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Coastal Erosion of Arctic Cultural Heritage in Danger: A Case Study from Svalbard, Norway

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Abstract: Strong cultural heritage management relies on a thorough evaluation of the threats faced by heritage sites, both in the present and in the future. In this study, we analysed the changes in the position of Hiorthhamn shoreline (Svalbard), which is affecting coastal cultural heritage sites, for a period of 93 years (1927–2020). Shoreline changes were mapped by using maps, ortophotos, drone images, terrestrial laser scanning (TLS), and topographic surveys. Also, TLS was used to 3D document the endangered coastal cultural heritage sites. Detailed sedimentological and morphological mapping was made in the field and from the newly acquired drone images in order to understand shoreline-landscape interaction and to depict changes occurring from 2019 to 2020. Short-term (2019–2020) and long-term (1927–2020) shoreline erosion/accretion was made with the help of the Digital Shoreline Analysis System (DSAS) and prompted a subdivision of three sectors, based on change pattern. Compared to a previous long-term analysis (1927–2019), this year's average erosion rate analysis (expressed by the EPR parameter) for the 93-year period is −0.14 m/yr. This shift in mean development is due to a newly formed spit-bar in Sector 2. Referring strictly to Sector 1, where the protected cultural heritage objects are located, the erosion rate increased from the previous analysis of –0.76 m/yr to −0.77 m/yr. The shoreline forecast analysis highlights that half of the protected cultural heritage objects will likely disappear over the next decade and almost all the cultural heritage objects analysed in this study will disappear in roughly two decades. This shows the great danger the Arctic's cultural heritage sites is in if no mitigation measures are undertaken by the local authorities.

Keywords: coastal erosion; cultural heritage; high arctic; monitoring; Svalbard; DSAS

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Citation: Nicu, I.C.; Rubensdotter, L.; Stalsberg, K.; Nau, E. Coastal Erosion of Arctic Cultural Heritage in Danger: A Case Study from Svalbard, Norway. *Water* **2021**, *13*, 784. https://doi.org/10.3390/w13060784

Academic Editor: Alexander Shiklomanov

Received: 23 February 2021
Accepted: 11 March 2021
Published: 13 March 2021

1. Introduction

Coastal areas are one of the most dynamic landforms on Earth and are under the direct effects of natural processes (sea-level rise, long- and short-term geological processes) and anthropic interventions (deforestations, urbanisation, changes in the habitat, etc.). Throughout history, coastal areas have acted as a magnet when it comes to attracting humans [1]. Today, coastal areas around the globe are under the direct effects of climatic changes; this has been reflected by numerous studies around the world showing increased erosion rates [2,3]. The erosion rates are exacerbated in the Arctic areas [4], which are warming two or three times faster than the global average. The Arctic coastal landscapes are especially sensitive to climate-change-induced morphological processes, from which they were previously protected due to permafrost and seasonal sea ice. Arctic coastal areas can experience erosion rates higher or similar to those in temperate regions because of some specific processes that are characteristic for these areas (extreme temperatures leading to shrinking ice cover and longer fetch lengths for waves, storm surge effects, and thawing permafrost) [5–7].

Cultural heritage represents a crucial component of a European set of values, that promotes a sense of identity and belonging [8]; moreover, it is the foundation upon which global and historical values are based on and represents a significant link between people, society, history, and landscape [9]. Therefore, it should be our moral duty to try to save and document as many cultural heritage assets that are on the verge of being destroyed as a consequence of natural or anthropic factors, such as in the case of the present study. Cultural heritage can be used to communicate a larger message about climate action. The direct effects of climate change on cultural heritage may be immediate or cumulative. Thus, disturbance from catastrophic events such as floods and storms are likely to increase in frequency at the same time as slow-onset environmental deterioration mechanisms, e.g., solifluction. Changes in sediment input to the fjord system due to increased fluvial erosion combined with reduced sea-ice cover may change shoreline sedimentation rates and hence shoreline displacements [10]. Therefore, cultural heritage located in coastal areas is at high risk from climate-change-induced [11] processes: tidal influences, sea-level rise [12], increased frequency of storm events, and greater wave energy, leading to flooding and coastal erosion [13].

At a global level, cultural heritage sites located on the coasts of seas and oceans [14], large man-made reservoirs [15,16], and large rivers [17] are at high risk of erosion [18,19]. On Svalbard, most of the existing cultural heritage sites are located along the coastline because of the type of activity (whaling, hunting, and mining); the study of cultural heritage in the Arctic represents a challenging task. All the remains left behind by different human activities are listed as cultural heritage sites. To be more specific, according to the Svalbard Environmental Protection Act, all the remains from before 1946 are automatically protected, along with a 100 m buffer zone around them [20,21].

Over the last several years, there has been an upward trend to assess the danger of Arctic cultural heritage being destroyed in the background of the global climatic changes; the areas where most studies occur are Greenland [22,23], Alaska [24], Yukon [6], with fewer in Svalbard [21]. Therefore, this study comes as a necessity to complement the lack of studies regarding the degradation of cultural heritage sires in Svalbard.

The present study aims to raise awareness and to report the results obtained following two field campaigns (2019 and 2020) made at an iconic Arctic cultural heritage site located in Hiorthhamn, Adventfjorden (Svalbard). The subject is represented by the remains of the abandoned coal mining settlement (loading dock and industrial infrastructure) Hiorthhamn, located right on the coast; its cultural heritage sites, especially the loading dock, are in danger of completely disappearing in the following years as a consequence of high rates of coastal erosion. Our approach has aimed at doing very detailed surveys of the coastline, sedimentological mapping, and documenting the coastal cultural heritage using the latest technology. The results can be used to evaluate the present state of the coastal cultural heritage and disaster risk reduction and management and can be a powerful tool for local authorities, stakeholders, and cultural heritage planners to plan future mitigation and adaptation [25] measures that are urgently needed.

The GEOCULT Project

Monitoring Geohazards Affecting Cultural Heritage Sites at Svalbard (GEOCULT) is a project financed by the Fram Centre Flagship 'Effects of climate change on terrestrial ecosystems, landscapes, society and indigenous peoples', part of the Work Package 2 'Effects of Changing Seasonality and Extreme Events' [26]. The project aims to understand and quantify rapid climate and weather induced geohazards in the coastal zones of Svalbard. Both slope processes and coastal erosion are threatening and destroying valuable cultural heritage sites. This project will enable high-resolution measurements for the purpose of geohazard understanding and quantifying rates of change. The sub-goals of this project are to (i) create year-by-year datasets of the position of the coastline, erosional edges, and solifluction markers in surface sediments around cultural heritage sites; (ii) calculate, compare, and predict rates of coastal changes in different settings on both a local and regional scale; and (iii) link detailed measurements of change with geomorphological and geological maps of Svalbard's coastline to extend and predict hazardous rates of coastal changes potentially affecting other CH sites along central Svalbard's coastlines.

2. Study Area

Our study area is located on Spitsbergen (Figure 1a), which is the largest island of the Svalbard archipelago. The area of interest is represented by a portion of the coastline of Hiorthhamn (78°14′50″ N, 15°42′30″ E) (Figure 1b), which is located at approximately 3 km north of Longyearbyen. 60% of the total land mass of the Svalbard archipelago is covered by ice, which makes the coastline very complex [27]. Previous studies [21] have highlighted significant changes in the position of the coastline, which can and will have a devastating effect on the cultural heritage sites.

Hiorthhamn fjord is oriented towards the southwest, with step-shaped slopes coming down from the Hiorthfjellet mountain to the Advent shores. The ages of the rocks range from Early Permian to Eocene [28]. The mean annual precipitation is 190 mm (occurring in the summer season), the mean annual temperature in central Spitsbergen is −5 °C, and the winds mainly come from the southwest and west. Many studies have shown that the Svalbard archipelago experiences an overall increasing temperature, especially during the spring, showing a warming trend between +0.27 °C/decade to +0.46 °C/decade [29]. Mean temperature differs in different parts of Svalbard, with lower temperature in eastern Svalbard and warmer temperature in western Svalbard. At Longyearbyen, where our area of interest is located, mean seasonal temperature varies from −15 °C in winter to 4 °C in summer, which has a tremendous influence on the shoreline dynamics. Data from Svalbard Airport (located in close proximity to our study area) show an increase of the annual average temperature by 1–2 °C between the periods 1961–1990 and 1981–2010. The annual temperature increase at Svalbard airport for the last two decades is almost 1.2 °C per decade [30].

More details on the geological, geomorphological, hydrological, and climatological aspects of the area can be found in [31–34]. Coastal areas of Svalbard are thoroughly studied in connection with other geomorphological processes [35,36]. A thorough view of Svalbard's human presence is offered by Kruse [37]. Our focus is on nine cultural heritage protected objects (Figure 1c) located along the coastline (Table 1).

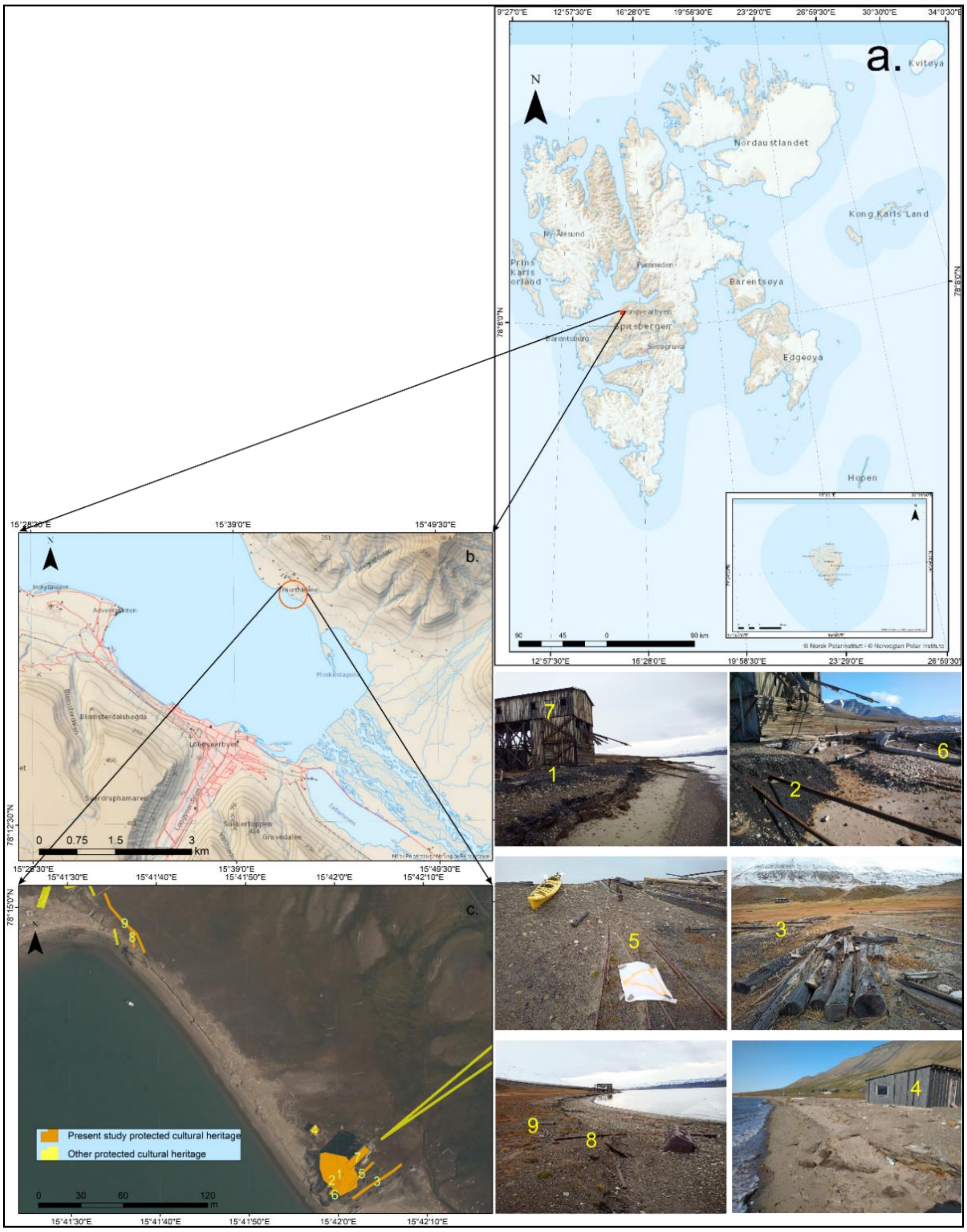

Figure 1. (**a**) General geographical location of the study area; (**b**) geographical location at the local level; (**c**) location of the nine cultural heritage protected objects approached in this study and other protected cultural heritage objects (photos from August 2020 of the nine protected cultural heritage objects; numbers inside the photos from the right side correspond to the ones in Figure 1c and from Table 1).

Table 1. Details of the nine protected cultural heritage objects (numbers in the first column correspond to the numbers in Figure 1, right side).

Nr. crt.	Heritage Site ID	Name	Function/Description
1	93040-12	Coal pile	Industry, production/coal pile at the cable-car central
2	93040-2	Track	Industry, manufacturing, production/route of trolley track
3	93049-19	Track	Industry, manufacturing, production/remnants of railroad
4	93040-5	Smithy	Industry, manufacturing, production/the building has a wooden frame; roofing-felt cladding on all sides, wooden door, windows are missing. Forging-hearth of yellow brick. The chimney is made out of oil drums. A lot of scrap iron in and around the building, along with remnants of a hand drill and iron ovens
5	93040-4	Track	Industry, manufacturing, production/route of trolley track
6	93040-3	Track	Industry, manufacturing, production/route of trolley track
7	93040-6	Cable-car Central	Industry, manufacturing, production/a large wooden construction for coal loading. The machinery inside is in good condition; with wheels and gears on cast foundations. A staircase leads to the top of the structure. Remains of two railway tracks bulge from the south side of the building towards the fjord
8	146668-20	Track	Industry, manufacturing, production/remnants of railroad
9	146668-21	Track	Industry, manufacturing, production/remnants of railroad

3. Materials and Methods

Shoreline dynamics were realised with the help of the Digital Shoreline Analysis System (DSAS) tool [38], an extension of ArcGIS; this tool is widely used at a global level to determine the erosion/accretion rates of coastlines [14,21]. The data used to compile the different temporal shorelines were gathered from historical maps from 1927, aerial images from 2009, and field surveys from August 2019 and 2020; more details about the data are available at Nicu et al., 2020 [21]. For this study, we focused our attention on the End Point Rate (EPR) parameter, which shows the average erosion rate. The confidence interval in DSAS was set at 95%. Field data acquisition is the same as [21]. Besides the erosion rate estimates, the shoreline forecast tool was also employed, based on historical shoreline data positions for the next 10 and 20 years, respectively; this comes along with the uncertainty bands that consider any positional and measurement uncertainties. In order to run the forecast analysis, DSAS needs a minimum number of four historical shoreline data sets.

Drone images were made in order to cover a larger area (8.5 km^2), compile a Digital Elevation Model (DEM), and help and complement the sedimentological mapping. Flights were made at an altitude of 120 m, using a number of five ground markers previously surveyed with the total station. In total, a number of 3389 images were made, with a ground resolution of 5.51 cm/pixel. Protected cultural heritage data were retrieved from the Norwegian Directorate for Cultural Heritage Management [39] (Table 1).

Creation of 3D spatial features illustrating cultural heritage objects [40] or sites are of high importance, especially in the Arctic [41,42] where data is scarce, and fieldwork assumes very detail planning and high material resources involved. For this reason, a 3D scan of the coastal area where the analysed protected cultural heritage objects are located was done; 3D data were collected using both terrestrial laser scanning (TLS) and image acquisition for subsequent image-based modelling (IBM) [43]. A Riegl VZ-2000i laser scanner with a top-mounted Nikon D610 camera was used for TLS and a Nikon D800E camera equipped with an AF-S Nikkor 24–70 mm lens for IBM collection. Single scans were collected with a resolution of 0.04 degrees (both horizontal and vertical scan lines) leading to an average point spacing of 0.7 mm at 10 m distance from the scanner.

Images were taken at a distance of 3–5 m from the targets, corresponding to a ground sampling distance (GSD) between 0.5 mm and 0.9 mm. A total of 328 scan positions and some 1400 single photographs were acquired during two days of fieldwork in August 2019. TLS was directed mainly towards the documentation of the coastline and protected cultural heritage objects. TLS data were pre-processed in RiScanPro and exported as point clouds in .ptx file format. Further 3D modelling was carried out in the RealityCapture photogrammetry [44] software package allowing for the combined processing of TLS and image data. Listed buildings and other cultural heritage remains were exported as high-resolution point clouds with an average point spacing between 0.5 mm and 2 mm for data visualisation and analysis within the Nubigon point cloud rendering software.

4. Results and Discussion

4.1. Geological Mapping and Short-Term Shoreline Erosion Changes

The study area of Hiorthhamn is an almost flat stretch of the lower slopes, between the steeper mountain sides and the sea (Figure 1). The sedimentological mapping in August 2020 focused on a better understanding of the sediments which are underlying many of the registered cultural heritage sites and which are currently being rapidly eroded by wave action. The result is presented as a sedimentological and morphological map in Figure 2 and annotated photographs in the same figure. The shoreline where the most rapid erosion occurs consists of sandy-to-gravelly, well sorted, older beach deposits (Figure 2b,c) that may have been slightly raised above today's sea-level by glacio-isostatic rebound. Secondary to the deposition of the beach sediments, it has been covered by a relatively thin layer of aeolian sediments (fine sand and silt, Figure 2c) together with localised peat-formation. Old photographs show that the flat area was already vegetated by grass in the 1930s, giving an age of >100 years for the sediments forming the base of this small marine plain.

The beach deposits exposed along the erosion scarp consist of a sometimes-visible lower unit of relatively horizontally laminated sediments with a significant amount of sand (unit II, Figure 2). Above this, and constituting a major part of the scarp, is a sediment unit with slightly larger particles with a clear, but varying, angle of laminations along the erosion scarp (unit III, Figure 2), gravel and rocks, unit IV. This unit is interpreted as progressively built-out beach bars and ridges, which is supported by the low relief beach ridges seen also on the surface of the near-shore area (Figure 2). Above this is the top-layer composed of the above mentioned aeolian silt and fine sand (unit IV, Figure 2), with a varying component of intermixed peat. In some places, unit IV is overlayed by recently deposited storm-wash sediments of gravel-to-cobble size (unit V, Figure 2).

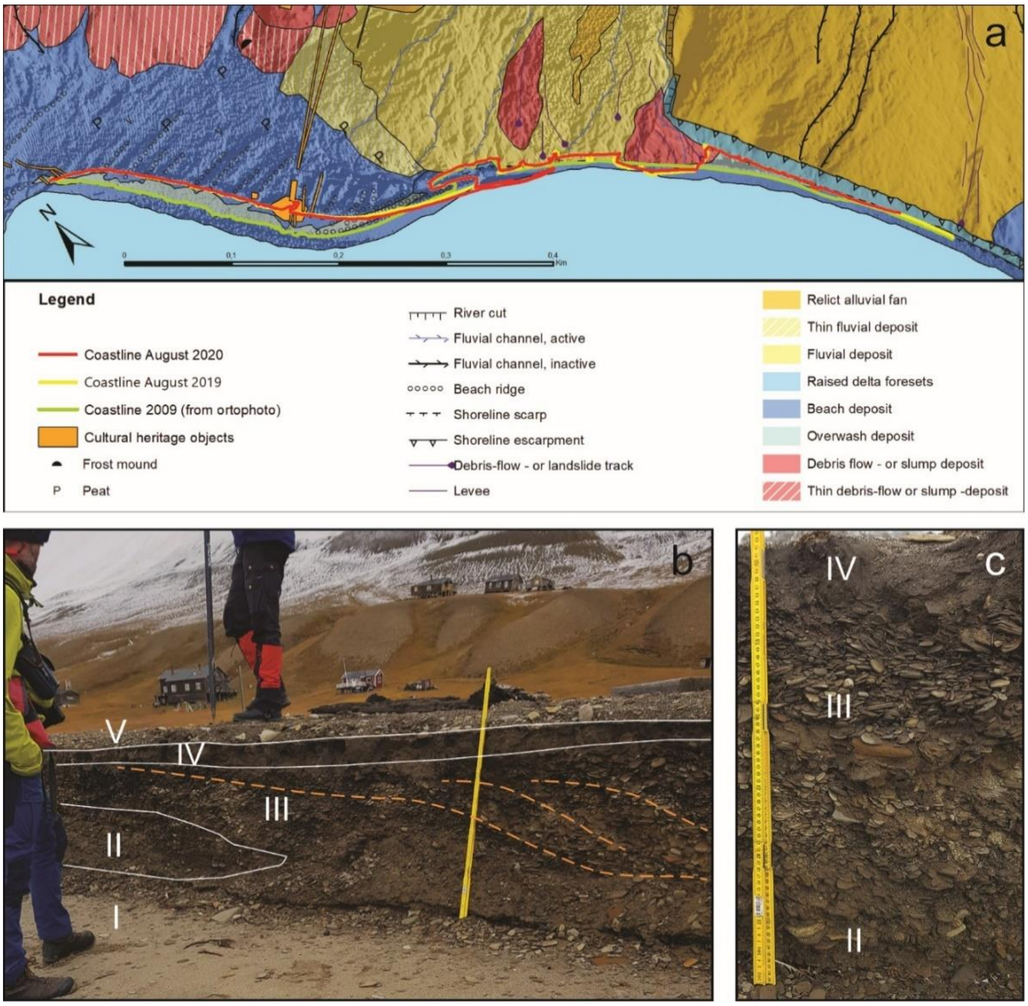

Figure 2. (**a**) Sedimentological map with a legend over the investigated shoreline. (**b**) Annotated overview image from 2020 of a part of the fresh shoreline scarp in Sector 1; Unit (I) today's low-energy swash sediment with mostly sand and some particles that has been falling out from the vertical erosion scarp. Unit (II) weakly horizontally laminated or massive near-shore or beach sediments. Unit (III) relatively coarse-grained beach unit of coarse sands to cobbles, tabulate rounded particles with a laminated stratigraphy, and many places with angled sedimentary structures dipping towards south-east. Unit (IV) well sorted, silty-to-fine sandy unit with a varying content of peat and organic particles interpreted as aeolian sedimentation on a vegetated surface. This unit has an irregular lower limit to unit c, interpreted as frost-deformation of the surface sediments. Unit (V) coarse gravel to stones with some sand is irregularly draped over some parts of the area above and along the beach-scarp. The sediments have no lichens and are loosely consolidated without stratigraphical patterns, which is interpreted as a sign of storm-swash deposition. (**c**) Detail of the eroded shoreline scarp. Note the lack of larger cobbles and boulders and the tabulate, rounded nature of the larger particles in unit II and III.

Most of the sediment exposed along the beach has a high proportion of tabular and rounded to well-rounded gravel, including cobble-sized particles with intermixed medium ones, to coarse sand. The shoreline erosion edge in today's Sector 1 forms a laterally persistent scarp of 20–100 cm height (Figures 1c, 2 and 3) along the whole sector. The well-sorted beach sediments exposed in the scarp consist of rounded medium coarse particles and no fines (clay and silt), which lacks cohesion forces between the grains and is therefore easily eroded by water and wave action. Every time the scarp dries out, there also occurs small gravitational dry grain-flows, further eroding the scarp. The lack of larger cobbles and boulders also means that no great lateral force is needed by the littoral drift to move the sediments further, once destabilized. This results in a rapid and complete removal of all eroded by the wave action, leaving no larger particles on the beach to protect the bluff from further erosion.

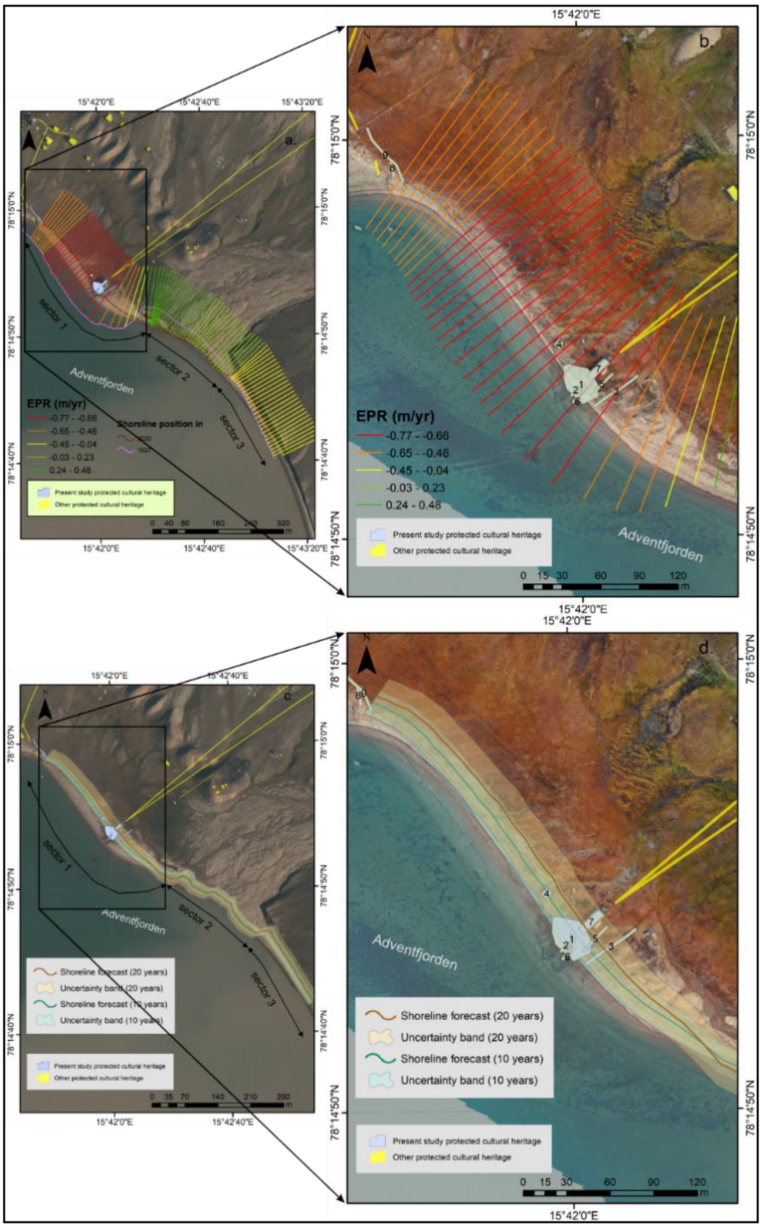

Figure 3. (**a**) End Point Rate (EPR) parameter of the study area; (**b**) detail of the EPR analysis for Sector 1, superimposed over the newly acquired drone images; (**c**) shoreline forecast analysis for the next 10 and 20 years of the entire study area; (**d**) detail of the shoreline forecast analysis for Sector 1, showing the endangered protected cultural heritage site.

4.2. Long-Term Shoreline Changes and Implications on Cultural Heritage

The overall long-term shoreline erosion rate (as indicated by the EPR parameter) is highlighted in Figure 3a for the period 1927–2020 (93 years) and has a value of −0.14 m/yr; it has decreased when compared with the analysis for the period 1927–2019 [21], which indicated an average erosion rate of −0.21 m/yr. Other parameters, like NSM and LRR, have also decreased when compared with the ones from [21]; from −19.11 m to −12.93 m (NSM) and from −0.16 m/yr to −0.14 m/yr (LRR), respectively. This is due to the newly formed spit-bar from Sector 2, which influences the overall values of the aforementioned parameters (Figure 2).

However, this does not reflect the situation from Sector 1 solely, where the erosion rate increased from −0.76 m/yr to −0.77 m/yr (Figure 3b). We refer to Sector 1 because here are located the nine protected cultural heritage objects which are under high threat from erosion (Figure 4). By dividing the analysis over the three sectors it can be concluded that Sector 1 is characterised by erosion, Sector 2 by accretion, and Sector 3 by relative stability.

Figure 4. Comparison of shoreline position and morphology between 2019 and 2020 around some of the most important cultural heritage buildings and remnants along the sea in Sector 1 (no. 4 and no. 7). White ellipse and hexagons represent identical objects in the respective photographs.

By comparing Sector 1 erosion rates solely to other studies approaching coastal erosion on Svalbard, ranging from −0.5 to −4.5 m/yr for Longyearbyen [35], and −0.28 m/yr for Isbjørnhamna [45], our area can be framed as a high erosion rate site. Erosion as shown by [21] Hiorthhamn coast are very dynamic; however, the overall erosion rates seem to be stable. This is because high erosion rates compensate with high accretion rates. Figure 3c shows the shoreline forecast analysis for the three sectors, while Figure 3d strictly refers to Sector 1. The forecast analysis estimates the approximate area(s) that will be destroyed in the next 10 and 20 years (along with the uncertainty bands). Over the next 10 years, cultural heritage objects identified in Figure 3d with the numbers 2 and 6 will completely disappear, while those with numbers 1, 4, 3, 5, and 9 will be partially affected, according to the uncertainty band. In two decades, all the nine protected cultural heritage objects will completely disappear if no immediate mitigation measures are taken by the local authorities. Figure 4 shows comparable photographs from Sector 1 from August 2019 and 2020, highlighting the rapid changes occurring in Sector 1 of the shoreline.

A short analysis of the DEM derived from the high-resolution drone imagery from 2020 revealed a series of relict beach ridges on the near-shore eroding plain, which clearly illustrates pre-recent progradation of beach sediments along this coast and supports the sedimentological conclusions. However, similar processes have the potential to bury present day cultural heritage objects if the beach dynamics change laterally over time.

The results of the 3D scans are shown in Figure 5 and Supplementary Materials (short movie). Having a better image of the shoreline dynamics would be of great help for the local authorities in identifying and prioritizing future mitigation measures for the most endangered cultural heritage objects; further on, this work can be the start of studying multi-hazard threats [9] to endangered Arctic cultural heritage sites. Three-dimensional documentation of endangered cultural heritage sites is of high significance, as the cultural heritage sites might disappear and their cultural memory should be passed on to future generations; moreover, 3D modelling can be used in future educational purposes, create animations and make 3D virtual reconstructions.

Figure 5. Textured 3D mesh model of the cultural heritage objects no. 1–7. The photogrammetric model was created using a combination of 3D laser scans and a series of single images. Geometry of the model is mainly based on laser scans, and photorealistic colour is derived from single images.

5. Conclusions

The main aims of this study were to raise awareness of the climate change induced processes (coastal erosion) on Arctic cultural heritage sites. This was done with the help of DSAS tool of ArcGIS, where the short- and long-term shoreline changes and the implications for coastal cultural heritage sites were analysed. Historical and present shoreline positions were mapped with remote sensing techniques encompassing several different geomorphological and sedimentological sectors. Following our analysis, the 1927–2020 (93 years) long-term average erosion rate over the entire length of the shoreline has decreased from −0.21 m/yr to −0.14 m/yr when compared to the period 1927–2019. This apparent decrease is due to a new spit-bar accumulating in Sector 2. Meanwhile, Sector 1, where the protected cultural heritage site is located, experienced a slight increase in mean erosion rate compared to the 2019 analysis, from −0.76 m/yr to −0.77 m/yr. Assessing the differential erosion pattern in the three sectors, it is apparent that Sector 1 is characterised by erosion of loosely consolidated beach sediments, Sector 2 by accretion of laterally transported new beach sediments, and Sector 3 by relative stability. The conclusion is that the pre-existing geology interacts with varying external erosion factors to form the basis for a complex pattern of hazards threatening coastal cultural heritage remains in Hiorthhamn, Svalbard. More studies like this are needed, that are able to bring significant advances in research on climate change risks, impacts, and adaptation. This will significantly improve decision- and policy-makers' capacity to support effective adaptation processes and thus gain environmental sustainability of the cultural heritage policy in a changing Arctic.

Supplementary Materials: The following are available online at https://www.mdpi.com/2073-4441/13/6/784/s1, Video S1: Results of the 3D laser scanning of Hiorthhamn coast and the protected cultural heritage.

Author Contributions: Conceptualization, I.C.N.; methodology, I.C.N., L.R., and K.S.; software, I.C.N., L.R., K.S., and E.N.; validation, I.C.N., L.R., and K.S.; formal analysis, I.C.N., L.R., and K.S.; investigation, I.C.N., L.R., K.S., and E.N.; resources, I.C.N., L.R., and K.S.; data curation, I.C.N., L.R., and K.S.; writing—original draft preparation, I.C.N.; writing—review and editing, I.C.N., L.R., K.S., and E.N.; visualization, I.C.N., L.R., K.S., and E.N.; supervision, I.C.N.; project administration, I.C.N.; funding acquisition, I.C.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Research Council of Norway, CULTCOAST–Monitor, Manage and Preserve Sites and Landscapes under Climate Change and Development Pressure (MILJØFORSK), project number 294314. and by the Fram Centre Flagship Climate effects on ecosystems, landscapes, communities and indigenous grants, GEOCULT—Monitoring Geohazards Affecting Cultural Heritage Sites at Svalbard, project number 369913.

Acknowledgments: Our thanks go to Richard Hann (Deptartment of Engineering Cybernetics) from the Norwegian University of Science and Technology (NTNU, Trondheim) that collected and processed the drone data, and to the Norwegian Polar Institute (NPI) personnel for the assistance in the logistic fieldwork. Three anonymous reviewers and the academic editor are kindly acknowledged for their constructive comments and observations.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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