelling domain to be treated as “ocean”, where water and sediment are permitted to exit the domain. Thus, for predictive modelling at these very long timescales, a larger modelling domain is required to assure sufficient place for the delta to expand naturally without any numerical limitations, in turn allowing it to generate accurate results. This same principle applies for constructing the sediment column prior to importing the bathymetric data; a sufficient sediment depth must be built (which comes with a computational load). The erosion in **Figure 26** and **Figure 29** highlight this necessity to ensure sufficient sediment is built up underneath each cell in a river with high erosive potential to ensure the entire sediment column is not eroded away, resulting in the water acting on the underlying unerodable bedrock surface. A working practice is to run the model several times, allowing for an approach of the minimum sediment column built-up height required while ensuring erosion down to the bedrock layer does not occur while maximising computational efficiency and reducing storage requirements.

ArcDelRCM provides the user with some control over climatological conditions impacting the ice and permafrost melting processes modelled; notably, the user can specify the number of days it takes to melt the sea ice, which forms at the beginning of each model year. This is of particular use in a river like the Coppermine River where there may be a substantial ice-free summer period with potential morphological change (in contrast with the 10-day model year used to represent the spring freshet in this study). This requires sufficient field information to be able to assess the ice melting period’s date, rate, and pattern. These data could be sourced from fixed cameras which have a view of the downstream section of the delta or river, which could be corroborated

with flow data to help quantitatively assess melting patterns (i.e., linear, tangential, etc.) and melting rates.

5.2 Sediment

A sediment fraction of the water volume of 0.001 was used, determined by rough approximation of reasonable ranges from other rivers across the globe (Vercruysse et al., 2017; Walling & Fang, 2003). Given that this sediment input is a major component in the model and can vary widely between rivers, the use of measured field data for this parameter is likely to improve the prediction accuracy of the outputs. Further, the use of a time-series of discharges (for which some data is currently available) would allow for more accurate modelling.

The sediment strata and bedrock errors (as seen in **Figure 29**) cause notable impacts on the water flow (**Figure 19**), creating irregular flow patterns and unrealistic flows downstream from the strata errors, which, in turn, have substantial impacts on the erosional and depositional processes in the model; **Figure 30** depicts a large portion of the modelling domain where these sediment processes were not observed downstream of the instability location after it formed. Water flow is present at these downstream locations (**Figure 18**), indicating that these strata and bedrock errors do not extend to all of the model calculations and may be limited to only sediment and morphological changes. Conversely, the lower spatial and temporal resolution of test cases C1-C5 resulted in no strata or bedrock errors over a very long time period, lending confidence to these results. The distribution of sediment and overall delta shapes depicted in **Figure 14** are consistent with long-term delta expansion, including results obtained by Chan et al. (2023). The coarse resolutions in these test cases limit their usefulness as a forecasting tool given the erosion rates seen in the Coppermine Delta at the decadal scale.

5.3 Model performance

The low computation time for ArcDelRCM presents a notable difference in modelling abilities when compared to a physics-based model such as Delft3D FM, where 4 days of modelling at 30-second time steps (11 520 time steps) has taken 4 hours on an Intel Xeon W-2235 processor (which has roughly twice the performance of the CPU used in this study, particularly when using multithreading capabilities), at finer spatial resolutions (i.e., 4 metre mesh in the nearshore environment). At its maximum, the ArcDelRCM file output sizes are not particularly efficient, but this can be remedied by the user choosing to export fewer time steps and only temporarily storing the sediment strata data to allow for the bathymetry data import. This presents ArcDelRCM as an

interesting opportunity to be applied to larger Arctic deltas or over much longer timescales, supported by validation of model erosional and depositional patterns with field data. The comparison of results provided by ArcDelRCM in this study to those in other modelling studies that use complex models is impractical at this time, given the model's instability and the unknown impact this has on specific morphological predictions.

The lack of notable erosion along the western Graveyard Island coastline (**Figure 27, Figure 30**) is consistent with observations from historical aerial imagery (Binette et al., 2024). The coarse spatial resolution of the simulations presented would require very substantial erosion of this coastline in the timeframes simulated to be apparent. Variations of the initial conditions between test cases, including physical parameters such as inlet flow speed and simulated year length and numerical parameters such as spatial resolution and time step, allowed for demonstration of the model's successful ability for these parameters to affect change in the deltaic system.

5.4 Limitations

5.4.1 Input data

The 0.49 m average error between the Hydroball® data and the satellite-derived bathymetry presents as a potential issue in the shallow waters of the Coppermine River, where the errors may represent a substantial portion of the true water column height. Thus, the field-based sources of bathymetry were used preferentially where possible to decrease bathymetric errors; however, the creation of the bathymetric map from these multiple data sources resulted in artificial variations over small spatial scales. The most notable case is that the locations where data were sourced from the single-beam (i.e., linear) Hydroball® contained a linear depression in the final bathymetry map. This effect could have been reduced by decreasing the sensitivity of the interpolation to local topography; however, this would impact the natural topographical edges seen elsewhere in the domain. Since the combination of the data sources produced a topographical edge, the use of edge-preserving features would not offer a solution due to their inability to differentiate between natural topographical variations and those artificially caused by the combination of data sources. Given that the relatively coarse spatial resolution used for modelling naturally decreased the sensitivity of the interpolation to local topography, the final bathymetric map contained less sharp topographical edges than may be truly present in the bathymetry of the Coppermine River.

5.4.2 Model limitations

ArcDelRCM uses the partitioning coefficient (γ) for the direction of water routing, meaning this user-defined value establishes the fraction of the water-surface gradient to consider when determining the direction water should flow between cells, with the remainder of the determining factor being the inertial forces. Presumably, this would have a considerable impact on the delta development. Given this is a parameter that was implemented into the model for the purposes of generating a delta, this parameter becomes a liability in the case of this study where an appropriate value is not known. Determining the partitioning coefficient for the Coppermine Delta would necessitate the use of two known delta states at different times, and multiple trial simulations to determine which value best reproduces the planform changes observed. The original DeltaRCM model established this as a calculated value

$$\gamma = g * S_0 * \frac{\delta c}{U_0^2} \quad (5.1)$$

where g is gravity, S_0 is the characteristic slope of the delta system, and U_0 can be roughly estimated as the inlet water velocity (Liang, Geleynse, et al., 2015). Chan et al. (2023) note for ArcDelRCM that for large δc , both the S_0 and the U_0 may have to be reassessed. Given that this is a free parameter and the characteristic slope of the Coppermine Delta system was unknown, a moderate value of 0.09 was used in all cases to reduce variability between simulations (Chan et al., 2023; Liang, Geleynse, et al., 2015).

More globally, two major processes which influence erosion patterns, water levels and waves, are not included in the model and may impact its ability to accurately forecast erosion of the coastlines (Van Rijn, 2011). This is particularly notable for Graveyard Island, with a large portion of its coastline being permafrost bluffs. The lack of incorporation of wave action in the model means one of the primary drivers of the erosion of this coastline is not included in the model's calculations (Jones et al., 2020). Some pan-Arctic research suggests that the Coppermine Delta is river-dominated, meaning that long-term planform changes in the delta are more likely to be successfully replicated by the model despite the small-scale erosion shortcomings that come with these exclusions in the modelling processes (Overeem et al. (suppl.), 2022).

Modelling deltaic systems can be challenging, as they have small variations in elevation, which form their distributary network structure. The use of elevation gradients as a predictor for delta evolution patterns may be insufficient given the diversity of processes that guide their

network development, particularly given the shallow slope present in many deltas, which can provide unreasonably low impact on the flow routing (Liang, Voller, et al., 2015). ArcDelRCM aims to resolve these challenges by incorporating both the water surface gradient and flow inertia in its flow routing scheme. While this allows for better predictions of flow around morphological features that impact local flow patterns while maintaining the low-average-slope environment of the overall delta, ArcDelRCM and similar models may have limited sensitivity to small-scale processes. Further, the low Froude numbers that are observed in RCMs in deep, slower channels result in hydrodynamic information propagating further upstream than might be expected (Liang, Voller, et al., 2015).

The grandparent model upon which ArcDelRCM was developed was not designed to accurately predict hydrodynamic processes, but to reproduce morphodynamic features that had previously only been produced by more complex models (Liang, Geleynse, et al., 2015). This calls into question the ability of ArcDelRCM to be able to successfully predict erosional patterns in the Coppermine Delta, where total water levels and flow properties may be substantial drivers of erosion. The use of a flow routing scheme for water movement throughout the model domain requires investigation as to its ability to predict flow patterns as accurately as hydrodynamic equations.

5.4.3 ArcDelRCM usefulness

The instability experienced during finer-resolution test cases were localised and expanded over time to surrounding areas. These typically occurred in the riverine portion of the modelling domain, impacting flow routing around the instability and communicating information into the deltaic portion of the domain, limiting confidence in the model's predictions in these areas.

The question of accurately predicting local characteristics is unsurprising, as similar to Murray & Paola's 1994 cellular model of braided rivers, ArcDelRCM aims not to reproduce the exact network distribution and morphology of a given deltaic system, but rather to accurately model the development of a delta with certain characteristics over time (Murray & Paola, 1994). The simplification of both water flow and sediment transport throughout the model domain aims to decrease computational costs while including the driving mechanisms that govern these processes as observed in nature. Reduced complexity models have been described as likely to be more useful as explanatory models (i.e., describing why certain morphological processes occur, to aid our understanding of a natural phenomenon) rather than as predictive models, a task well served by more complex physics-based models such as DELFT3D (Bokulich, 2013).

ArcDelRCM was developed to investigate the physical processes that contribute to the ubiquitous formation of shallow ramp features in Arctic deltas, suggesting that it may not offer quantitatively accurate results useful for predicting the erosional patterns in a given delta (Chan et al., 2023).

6 CONCLUSIONS

This study provided an investigation into the viability of ArcDelRCM as an alternative option to physics-based models for Arctic delta modelling. The model incorporates a number of Arctic-specific processes that theoretically improve its accuracy in this discipline while maintaining a goal of having low computational cost, with a designed use as a delta creation and evolution model. This research finds that the modification of ArcDelRCM to act as a predictive model for established deltaic systems is not currently possible.

This study established that:

- Sediment strata and bedrock errors caused by the import of bathymetric data currently hinder ArcDelRCM's ability to be used predictively.
 - These errors tend to occur in upstream locations in the Coppermine River, impacting the entire downstream modelling domain.
 - These errors are particularly occurrent at higher spatial resolutions.
- The model outputs are generally not in alignment with expected delta behaviour.

Future work would benefit from:

- The resolution of sediment strata and bedrock errors related to bathymetric data import.
- An investigation of the use of ArcDelRCM in solely the deltaic section of the river-delta system.
- A comparison of the accuracy of ArcDelRCM versus established physics-based models, particularly those that include permafrost and ice cover functionalities.

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