Coastal Sand Mining Near Landeyjahöfn

Assessment on wave climate and coastal morphology

Prepared for HeidelbergCement Pozzolanic Materials

Vatnaskil report no. 23.05

LVRS-Consultancy report no. 2023-NMSL-Final

December 2023

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Report no: 23.05 / 2023-NMSL-Final	Published: December 2023	Number of pages: 90	Distribution: Open ☒ Closed ☐

Report title:
Coastal Sand Mining Near Landeyjahöfn. Assessment on wave climate and coastal morphology.

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Abstract:
HeidelbergCement Pozzolonic Materials (HPM) plans to mine up to 2 million cubic meters of sand from the coastal bottom near Landeyjahöfn harbour in Southern Iceland. In this report, the general concept of mining operations within the investigation area is addressed and the possible effects to the nearshore wave climate and coastal morphology.

Three primary factors set the planned mining operations apart from previous mining of seabed materials in Iceland: The planned amount of bottom material to be mined; The extent of the potential area to be mined; and the characteristics of the mining area. The mining activities are to be performed along the exposed, sandy Southern Iceland coast, within approximately 2-4 km from shore. The black basalt sand coast experiences severe weather conditions with very high waves, resulting in significant sand transport and dynamic conditions.

In the present assessment an integrative approach is taken, led by a comprehensive background to account for coastal processes, the concept of coastal sand mining and the morphological behaviour of mining pits, as well as some of the guidelines internationally available for nearshore mining parallel to Icelandic guidelines. This background sets the stage for the primary environmental conditions and site characteristics to be described for the investigation area in question. The modelling performed to support the overall assessment of the mining activities draws from the environmental conditions and the challenges they impose on the investigation.

The surf zone landward of the outer bar crest is a relatively narrow strip with inner and outer breaker bar which act as the first line of defence against wave attack and coastal erosion. Mining of sand in this zone could lead to degeneration of the breaker bars and ultimately to a more severe wave attack at the beach, which should be prevented to avoid land erosion. Integrating information from literature, available experience elsewhere and the modelling results presented here suggest that mining landward of the outer bar may have severe negative effect on the coastal morphology and hydrodynamics of the system.

By securing the mining activities far enough offshore, however, at least beyond a depth that would be chosen in close agreement with the closure depth, a limit beyond which no measurable bed level variations due to wave and current motion are assumed to occur, Icelandic guidelines on wave climate modifications and some of the goals addressed in international guidelines and regulations may be met.

An overall concept of long-shore offshore mining arrangement is introduced, which can be kept as indicative at the onset of further research and investigations in the area. However, the modelling results suggest that most likely the mining must occur at somewhat greater depths, beyond the closure depth or approximately 20 m.

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Keywords:
Landeyjar, Iceland, offshore mining, assessment, sediment, wave, tidal

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Íslensk samantekt (Icelandic summary)

Fyrirhuguð efnistaka

HeidelbergCement Pozzolonic Materials (HPM) stefnir á að vinna allt að 2 milljónir rúmmetra af sandi af strandsjávarbotninum í nágrenni Landeyjahafnar við suðurströnd landsins. Athugunarsvæði hefur verið skilgreint vegna starfseminnar með útgangspunkt um að hún fari fram utan netlaga, þ.e. í lágmarksfjarlægð 115 m frá stórstraumsfjörumörkum.

Sem lið í umhversismati verkefnisins hefur HPM falið Vatnaskilum og LVRS að meta möguleg áhrif af efnistökunni innan athugunarsvæðisins á öldufar og formfræði strandarinnar, þ.m.t. álag við ströndu sem leitt gæti af sér landrof.

Á þessu stigi liggur ekki fyrir hvernig efnistakan verður útfærð, hvorki m.t.t. staðsetningar námusvæðis innan athugunarsvæðisins né hvernig tíðni efnisnáms verði háttað. Í skýrslunni er því tekin almenn nálgun um námuvinnslu innan skilgreinds athugunarsvæðis.

Þrír meginþættir fyrirhugaðrar starfsemi leiða það af sér að hún gæti talist nokkuð sérstæð með hliðsjón af fyrri reynslu af námuvinnslu við íslenskar strendur:

1. *Fyrirhugað magn efnisvinnslunnar*. Allt að 2 milljónum rúmmetra af sandi verður dælt upp af sjávarbotninum yfir 30 ára tímabil, sem leiðir til heildarvinnslu nálægt 60-75 milljónum rúmmetrum. Þetta er mögulega mesta rúmmál af sandi sem numið hefur verið af sjávarbotni við íslenskar strendur innan skilgreinds námusvæðis.
2. *Stærð mögulegs námusvæðis*. Í byrjun árs 2023 voru í gildi tvö rannsóknarleyfi vegna efnistöku á sjávarbotni og 13 nýtingarleyfi voru í gildi vegna slíkrar efnistöku við strendur Íslands. Heildarflatarmál svæða undir nýtingarleyfunum er um 14,5 km^2 skv. vefsíðu Orkustofnunar. Til samanburðar er athugunarsvæði HPM 119,5 km^2. Þótt ekki hafi verið ákvarðað hversu stór hluti af því svæði gæti talist til námusvæðis verður að telja líklegt að stærð þess geti orðið umtalsverð.
3. *Sérkenni námusvæðis*: Námuvinnslan á að fara fram innan u.þ.b. 2-4 km frá suðurströnd landsins, sem er verulega útsett fyrir mjög háum öldum og byggist upp af svörtum basaltsandi. Leiðir þetta af sér að sandflutningur eftir ströndinni er verulegur og breytileiki allur á formi strandsvæðisins mikill.

Nálgun við matsvinnuna

Leiðbeiningar námuvinnslu á sjávarbotni eru takmarkaðar í íslenskri löggjöf og reglugerðum, sér í lagi gagnvart heppilegum eiginleikum námusvæða og þeim aðstæðum sem þarf að taka tillit til. Slík svæði geta þó verið háð ýmsum takmörkunum og jafnvel verndarsjónarmiðum. Siglingastofnun, nú hluti Vegagerðarinnar, hefur þó lagt fram viðmið um efri mörk áhrifa námuvinnslu á ölduálag við strönd með það að markmiði að lágmarka landrof. Jafnframt hefur Vegagerðin skilgreint verndarflokkun fyrir námur með hliðsjón af mismunandi námuvinnslu.

Þar sem reynsla á Íslandi er takmörkuð gagnvart sams konar námuvinnslu og HPM stefnir að og íslenskar leiðbeiningar gagnvart slíkum framkvæmdum eru af skornum skammti, hjálpar að horfa til alþjóðlegrar reynslu á þessu sviði til mats á áhrifum námuvinnslunnar.

Í ljósi þess er tekin samþætt nálgun að viðfangsefninu, með yfirgripsmiklum bakgrunni um strand-svæði, almennri þekkingu og reynslu um sandnám á strandsvæðum og formbreytingum námusvæða auk tiltækra erlendra leiðbeininga fyrir námuvinnslu við strendur. Þannig fást fram þeir meginþættir sem þarf að fjalla um gagnvart fyrirhuguðu námusvæði og ákvarða má þá líkangerð sem styður við heildarmat fyrirhugaðrar námuvinnslu, eins og nánar er greint frá í skýrslunni.

Ítarlega er farið yfir sandnám á strandsvæðum, m.a. í samhengi við öldufar og formbreytingar botns og strandar í nágrenni fyrirhugaðrar vinnslu. Jafnframt lýsingu á umhverfisaðstæðum á fyrirhuguðu vinnslusvæði, þ.m.t. mat á sandflutningi eftir ströndinni sem ræður einna mestu um framboðið af sandi og mögulega endurfyllingu námusvæða. Greint er frá meginforsendum og helstu niðurstöðum líkangerðar þar sem sér í lagi er lagt mat á eftirfarandi:

1. Áhrif formbreytinga sjávarbotns á öldufar.
2. Áhrif öldufars á styttri tímaskölum á formbreytingar sjávarbotns.
3. Áhrif stórtækrar námuvinnslu innan ytra rifs á ölduálag við ströndu.
4. Áhrif stórtækrar námuvinnslu á dýpri svæðum utan ytra rifs á ölduálag við ströndu.

Með liðum 1 og 2 næst fram mat á hegðun kerfisins óháð námuvinnslu með áherslu á samband öldufars og formbreytingar sjávarbotns. Með liðum 3 og 4 næst hins vegar fram mat á mögulegum áhrifum námuvinnslunnar, sett í samhengi við ríkjandi aðstæður.

Meginniðurstöður

Strandsvæðið innan ytra rifs er frekar mjó ræma (innan við 1 km) með innra og ytra rifi sem verka sem vörn gegn öldugangi og strandrofi. Efnistaka á þessu svæði getur leitt til lækkunar rifanna og auknu ölduálagi við ströndu, sem þarf að varna til að koma í veg fyrir landrof.

Að saman teknum upplýsingum úr fagritum, tiltækri reynslu hér heima og erlendis og niðurstöðum líkangerðarinnar má ráða að efnistaka innan ytra rifs getur leitt til mjög neikvæðra áhrifa á formbreytingar sjávarbotnsins og straumhegðun kerfisins.

Með því að tryggja að efnistakan fari fram nægjanlega langt frá ströndu, á meira dýpi en sem myndi svara til eins konar jafnvægisdýpis þar sem óverulegar botnbreytingar eiga sér stað (closure depth) má halda áhrifum innan íslenskra viðmiða um öldufarsbreytingar og ná sumum af þeim markmiðum sem lögð eru fram í alþjóðlegum leiðbeiningum og reglugerðum, þ.m.t. í Stóra-Bretlandi og Hollandi.

Þörf er á frekari greiningu að fenginni reynslu af undirbúningi efnistökunnar og tilsvarandi rannsóknum svo tryggja megi að valin fjarlægð frá ströndu og heppilegt dýpi efnistökunnar leiði af sér að áhrif á ytra rif verði lágmarkað, þar sem jafnvægisástand strandarinnar er mjög háð rifinu.

Í líkangerðinni var dæmi tekið um efnistökusvæði milli -15 m og -20 m dýpis (kortadýpi) sem er um 1 km að breidd, með 1 m efnistökulagi, og efnistökusvæði milli -20 m og -35 m dýpis (kortadýpi) sem er um 1,5 km að breidd, með 2 m efnistökulagi. Sameiginlegt efnistökurúmmál þessara svæða á einingar-lengd eftir ströndu er á stærðargráðunni 3500 m^3/m og má því ætla að það geti staðið undir þeirri langtíma efnistöku sem stefnt er að innan 20 – 30 km lengd eftir ströndinni.

Ganga má út frá þessari grunnhugmynd langtíma efnistöku þegar gengið verður í frekari rannsóknir á svæðinu. Hins vegar, líkt og niðurstöður líkangerðarinnar gefa til kynna, má ætla að efnistakan þurfi að fara fram á nokkru meira dýpi, umfram það dýpi þar sem óverulegar botnbreytingar eiga sér stað (closure depth).

Af greiningu tiltækra dýptarmælinga og niðurstöðum líkanreikninga á formbreytingum sjávarbotns má ráða að greina má frekar dýpri hluta dýptarmælinganna. Enn fremur að tvinna saman slíka greiningu við líkanreikninga á sandflutningi eftir ströndinni á þessum dýpri hluta og hugsanlegum formbreytingum sjávarbotnsins. Þetta getur stutt rannsóknir og undirbúning að efnistökunni þ.m.t. ákvörðun á öruggu dýpi til vinnslu á hverjum stað eftir ætluðu efnistökusvæði. Enn fremur má með þessu ákvarða mögulegan endurheimtartíma efnistökusvæða, bæði til mats á líftíma vinnslunnar og varanda þeirra áhrifa sem efnistakan getur leitt af sér.

Þegar fyrirhuguð efnistaka hefst þarf vöktun hennar að innifela tíðar dýptarmælingar, þ.m.t. reglubundnar mælingar á stærra svæði. Enn fremur þurfa að fara fram nákvæmar landhæðarmælingar við ströndina þegar lágstreymt er samhliða loftmyndatöku. Verður þannig unnt að greina með nokkurri nákvæmni formbreytingar og með samanburði við eldri gögn má draga ályktanir um möguleg áhrif efnistökunnar. Til viðbótar við þessa vöktun mun hjálpa að fylgjast með breytingum í kornastærð sands innan námusvæðanna og í nágrenni þeirra til að meta langtíma áhrif efnistökunnar.

Reglulega á líftíma efnistökunnar þarf að rýna í framkvæmd hennar og þau vöktunargögn sem safnast, samhliða nákvæmri greiningu þeirra og líkangerð henni til stuðnings. Þetta er mjög mikilvægt þar sem það getur tekið formbreytingar vegna efnistökunnar nokkurn tíma að koma fram og því getur verið erfitt að greina áhrifin frá náttúrulegum breytileika án slíkra aðgerða.

1 Introduction

HeidelbergCement Pozzolonic Materials (HPM) plans to enter into a long-term program of mining sand from the coastal bottom near Landeyjahöfn harbour in Southern Iceland. The operation plan presumes that up to 2 million cubic meters of bottom sediments will be collected on a yearly basis. An investigation area has been defined for the planned operation (Figure 1), with mining operations occurring in a minimum distance of 115 m from spring tide ebb levels at the coast (Mannvit, 2023).

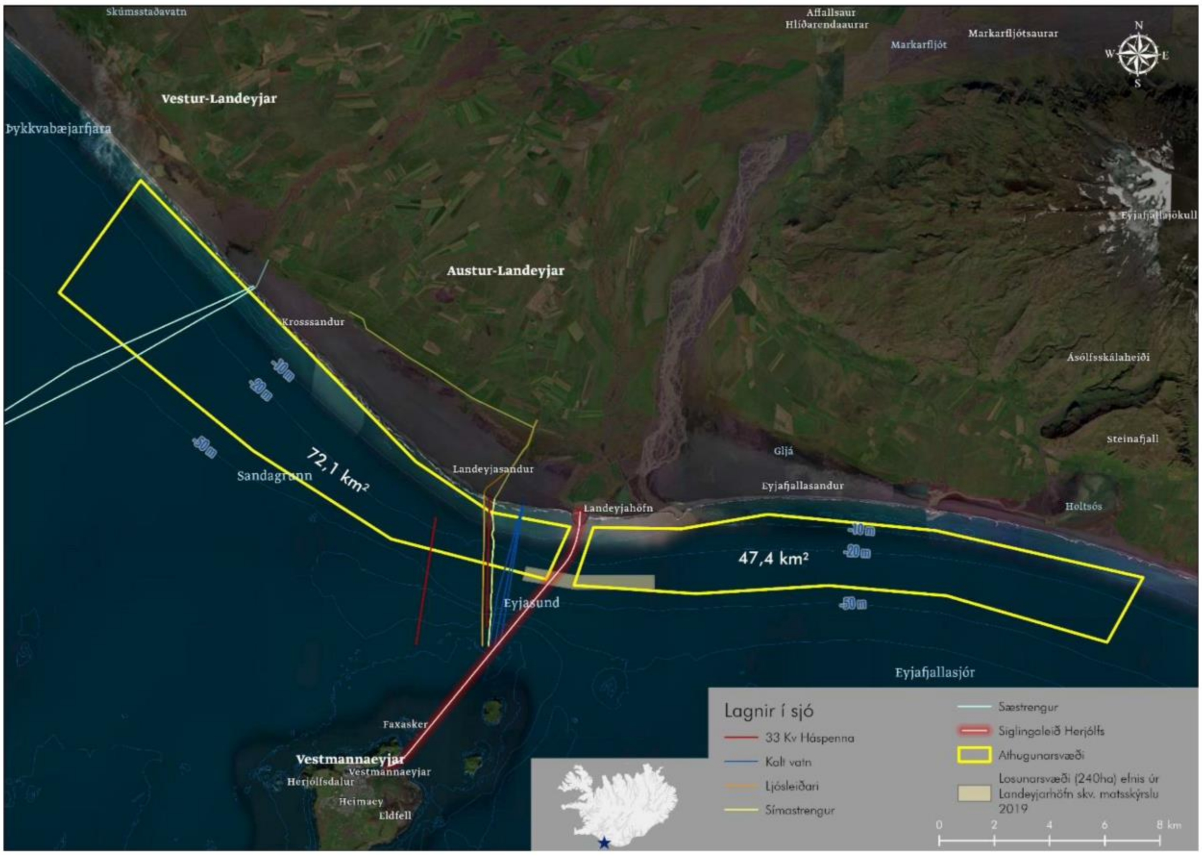


Figure 1. The investigation area (yellow lines) for the proposed mining operations (Mannvit, 2023).

As a part of the environmental impact assessment process HPM has requested that Vatnaskil and LVRS will assess the potential effects of the planned operations on wave climate and coastal morphology, including forcing at the shoreline that may lead to land erosion.

At this stage, a plan for the mining operations has not been defined. This includes identification of primary mining areas within the investigation area and their frequency of operation. The assessment presented in this report, therefore addresses the general concept of mining operations within the investigation area and the possible affects to the aforementioned factors by different mining pit locations. Furthermore, a sense for both shorter- and longer-term effects is established. Collectively, this allows for an assessment of the mining operations on the wave climate and coastal morphology in the vicinity of the investigation area.

There are three primary factors that set the planned mining operations apart from previous mining of seabed materials in Iceland:

1. *The planned amount of bottom material to be mined*. Approximately 2 million m^3 of sand are to be mined per year over 30 years for a total of 60-75 million m^3 of sand. This may be the largest volume of sand mined near the Icelandic coast in a defined mining area. For comparison, 6 million m^3 of gravel sand and shell sand were mined in southern Faxaflói bay during 48-year period (1960-2008) and plans were for further 23,5 million m^3 during a 10-year period (2008-2018) in the same area (Mannvit og Jarðfræðistofa Kjartans Thors, 2009). There are many other mining areas within Faxaflói bay, where most of the seabed mining activities have been in Iceland so far, for instance in Kollafjörður. Experience has been obtained with dredging activities in the vicinity of the proposed mining activities. On average, dredging activities near Landeyjahöfn harbour since 2010 have amounted to about 400,000 m^3/year (Vatnaskil and LVRS, 2023). These sediments are though not permanently removed from the system since they are deposited in other parts of the area.
2. *The extent of the potential area to be mined*. At the beginning of 2023, there were two valid exploration and research permits for minerals on seabed, and 13 permits for the exploitation of minerals on the seabed. The combined size of the exploitation license areas is 14.5 km^2 (National Energy Authority website). For comparison, the total area of HPM's investigation area is 119,5 km^2. Although the eventual portion of that as mining area still needs to be determined, the areal extend can be considered considerable.
3. *The characteristics of the mining area*. The mining activities are to be performed along the exposed, sandy Southern Iceland coast, within approximately 2-4 km from shore. The black basalt sand coast experiences severe weather conditions with very high waves, resulting in significant sand transport and dynamic conditions.

Furthermore, guidelines for mining activities are limited in Icelandic legislation and regulations with respect to suitable physical characteristics for mining sites. Such sites can though be subject to numerous limitations and even protective measures. Some measures have been defined, primarily by the Icelandic Road and Coastal Administration (IRCA) and the Icelandic Maritime Administration (IMA) now part of the IRCA, both for upper limits on changes to wave climate to minimize land erosion (IMA, 2007; IMA 2008; IRCA, 2016) and the level of protection for areas subject to various mining activities (IRCA, 2002).

Given limited experience in Iceland with similar mining activities as are proposed by HPM and limited Icelandic guidelines to direct such activities, a broader international view will aid in the overall assessment of the effects of the proposed mining.

An integrative approach must therefore be taken for the assessment at hand, led by a comprehensive background to account for coastal processes, the concept of coastal sand mining and the morphological behaviour of mining pits, as well as some of the guidelines internationally available for nearshore mining. This background sets the stage for the primary environmental conditions and site characteristics to be described for the investigation area in question. The modelling performed to support the overall assessment of the mining activities draws from the environmental conditions and the challenges they impose on the investigation.

In the following chapters, a background is provided for the general concept of costal sand mining and the interrelationship with the wave climate and morphological changes, followed by a description of the environmental conditions at the investigation area, including an assessment on the longshore sand transport, which dominates the sediment availability and the possible recharge of sediments in the mining area.

Following the background description and outline of site characteristics, the main results of the numerical modelling are delineated followed by an assessment on the effects of the planned mining operations. Primary findings are summarized followed by concluding remarks.

2 Background

2.1 Coastal sand mining and its potential effects

Mining of sand in coastal waters to obtain sediment material for beach nourishment and industry takes place internationally in a wide range of depths, from shallow water with depths of 5 to 10 m in New Zealand and Japan (Uda et al., 1995; Hilton and Hesp, 1996) up to deep water with depths of 30 to 40 m in Holland (Van Rijn, 2015) and Japan (Tsurusaki et al., 1988; Kojima et al., 1986). Geomorphic features (shoals) in the marine environment are usually composed of sand or sand-gravel mixtures and are potentially usable for extraction sources. Most of these features are of recent (modern) age but some may have been formed during the Holocene transgression and are essentially relict (formed by processes no longer prevalent).

Commonly, mining operations are executed in pits, channels, trenches dredged in the seabed or at large-scale geomorphic features present on the seabed (sand shoals and sand banks). The available mining methods basically fall into two categories: wide, shallow mining pits or small, deep mining pits. In most cases shallow pits not deeper than a few metres are excavated in deeper waters to obtain sand for beach nourishments. Deep mining pits have not yet been made extensively.

The mining of sea sand will affect both the ecology and morphology of the coastal system. Therefore, the technical evaluation of sand mining activities requires fundamental knowledge of morphological processes, sand transport processes, sand budgets and ecology in the offshore coastal zones. The focus of the present investigation is on the morphology and related processes. The potential effect on the ecology is dealt with elsewhere, however, some basic notion on the possible ecological effects helps to put the present study of physical characteristics into a broader perspective. Generally, ecological effects relate to damaged local bed flora and fauna by the mining activities, directly impacting living organism's dependent on the bed fauna for their food. Furthermore, the release of very fine sediments (silt and clay) from the bed into the water column may directly influence the ecological system. The recovery period may increase considerably with increasing excavation depth (dead water zone at bottom of deep pit).

The morphology is affected in the sense that locally the bed level is lowered substantially in the front of an extraction area, pit (or channel), which may influence the local flow and wave fields and hence the sand transport rates. Waves fields are modified by shoaling, refraction, and reflection processes (interception of onshore sand transport). The pit area (slopes) may migrate towards the shore over time and/or may act as a sink (trapping) for sediments from the nearshore system (beach drawdown). On long term the area of influence may extend well outside the original mining area. Furthermore, the small-scale and large-scale bed forms (from mega-ripples to sand waves) may be destroyed locally, which may also have an effect on the hydrodynamic system (less friction and turbulence).

Large-scale mining pits may have a significant impact on the near-field and far-field (up to the coast) flow and wave patterns; the flow velocities inside the mining area may be lower and the wave heights may also be lower, depending on the depth of the mining area. Consequently, the sand transport capacity inside the mining area will decrease and sediments will settle in the mining area, resulting in deposition. Thus, the mining area can act as a sink for sediments originating from the surrounding areas and depending on the local flow and wave patterns. Erosion of the sea floor may take place in the (immediate) surrounding of the mining area. This may lead to a direct loss of sediment from the nearshore zone (beaches).

Indirect effects result from the modification of the waves moving and refracting over the excavation area (pit), which may lead to modification of the nearshore wave conditions (wave breaking) and hence longshore currents and sediment transport gradients and thus to shoreline variations. In the case of massive mining of sand, typically the mining areas need to be situated in the offshore shoreface zone to minimise the effects of nearshore coastal erosion. On the other hand, the mining of sand is progressively more expensive at greater distances from the shore. Therefore, generally research is required to find the optimum solution between the effect on the coast and the costs of mining.

2.2 Regulations and guidelines on nearshore mining

The Icelandic state owns all seabed resources beyond territorial waters, defined as extending 115 m from spring tide ebb levels at the coast. The National Energy Authority (NEA) has a legal role in issuing permits for exploration and utilization of minerals at the seabed in this area, as well as monitoring such permits.

The IRCA has issued a categorization on the level of protection for areas subject to various mining activities (IMA, 2007; IMA 2008; IRCA, 2016). A total of five levels are defined. Under second level, with high protective value, falls mining of seabed materials in areas with ecological significance, e.g. spawning areas, or where there may be risk of land erosion. Areas where such risk is not present and ecological characteristics are less noteworthy fall under the fourth level, with low protective value (IRCA, 2002).

The IMA, now IRCA, has furthermore suggested guidelines for limits in wave height changes to minimize land erosion (IMA, 2007; IMA 2008; IRCA, 2016). For sand beaches, they suggest an upper limit in wave height to be 0 – 3% for beaches under average forcing bot 3 – 6% for sheltered beaches. The lower range is considered for long coastlines and the upper one for short coastlines. Sheltered conditions are considered to have significant wave height with one year return interval and 12-hour duration between 0 and 1 m, average forcing is considered to be between 1 and 3 m, whereas high forcing is above 3 m. They furthermore assign a reference to a closure depth, below which bottom changes between winter and summer conditions are minimal and suggest that mines should not be in shallower water than equals a significant wave height with one year return interval and 12-hour duration.

Points of attention in formulating regulations and guidelines in other countries generally include ecology (bottom fauna, algae, bird habitat), dispersion of mud, morphology of shoreface and coastline, and morphological interaction with existing and future engineering works (navigation channels, pipelines, land reclamation, etc.). It is helpful to explore this in more detail with respect to regulations in Great Britain (TSO, 2002) and The Netherlands (Rijkswaterstaat, 2001).

As a part of the licensing system for offshore dredging in Great Britain a coastal impact study and a wider-ranging environmental impact assessment are performed. Within the coastal impact study, the following phenomena are studied and evaluated:

- The beach should not be affected from drawdown into the dredged area (no permanent trapping of beach sediments into dredged area).

- The supply of sediments to the coastline should not be affected.
- Bars and banks providing protection to the coast from wave attack should not be damaged/affected.
- Significant changes in wave refraction patterns altering nearshore waves and hence the alongshore transport of sediment should not occur.
- Significant changes to tidal currents close to the coastline should not occur.

These studies require an estimation of the effects of modified flow and wave patterns on the changes to sediment transport along the seabed and hence to (coastal) morphology based on regional and local modelling and existing field data (e.g. bedforms, sediment distribution/ mobility calculations).

An environmental assessment report is also required, often concentrating on the production of turbid plumes and deposition of sand or finer-grained sediment on the seabed outside the extraction area. It includes a description of the existing environment and the impacts of the proposed dredging compared to alternatives. Consideration of "cumulative impacts" of multiple dredging (or other) activities in same general region is also required.

With regards to regulations and criteria, no fixed limits are used, but mining is rare in water depths less than 15 m (lowest tide). Each application is subject to specific studies of effects on coast and of other environmental impacts, considering beach drawdown, seabed sediment transport, sand bar and banks, effects on wave refraction and currents.

- The approximate depth limit for offshore sediment movement off the south coast of England is considered to be about 10 metres below chart datum (CD). This is the minimum depth to ensure that beach drawdown will not take place; an additional limit is a minimum distance of 600 m from the shore. Almost all extraction areas are in much deeper water.
- Shingle (gravel) is unlikely to be mobile below 18 m (CD) based on field tracer studies, but more detailed and specific studies are required for sand transport (even if extraction is for shingle).
- Minimum depth based on special studies depending on location (Sand bar and banks); dredging of banks adjacent to coastline is not allowed; except in conditions with high accretion rates.
- An old rule-of-thumb was a minimum water depth of 14 m based on wave refraction studies along the south coast of England. Now it is sometimes simpler to carry out wave refraction modelling for areas even in much deeper water, than to risk criticism that the effect has been ignored.
- Effects on currents are not a real issue except very close to the extraction area (near-field) but may affect sediment transport locally as well (and hence affect the biology of adjacent areas).

Regulations on mining activities in the Dutch Sector of the North Sea are mainly concerned with mining depth and mining area in relation to the water depth at the mining location. The maximum mining depth for the present mining activities in shallow pits is 2 m. The regulations for deep sand mining pits (deeper than 2 m) are:

- Sand mining in deep pits, outside the NAP - 20 m depth contour (Amsterdam Ordnance Datum or Normaal Amsterdams Peil) is conditionally allowed if the presence of sufficient amounts of course sand is made plausible first.
- Inventory of the environmental effects of the proposed mining activities (EIA).
- A monitoring program aimed at the effects of the mining activities may be required.

The maximum depth is restricted in the sense that irreversible negative effects on the environment are not allowed. Some criteria given for the maximum depth are:

- The new surface sediments should not deviate too much from the original ones.
- At the bottom of the pit no reduction of the water exchange is allowed, in order to prevent reduction of the oxygen content.
- Ecological recovery of the mining area within a reasonable amount of time (10 years).

2.3 Coastal processes

On the coastline the shoreface is generally divided into three zones: upper shoreface, middle shoreface, and lower shoreface. The definition of these zones can vary depending on site-specific wave-climate and tidal prism. The upper shoreface, also known as the surf zone, is the closest zone to the shoreline, generally defined landward of the -8 m depth contour where wave-driven processes (shoaling and wave breaking) are dominant.

The zone generally located between -8 and -20 m depth contours is called the middle shoreface. There, wind-, density- and tide-driven flows are controlled by bottom friction and the currents are generally parallel to the coast. During storms a secondary circulation (in transects normal to coast) superimposed on the main longshore current is often present, yielding a spiral type of fluid motion with landward flow in the surface layers and seaward flow in the near-bed layers.

Seaward of the -20 m contour the lower shoreface is located. There, currents are controlled by pressure gradients and wind forces in combination with Coriolis forces (Ekman spiral, geostrophic flows).

The fluid in the shoreface zone may be homogeneous (well-mixed) or stratified with a surface layer consisting of relatively low fluid density (fresh warmer water in summer) and a bottom layer of relatively high density (saline colder water in summer). Strong horizontal density-related pressure gradients may occur in regions close to a river mouth. In micro-tidal environments (such as Atlantic Shelf, Gulf of Mexico Shelf) the tidal currents generally are less important (<0.5 m/s) than wind-driven currents. In meso-tidal environments like the North Sea both tide- and wind-induced currents are important.

Sand can be transported by wind-, wave-, tide- and density-driven currents (current-related transport), or by the oscillatory water motion itself (wave-related transport). The waves generally act as a sediment stirring agent, whereas the sediments are transported by the mean current. Wave-related transport may be caused by the deformation of short waves (wave asymmetry) under the influence of decreasing water depth. Low-frequency waves interacting with short waves may also contribute to the sediment transport process (wave-related transport), especially in shallow water in the surf zone.

In friction-dominated deeper water on the lower shoreface zone, the transport process generally is concentrated in a layer close to the seabed and mainly takes place as bed-load transport in close interaction with small bed forms (ripples). Bed-load transport is dominant in areas where the mean currents are relatively weak compared to the wave motion (small ratio of depth-averaged velocity and peak orbital velocity). Net sediment transport by the oscillatory motion is relatively small in depths larger than 15 m, because the wave motion tends to be more symmetrical in deeper water.

Suspension of sediments on the lower shoreface can be generated by ripple-related vortices. Suspended load transport will become increasingly important with increasing strength of the tide- and wind-driven mean currents due to the turbulence-related mixing capacity of the mean current (shearing in boundary layer). By this mechanism the sediments will be mixed up from the bed-load layer to the upper layers of the flow. On the lower shoreface the suspended sand transport may be dominant during storm conditions, depending on conditions (wave height in relation to water depth; additional wind-driven flow).

The most important contributions to the long-term sediment transport are made by fairly large (in relation to depth) but not too infrequent waves, combined with tidal currents between mean neap and maximum spring tide. Weak currents and low waves in relation to water depth give a small contribution, because their potential for sediment transport is low, although their frequency is high. Extreme conditions also are relatively unimportant, since their frequency is too low, although their transport potential is high.

Characteristic morphological features occurring on the shoreface are breaker bars in the nearshore zone and large sand banks, ridges, or shoals on the middle and lower shorefaces, which are at some places connected to the shore. Small-scale bed forms may be superimposed on these large-scale features ranging from wave-induced micro ripples to mega-ripples.

Generally, the sand bodies consist of well-sorted, medium-grained sand with fragmented shell debris. Core analyses reveal cross-bedding features and a coarsening-upward sequence due to winnowing of fines from the ridge/bank crest and deposition of fines in the troughs.

Hallermeier (1981) introduced the concept of offshore closure depth defining a limit beyond which no measurable bed level variations due to wave and current motion are assumed to occur (approximately <0.2 m). This limit may also be identified on the basis of field observations related to transition in sediment size, transition in slope, transition in bed forms or/and transition in observed bed level variation. Along meso/macro-tidal coasts, like in the south of Iceland, there may be a transition from finer to coarser sand in depths of about 20 m due to the presence of longshore tidal currents winnowing the fines from the seabed. The nearshore bed can also consist of coarser sand with a significantly steeper slope. Bed forms can also change with periodic bed forms generally absent in depths larger than about 25 to 30 m. Also, maximum observed bed level variations seaward of the 20 m depth line are generally less than 0.1 to 0.2 m.

Cross-shore transport processes and sediment sorting along the bed profile are often caused by rip currents. Rips are characterized by rip heads where the jet-like rip current at the seaward end breaks up into irregular to highly organised vortices and rip-transported sediment is dispersed. Rip currents are known to transport significant quantities of sediment seawards specifically in storm conditions when seaward flows may be significant up to depths of at least 15 m.

Indications of sediment particle movement along the shoreface in relation to water depth can be obtained from tracer studies. Migniot and Viguier (1980) present information of tracer studies using radioactive sand tracers in the Gulf of Casgogne north of Biaritz (France) facing the Atlantic Ocean (severe wave climate). The experiments were carried out at depths between 6 and 22 m in the period between 15 September and 15 December 1975 (autumn and winter) in conditions with incident waves almost normal to the shore. The results show significant particle movement (fine to medium coarse sand of 0.1 to 0.8 mm) with transport rates of about 0.5 m^3/m over 3 months at a depth of 22 m up to transport rates of about 80 m^3/m over 3 months at depths of 6 to 8 m.

2.4 Morphological behaviour of mining pits

The morphological behaviour of mining pits can be described with respect to sand transport rates, trapping of sediments in the pit, the effect of a mining pit on the coast, results of data sets of mining areas and results of mathematical model studies of mining areas. In the following sections these factors will be explained.

2.4.1 Sand transport at shoreface

Information on sand transport rates at the shoreface can be obtained from various studies in The Netherlands. Van Rijn (1997) studied the net transport rates (tide-averaged values) at the 20 m depth contour of the Holland coast in the North Sea. The median size of the bed material on the lower shoreface (20 m depth) varies between 0.15 and 0.25 mm. The tidal range is between 1 and 2 m. The peak tidal current velocities are about 0.7 m/s during flood to the north and 0.6 m/s during ebb to the south.

The net annual cross-shore transport rates at the -20 m depth contour were estimated (based on these model computations) to be in the range of 0 to 15 m^3/m/year normal to the coast. The net annual longshore transport rate at the -20 m depth contour was estimated to be in the range of 25 to 75 m^3/m/year parallel to the coast. These computed transport rates show reasonable agreement with transport rates derived from available field data of the middle and lower shorefaces (dump site Hoek van Holland 1982; dump site Wijk aan Zee 1982; Simon Stevin pit 1981).

2.4.2 Trapping of sediments

The sedimentation, erosion and migration of a mining or extraction area (pit, channel, or trench) in a coastal environment strongly depend on the sediment supply, the hydraulic conditions and the orientation of the mining area.

When a current passes a mining area (perpendicular or oblique), the current velocities decrease due to the increase of the water depths in the mining area resulting in a decrease of the sediment transport capacity. Consequently, the bed-load particles and a certain amount of the suspended sediment particles will be deposited in the mining area. The settling of sediment particles is the dominant process in the down sloping section (deceleration) and in the middle section of the mining area. The most relevant processes are convection of sediment particles by the horizontal and vertical fluid velocities, mixing of sediment particles by turbulent and orbital motions, settling of the particles due to gravity and pick-up of the particles from the bed by current and wave-induced bed-shear stresses. The effect of the waves is that of an intensified stirring action in the near-bed region resulting in larger sediment concentrations, while the current is responsible for the transportation of the sediment. In case of flow parallel or almost parallel with the pit or channel axis, the side slopes are flattened and smoothed due to gravitational effects. When a sediment particle resting on the side slope is set into motion by waves or currents, the resulting movement of the particle will, due to gravity, have a component in downward direction. By this mechanism sediment material will always be transported to the deeper part of the pit or channel yielding reduced depths and smoothed side slopes. Slope instability may occur in case of relatively steep slopes immediately after (capital) dredging, especially in deep mining areas.

Wave action over a muddy bed may generate a high-concentration fluid mud layer close to the bed. The sediment concentrations in this layer may be of the order of 100 to 300 kg/m^3. The sediment concentrations above this layer generally are an order of magnitude smaller. Tide-driven, wave-driven, wind-driven, or gravity-driven (on slopes) currents are able to transport the fluid mud layers towards the mining area resulting in excessive deposition on short term time scales (storms).

The sedimentation in mining areas basically consists of two elements: sediment transport (mud, silt and sand) carried by the approaching flow to the mining area, depending on flow, wave and sediment properties, and trapping of sediment in the mining area, depending on dimensions, orientation and sediment characteristics.

2.4.3 Effect on coast

The effects of a nearshore mining area on the shoreline can be broken down into four main effects: beach drawdown, interception of onshore sand transport, modification of offshore sand banks, and generation of alongshore transport gradients. In Figure 2, a schematized overview of the effects of nearshore mining are shown.

Beach drawdown (sink effect) usually occurs during storms due to the action of high steep waves generating breaking wave conditions and hence a relatively strong near-bed, offshore-directed currents (undertow); beach material is eroded from the upper shoreface and moved seawards; during periods of calmer weather the material is returned to the beach by shoaling, non-breaking waves (sea and sell waves); if the mining area is situated near the shoreline then this dynamic equilibrium is disturbed and sediment may be trapped in the deeper mining area (acting as a sink) and erosion of the foreshore may result (see top of Figure 2).

The interception of onshore sand transport can occur when a beach is being nourished by sediments coming from the shelf by onshore-directed transport processes (wave action). Then the deeper mining area will trap a proportion of this sediment and interrupt the supply of sediment to the shore (see Figure 2).

Modification of offshore sand banks, by dredging, such as permanent or temporary lowering of the sand bank crests present in the nearshore zone leads to lower protection level of the shoreline against wave attack. The offshore sand banks help to protect the shoreline against wave attack by either dissipating wave energy as a result of bed friction, partial breaking of the waves and by reflection.

The generation of alongshore transport gradients can develop with the presence of a deeper mining area leading to local changes in the wave refraction patterns and associated wave height patterns at the edge of the surf zone. This will result in alongshore variations (gradients) of the littoral drift and hence in shoreline changes.

The effect of mining area on the shoreline strongly depends on the distance to the shore. Nearshore mining of sand in depths < 8 m will immediately have negative effects, but offshore mining pits (depths> 20 m) generally have much smaller direct effects. Even when the immediate direct effects on the shoreline are negligible some negative effects may be realised in the long term after the mining area has migrated to the shore. The migration rates often vary roughly between 0.2 m/year at the 20 m depth contour to about 1.5 m/year at the 10 m depth contour.

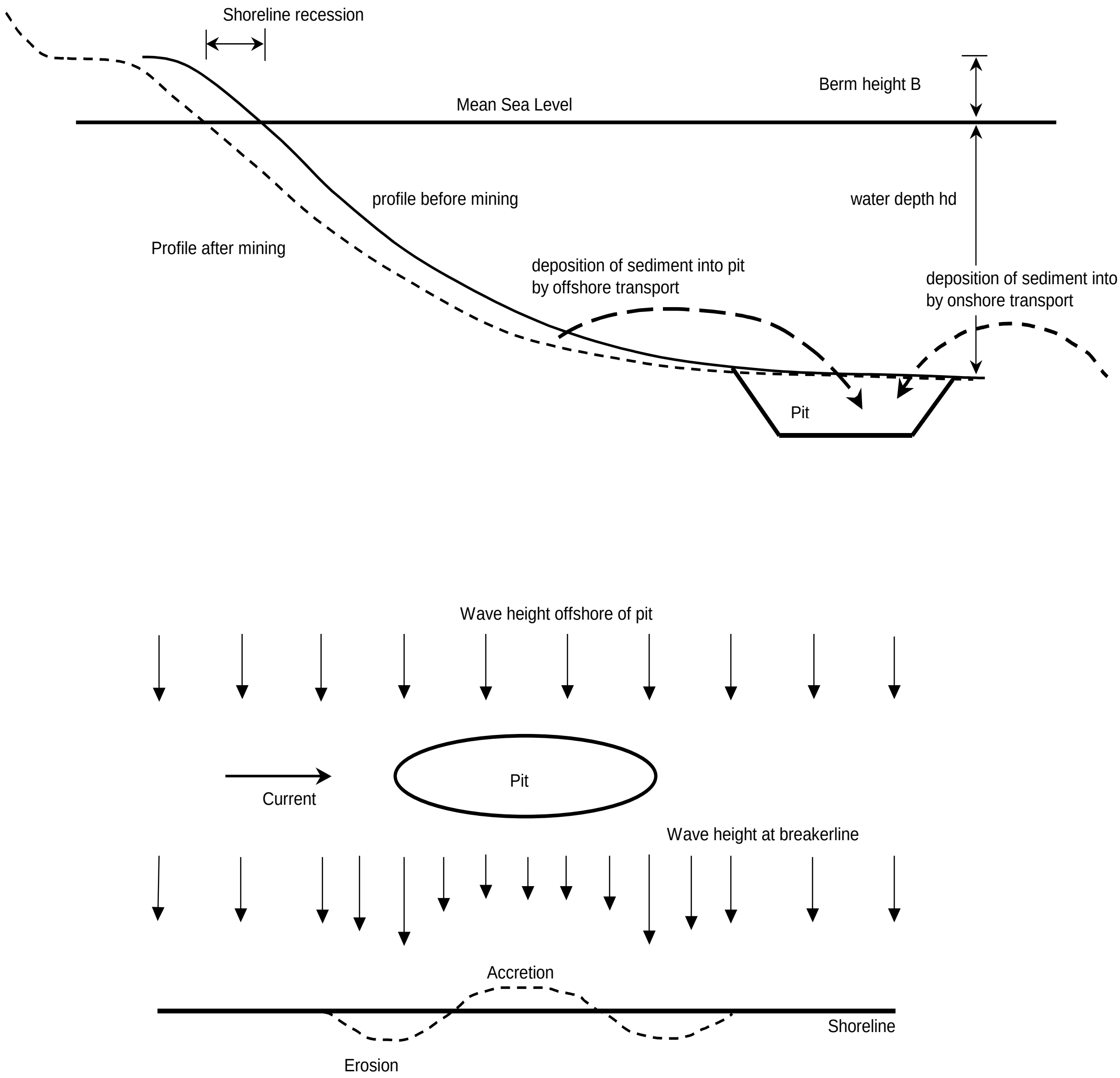


Figure 2. Effects of sand extraction pit on shoreline, cross-shore effects (top), longshore effects (bottom).

2.4.4 Field data and research

The available information on the coastal impact of mining pits (extraction pits for beach nourishments, mostly in USA 1955 to 1965; Van Rijn 2015) can be summarized by the location of the shoreface.

At the depth of 2 to 5 m (inshore at the foot of shoreface), mining can sometimes be established for sheltered beaches (mild wave regimes; small littoral drift). There the infill from the beachside and from the seaside occurs with an annual infill rate not more than about 3% of initial pit volume and infill rates between 5 and 15 m^3/m/yr, depending on wave climate. The filling time scale is 20 to 30 years. There, a local recirculation of sand persists with no new extraction sand added to the beach system.

At the depth of 5 to 15 m (upper shoreface), research has shown that mining has a relatively strong impact on inshore wave climate due to modified refraction and diffraction effects. Significant shoreline changes (growth of beach salients) can be the result of relatively strong modification of gradients of littoral drift in lee of a pit. The extraction pit can fill relatively fast with sediments from landside (beach zone) where annual infill rates can be up to 20% of initial pit volume in shallow water (filling time scale is 5 to 10 years). There, a local recirculation of sediment exists with no new extraction sand is added to the nearshore system.

At the depth of 15 to 25 m (middle shoreface), research has shown that mining has a negligible impact on nearshore wave climate and nearshore littoral drift, resulting in no measurable shoreline changes. In some cases, new extraction sand is added to nearshore morphological system (nourishment). The infill of extraction pit comes mainly from the landside with sediments eroded from upper shoreface by near-bed offshore-directed currents during storm events (see Migniot and Viguier, 1980; Kojima et al., 1986). The annual infill rate is about 1% of initial pit volume resulting in filling time scale of close to 100 years. The pits can also trap mud leading to a negative ecological effect. Particle tracer studies have shown small but measurable transport rates, mainly due to storm waves. Mining at this zone can lead to long-term deficit of sand at the upper shoreface.

At a depth beyond 25 m (lower shoreface), research has shown that mining has almost no impact on the nearshore wave climate and the nearshore littoral drift resulting in no measurable shoreline changes. In many cases new extraction sand is added to nearshore morphological system (nourishment). Only a minor infill of sand has been observed in extraction pits at the lower shoreface, only during super storms. The pits can also trap mud leading to negative ecological effect. Particle tracer studies have shown minor bed level variations (of the order of 0.03 m over winter period) during storms.

Extraction pits in the middle and lower shoreface should be designed with their longest axis normal to the shore to minimize the trapping of sand from the nearshore zone during storm events. The estimated time scales for the middle and lower shoreface are extremely uncertain due to lack of sand transport data at these locations.

2.4.5 Modelling studies

The hydrodynamic and morphodynamical effects of extraction pits (various cases in USA, UK, Canada and The Netherlands) at various depths in the nearshore coastal zone have been studied by using wave refraction, flow, sand transport and shoreline change models (Van Rijn, 2015).

With regards to hydrodynamics, the wave climate at and inshore of the extraction area is affected (reduced wave heights). The flow patterns outside the extraction area are modified over a distance of maximum twice the width and length of the extraction area. The wave transformation and flow patterns can be simulated quite well provided that the boundary conditions at the model inlet are accurately known.

With regards to morphodynamics, the cross-shore morphological changes are relatively small for pits beyond the 15 m depth contour; the migration rates are mainly affected by the local water depth and not by the pit dimensions (depth, width, length). The migration velocity of the pit in longshore direction was found to be 10 to 15 m/year. The morphological changes remain within the local surrounding of the pits. On the time scale of 100 years the overall longshore migration of the pit is of the order of 1 to 2 km. The sedimentation of the pit (infilling rate) increases strongly with decreasing water depth outside the pit. At present, the modelling of morphodynamics is not very accurate due to the absence of accurate field data of sand transport processes in deeper water. In the absence of such data the uncertainty margins are relatively large (up to factor 5).

The presence of a sand pit results in the formation of circulation cells which may trigger the development of a sandbank pattern (based on stability analysis studies). As time evolves, the sand bank pattern spreads out and migrates, alternatingly generating trough and crest zones. The pit itself deepens and the pattern spreads at a rate of 10 to 100 m/year. The migration rate of the centre of the pit is of the order of 1 to 10 m/year.

Beach erosion in the lee area of the pit was found to increase with increasing pit depth and with decreasing original water depth. It can be concluded that extraction pits beyond the 15 m depth contour do not lead to any significant shoreline erosion.

3 Environmental conditions – site characteristics

The south coastline of Iceland is characterized by black beach sands (basalt sand) and high offshore waves. At the centre of the coastline a dynamic river Markarfljót with pronounced meandering and braiding processes is situated with a very variable discharge between about 100 and 1000 m^3/s and a large sand input of about 100,000 to 200,000 m^3 per year. Historic observations show that the location of the river mouth is shifting regularly. The river mouth consists of a marked delta protruding into the sea. The delta sand is redistributed by the waves; the wave direction determines whether the sand in the delta is pushed to the east or to the west, often in the form of a spit. If the supply is large, the spit can grow extensively during events with waves coming from southeast. For analysis of environmental conditions along the coastline, 7 locations were defined with regards to the Landeyjahöfn harbour. One location south of the harbour and six locations west and east of the harbour covering the research area of the project, see Figure 3.

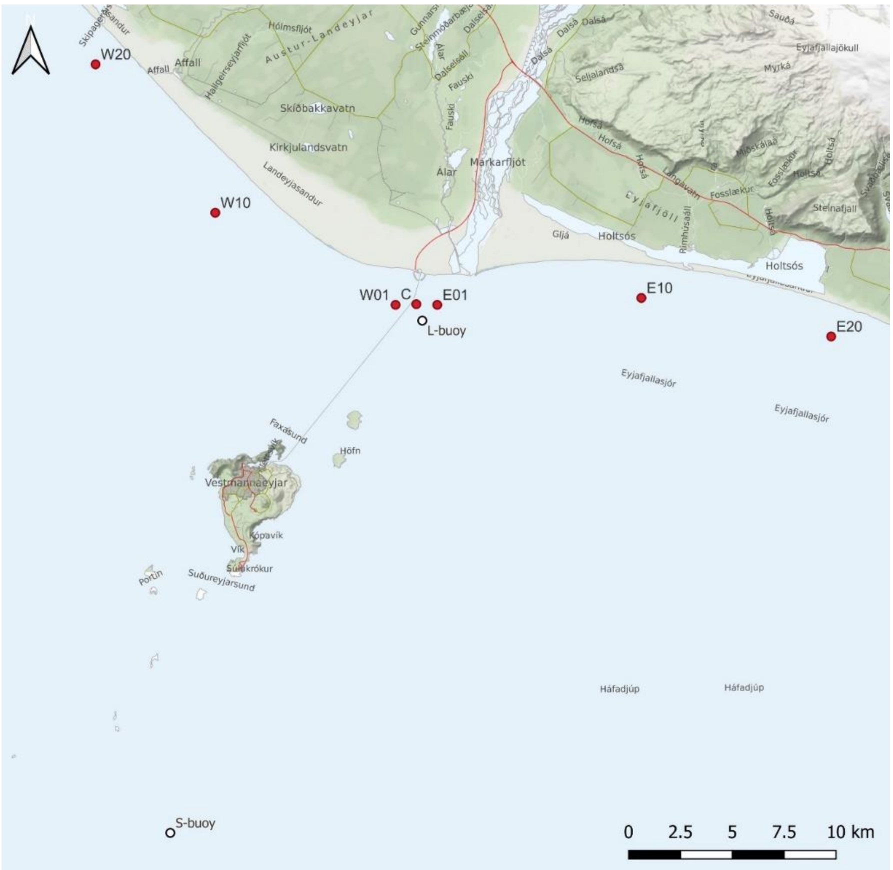


Figure 3. Locations of buoys and points for analysis of environmental conditions at the southern coastline.

3.1 Tides and currents

The tidal system along the south coast of Iceland is dominated by two amphidromic systems, as shown in Figure 4 based on the work of Tomasson and Eliasson (1995). The tide along the south coast runs from East to West.

In Figure 5 sea level fluctuations outside Landeyjahöfn harbour are shown for a period from spring to neap tide in March 2018. During neap tide the tide is about 1 m and the peak tidal current is about 0.2 m/s while during spring tide the tide is almost 3 m and the peak tidal currents above 0.5 m/s (Vatnaskil and LVRS, 2023).

Detailed analysis shows that the phase shift between the horizontal tide (currents) and the vertical tide (water levels) is about 3 to 4 hours. This rather large phase shift means that the time of maximum flood flow to the west is 3 to 4 hours before HW. At that time of maximum flow, the water level is still below the mean sea level (but rising). Most likely, this large phase shift is caused by the location of Landeyjahöfn at the border of two amphidromic tidal systems.

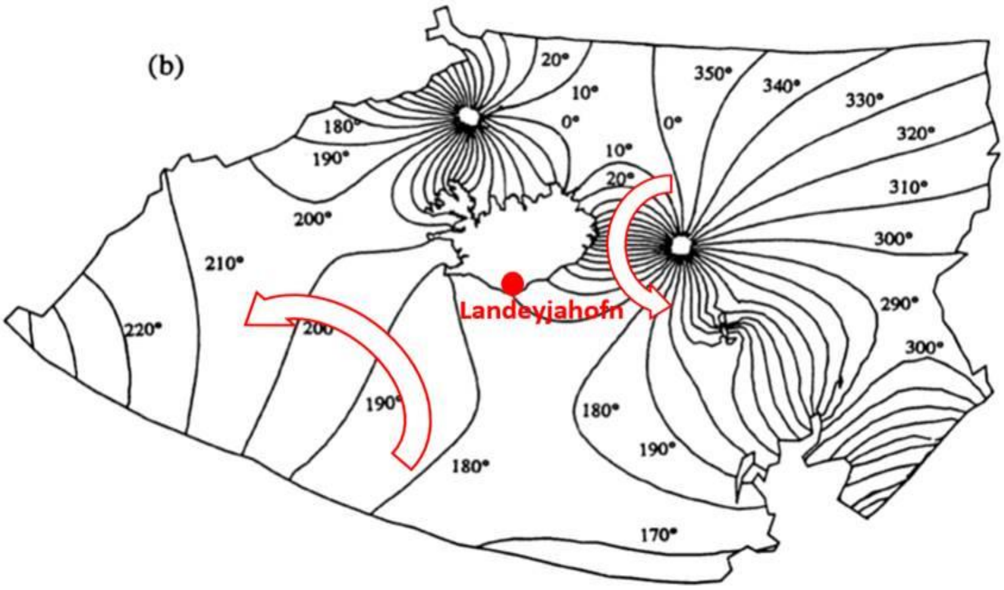


Figure 4. Amphidromic tidal system around Iceland; phase lags of cotidal curves of M2-tide, (0^o=HW at t=0; 180^o=LW at t=12 hours; relative to Greenwich); Tomasson and Eliasson, 1995.

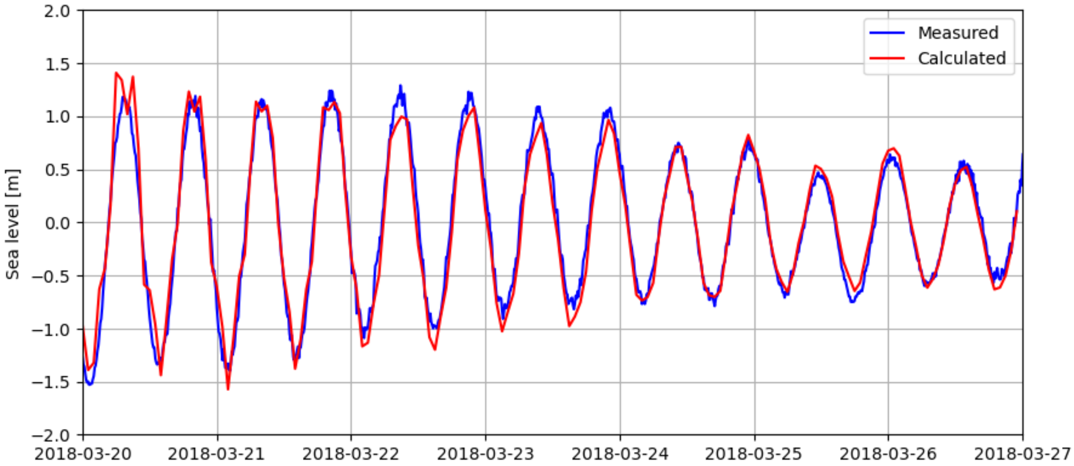


Figure 5. Sea levels during spring tide to neap tide period outside of Landeyjahöfn in March 2018. Comparison of measured and calculated sea level changes.

3.2 Wave climate

The Icelandic Road and Coastal Administration (IRCA) has for a long time carried out wave measurements at the south coast. In the vicinity of Surtsey island a buoy has measured offshore wave height since 1979. Closer to shore just outside of Landeyjahöfn harbour a buoy has been deployed since 2003 and since 2015 the buoy has been equipped to measure wave direction. In Figure 3 the locations of the measurement buoys are shown.

Vatnaskil has developed a coupled flow and wave model for the area which has been calibrated with regards to the measurements at the two buoys (Vatnaskil and LVRS, 2023). The model produces very reasonable results at the nearshore L-buoy location. The computed wave heights are though, on average, somewhat too low for waves from south-westerly directions. The discrepancies between measured and computed wave heights at L-buoy location are rather variable for the other directions (under/overprediction), which is most likely related to the location of the L-buoy at the edge or in the sheltering area of the Westman Islands for waves from the south and south-west. Results from earlier waves studies show similar discrepancies (DHI, 2006, 2007, 2010, 2013).

The computed wave heights and directions of the model are as good as possible without any systematic errors and can be used with some confidence for the computation of sand transport rates and harbour deposition rates. However, the uncertainties related to the computed nearshore wave heights are relatively high (on average ±20%) which will enhance the uncertainties of predicted sand transport and deposition rates for combined wave-current conditions.

A simulation of 10 years was carried out for the present study, for the period 2011-2021. In Figure 6 wave roses are shown for the predefined analysis locations east and west of Landeyjahöfn harbour. The stations closest to the harbour (W01 and E01) are somewhat affected by the Westmann Islands, with lower waves and more variance in wave direction. For the westerly stations located 10 and 20 km from the harbour (W10 and W20) the pronounced SW wave directions are observed approximately 40% of the time. The station 10 km east of the harbour, E10, seems to be affected to some degree by the islands, with S-SW waves occurring 35% of the time and S waves 25% of the time. However, at the station 10 km farther eastwards, E20, the S-SW wave account for 40% of the time and other directions are within 15%.

In Table 1 Percentage of Time (POT) analysis is shown for the stations for specific wave classes and direction. Overall, the same patterns are observed as in Figure 6 with dominating SW and S-SW wave directions while for the seasonal variance the winter period (December-February) as expected has the most severe wave conditions.

At station W20 the wave climate is the most severe. Waves come mostly from the south to west direction, 83% to 91% of the time depending on the period, with more variation in direction during the summer months and less in winter. During the winter months, waves with significant wave height above 4 m can be expected 16.5% of the time. Only smaller waves, significant wave height less than 2 m, can be expected from the easterly directions.

At station W10 similar behaviour as in station W20 can be observed although the wave climate is slightly less severe. Westerly waves are not as prominent at station W10, 72% to 84% of the time depending on the period. During the winter months, waves with significant wave height above 4 m can be expected 15.8% of the time. A very small percentage of waves, Hs=2-3m, can be expected to come from easterly directions.

At the stations closest to Landeyjahöfn harbour (W01, C, and E01), the sheltering effect of the Westman Islands is eminent with significantly less severe wave climate than for the stations further west. The south-west wave direction is significantly less pronounced with POT values ranging from 53% to 62% at W01, 51% to 58% at C, and 50% to 57% at E01. Interestingly, waves above 4 m are more likely to come from the east than west at stations C and E01.

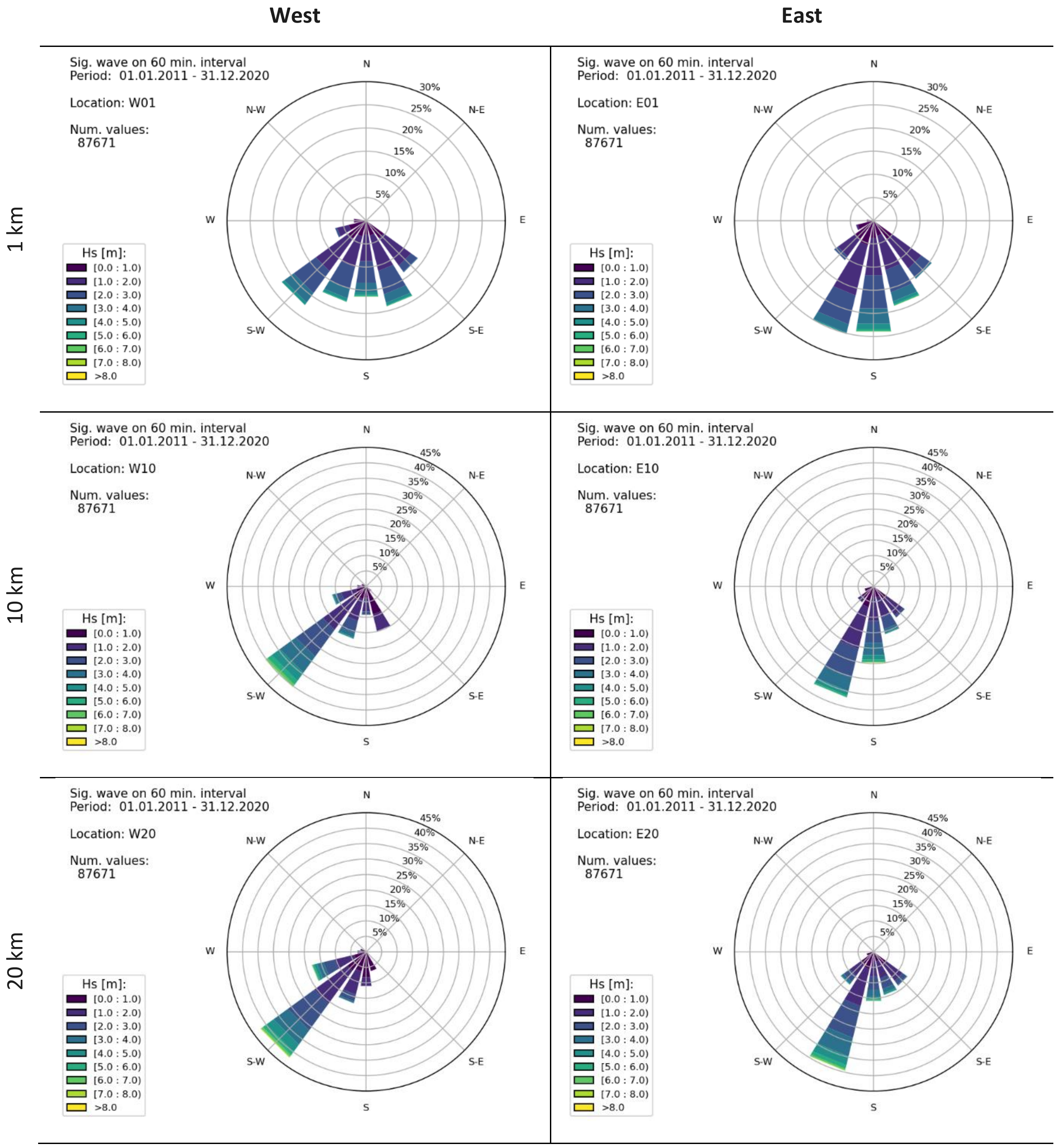


Figure 6. Wave roses derived from Vatnaskil's wave model for locations west (W01,W10, W20) and east (E01, E10, E20) of Landeyjahöfn harbour at distances of 1, 10 and 20 km. Period of wave calculations 2011 to 2021.

Table 1. Percentage Of Time (POT) analysis for station outside Landeyjahöfn harbour (C) and stations located 1, 10, and 20 km west (W) and east (E) of the harbour for specific wave classes and waves coming from east to south (0/180) and south to west (180/360). Analysis shown for whole calculation period 2011-2021 (Full) and seasonal variance; Winter (December-February), Spring (March-May), Summer (June-August) and Autumn (September-November).

		Hs = 0-8m		Hs = 2-3m		Hs = 3-4m		Hs = >4m	
Station	**Period**	**0/180**	**180/360**	**0/180**	**180/360**	**0/180**	**180/360**	**0/180**	**180/360**
W20	Full	12.3	87.7	0.0	16.7	0.0	8.3	0.0	7.1
	Winter	8.7	91.2	0.0	24.1	0.0	16.2	0.0	16.5
	Spring	13.4	86.6	0.0	17.9	0.0	8.4	0.0	7.3
	Summer	17.0	83.0	0.0	3.7	0.0	0.7	0.0	0.1
	Autumn	9.8	90.2	0.0	21.3	0.0	8.1	0.0	4.3
W10	Full	21.4	78.5	0.4	17.5	0.0	8.6	0.0	6.7
	Winter	16.0	83.9	0.8	25.0	0.0	17.2	0.0	15.8
	Spring	22.7	77.3	0.4	19.2	0.0	8.3	0.0	6.9
	Summer	28.3	71.7	0.0	3.9	0.0	0.8	0.0	0.1
	Autumn	18.5	81.5	0.6	22.3	0.0	8.5	0.0	4.1
W01	Full	42.0	58.0	9.3	13.5	3.1	5.5	1.3	2.0
	Winter	38.1	61.9	14.3	22.4	6.1	12.8	3.1	4.8
	Spring	43.7	56.3	10.0	14.8	2.7	5.3	0.9	2.1
	Summer	47.2	52.8	2.5	1.9	0.2	0.2	0.0	0.0
	Autumn	39.1	60.9	10.6	15.0	3.3	4.0	1.3	0.9
C	Full	44.6	55.4	10.2	12.2	3.7	4.1	1.8	1.1
	Winter	41.8	58.2	15.5	21.3	7.4	9.5	4.4	2.7
	Spring	45.8	54.2	11.0	13.5	3.2	3.9	1.3	1.3
	Summer	49.2	50.8	3.0	1.5	0.3	0.2	0.1	0.0
	Autumn	41.6	58.4	11.5	12.7	4.1	2.9	1.6	0.5
E01	Full	46.2	53.8	10.7	11.3	4.0	3.6	2.0	1.1
	Winter	44.2	55.8	16.2	19.6	8.0	8.3	4.7	2.6
	Spring	47.3	52.7	11.5	12.4	3.4	3.5	1.5	1.3
	Summer	50.4	49.6	3.2	1.4	0.3	0.2	0.1	0.1
	Autumn	42.8	57.2	12.0	11.8	4.4	2.6	1.7	0.4
E10	Full	39.3	60.7	7.7	14.1	2.8	6.8	1.4	3.6
	Winter	34.7	65.2	12.1	21.0	5.2	14.3	3.3	8.7
	Spring	40.6	59.4	8.1	15.9	2.5	6.7	0.8	3.8
	Summer	45.6	54.4	2.4	2.8	0.1	0.7	0.0	0.1
	Autumn	36.1	63.9	8.6	16.8	3.5	5.8	1.4	1.9
E20	Full	34.6	65.4	7.0	15.6	2.4	8.5	1.2	6.1
	Winter	29.1	70.8	10.4	21.4	4.4	16.6	2.7	14.7
	Spring	36.3	63.7	7.4	17.8	2.1	8.5	1.1	5.8
	Summer	42.0	58.0	2.7	3.9	0.2	0.9	0.0	0.2
	Autumn	30.8	69.2	7.5	19.5	3.0	8.3	1.0	3.8

3.3 Sediments

Many bed material samples were collected prior to the construction of Landeyjahöfn harbour along lines perpendicular to the coastline (IRCA, 2006). Sand is found to be finer (0.15 mm) offshore of the outer sand bar and in the trough and coarser (0.3 to 0.45 mm) on the bar crest and near the beach. The mean grain size varies between 0.15 mm to 0.45 mm. The average size is 0.25 mm. The density of basalt sand is about 2850 kg/m^3. Samples were collected at 13 to 19 locations in Landeyjahöfn basin, harbour mouth, wing areas and outer bar (reef) areas during four repeated sampling campaigns in May 2015, October 2017, March 2018 and July 2018. Another series of samples were collected in the period of May 2015 to July 2018 (IRCA, 2018), see Figure 7.

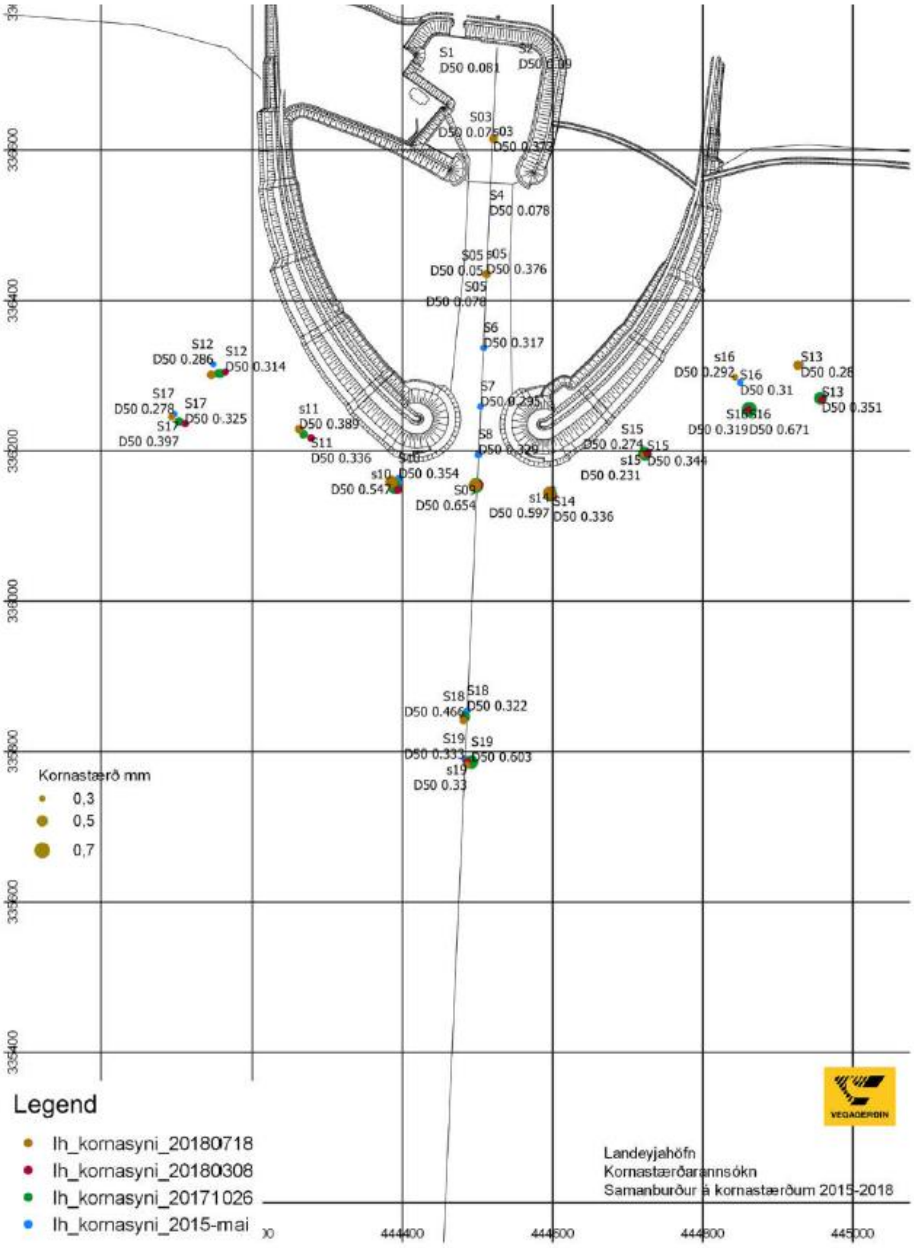


Figure 7. Bed material size (d_{50}) around Landeyjahöfn harbour (IRCA, 2018).

The sediment collection method was done by manually operating a 2 liter Van Veen grabber from a boat. The main results of May 2015 to July 2018 are summarized, as follows:

- Inside the harbour: More fine material and a smaller d_{50} from 0.1 to 0.4 mm.
- Harbour mouth: d_{50} varies between 0.3 and 0.7 mm.
- East of the harbour: d_{50} varies between 0.2 and 0.7 mm.
- West of the harbour: d_{50} varies between 0.3 and 0.4 mm.
- Outer bar area: d_{50} varies between 0.3 to 0.6 m.
- Sediment is somewhat coarser (d_{50} between 0.4 and 0.7 mm) in October 2017 after storm impact.
- d_{10}-values of samples outside harbour mouth are in the range of 0.15 to 0.25 mm.
- d_{90}-values of samples outside harbour mouth are of the order of 1 mm.

3.4 Morphology

The IRCA has carried out extensive bathymetry measurements at the coastline around Landeyjahöfn harbour in the past 20 years. The bathymetry measurements have been processed by the IRCA into a database of bathymetry data on a 20x20 m grid for the years 2002-2023, a total of 101 datasets. The bathymetry measurements vary greatly in extent with the focus on the area inside and in front of the harbour as shown in Figure 8 where statistics of the available bathymetry data is shown, including number of datapoints, range of values and standard deviation of measurements.

An overview of previous studies on morphology and sediments has been given in the independent study on the harbour from 2020 (Mannvit et. al., 2020). Previous studies mostly cover morphological changes prior and just after the construction of the harbour in 2009, the period 2009-2012. In the reports of DHI from 2007 and 2013, a detailed analysis on the morphology in relation with main driving factors of morphological changes is presented. Their main findings were:

- The bathymetry at Landeyjahöfn harbour location consists of a bar-trough system at the west side of the harbour with local bar depressions for outflow of rip-currents located at the harbour location and east of it where the ever-meandering spit formation from the river delta of the Markarfljót river takes over.
- During some periods, the growth of a spit formation from the delta off the river mouth can be observed. This spit is growing towards the west. However, the spit is not observed to have reached the location of the harbour. It is noted that the events with west-going transport and spit growth have typically been followed with periods of east-going transport. The growth of the spit is not only limited by the transport capacity towards the west but also by the limited source of sand in the delta. The spit is often removed (eroded) during winter period with high waves.
- The outer bar system may be interrupted locally (depression) due to the generation of local rip currents. Such an interruption is often present at the harbour location, where a major outgoing flow pattern may occur as part of flow passing around the river delta.

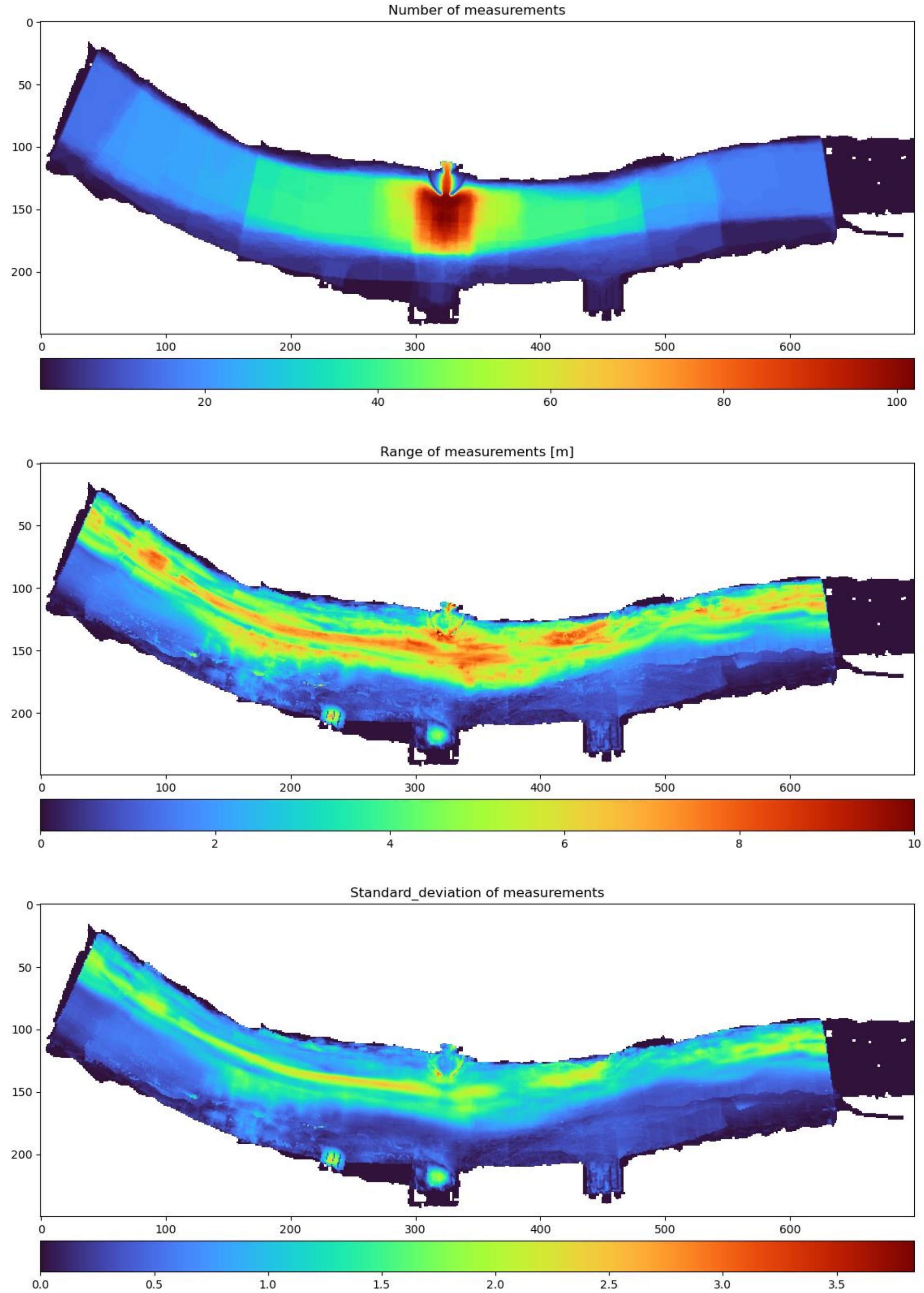


Figure 8. Statistics of available bathymetry data, horizontal and vertical scales given in meters (Vatnaskil and LVRS, 2023).

An analysis of the extensive collection of bathymetry data was carried out with the aim to shed light on the morphology over the past 13 years since Landeyjahöfn was open. For this purpose, various transects where defined at specified distances west and east of the navigation channel of Landeyjahöfn harbour. An overview of the transects is shown in Figure 9. Maintenance dredging was carried out regularly along the navigation channel to keep the bed level at -8 m to MSL as much as possible (mainly during the spring and fall period of each year). Hence, the transect data reflects both natural and artificial (dredging) bed level changes closest to the harbour.

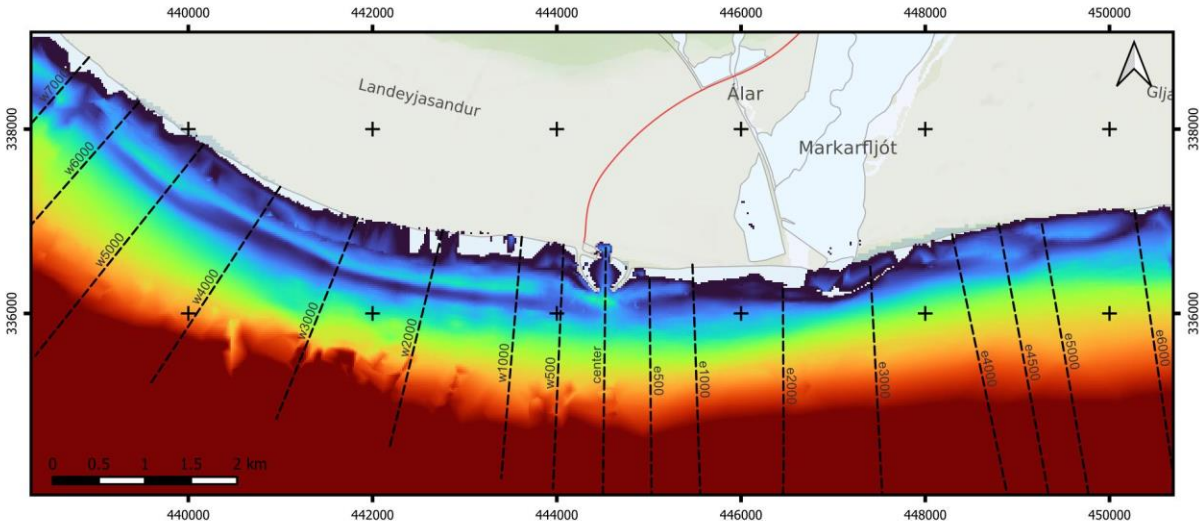


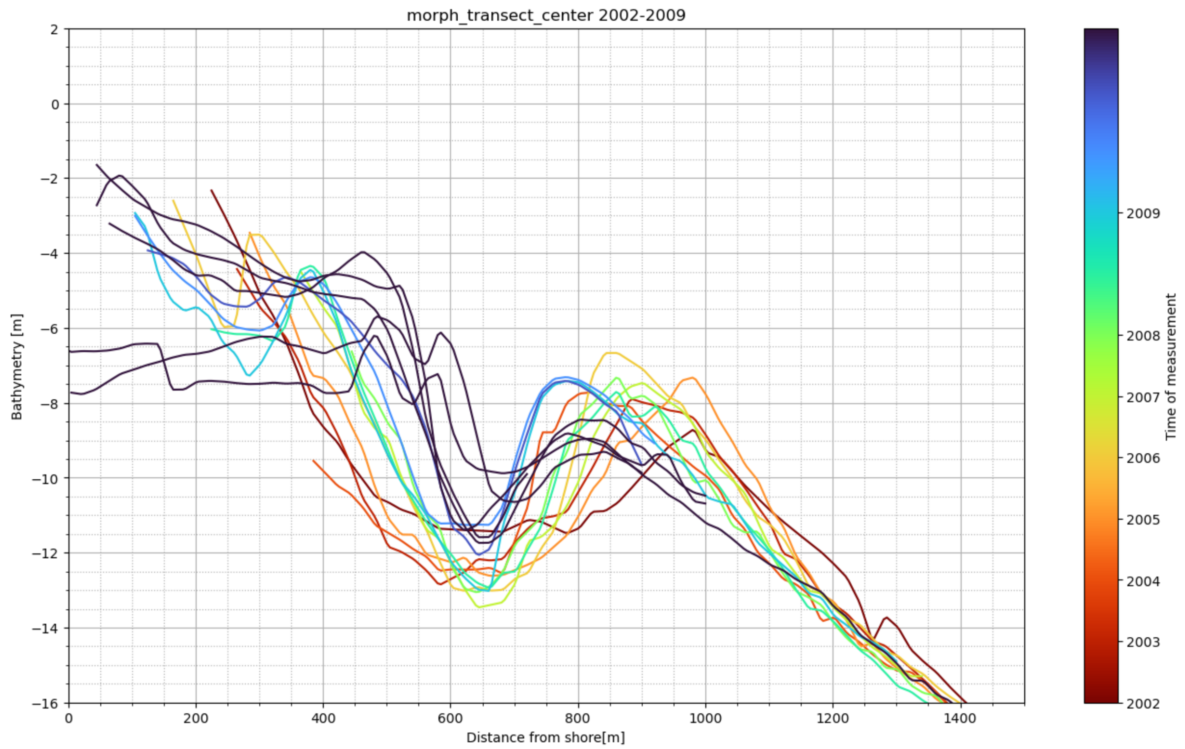
Figure 9. Transects near Landeyjahöfn harbour.

Measured bed profiles in the navigation channel are shown in Figure 10. Measurements covering the period before construction of the harbour (2002-2010) are shown at the top and measurements covering the period after construction (2010-2023) at the bottom. The bed profiles show fairly natural morphological patterns below mean sea level (mean sea level, MSL, is about 1.3 m above chart datum, CD) without typical dredging marks, mainly because most survey dates are well after the end of dredging activities. From the bed profiles some distinct features and phenomena can be observed, including an inner breaker bar in the period before harbour construction, an entrance bar in the period after harbour construction and prevailing outer breaker bar. Also, prior to construction a deep trough zone between both breaker bars in the zone between 100 and 250 m from the entrance is quite stable with a minimum depth of about -9 m below mean sea level. After construction the trough has widened substantially with the outer bar being pushed further offshore.

In Figure 11 measured bed profiles are shown for a transect located 1 km west of navigation channel. The profiles show similar pattern as can be observed in the navigation channel. The outer bar disappears in 2010 and then starts to form again. The outer bar has since then been pushing seaward to a location 800 – 1000 m offshore, a similar location observed since prior to the disappearance of the bar in 2010. DHI analysed the disappearance of the outer bar (DHI, 2013). They found out that the disappearance of the outer bar was caused by an extraordinary absence of waves from the west from July 2009 to December 2010 which usually cause transport towards to the east. This had the effect that the wave climate during this period was mild and the direction of the net littoral drift temporarily changed towards the west. This caused landward migration of the bar and filling of the trough, likely coupled with westward migration of the bar observed in the surveys from August 2010.

The newest measurements show the outer bar starting to recede back towards shore. Time will tell whether the shore migration further offshore has receded, and its former natural morphological cycle has been reached. In 0, bed profiles for transects further west are shown. They show the same behaviour as shown in Figure 11, with the natural morphological cycle being shorter and more dynamic in the transects further westward of the harbour.

In Figure 12 measured bed profiles are shown for a transect located 1 km east of the navigational channel. The profiles show different pattern than can be observed west of Landeyjahöfn harbour with a bar forming close to shore but being pushed offshore until it diminishes and a new one is formed again close to shore. There is more rapid cycle of bathymetric changes east of Landeyjahöfn harbour, this can be observed in bed profiles for transects further to the east shown in 0.



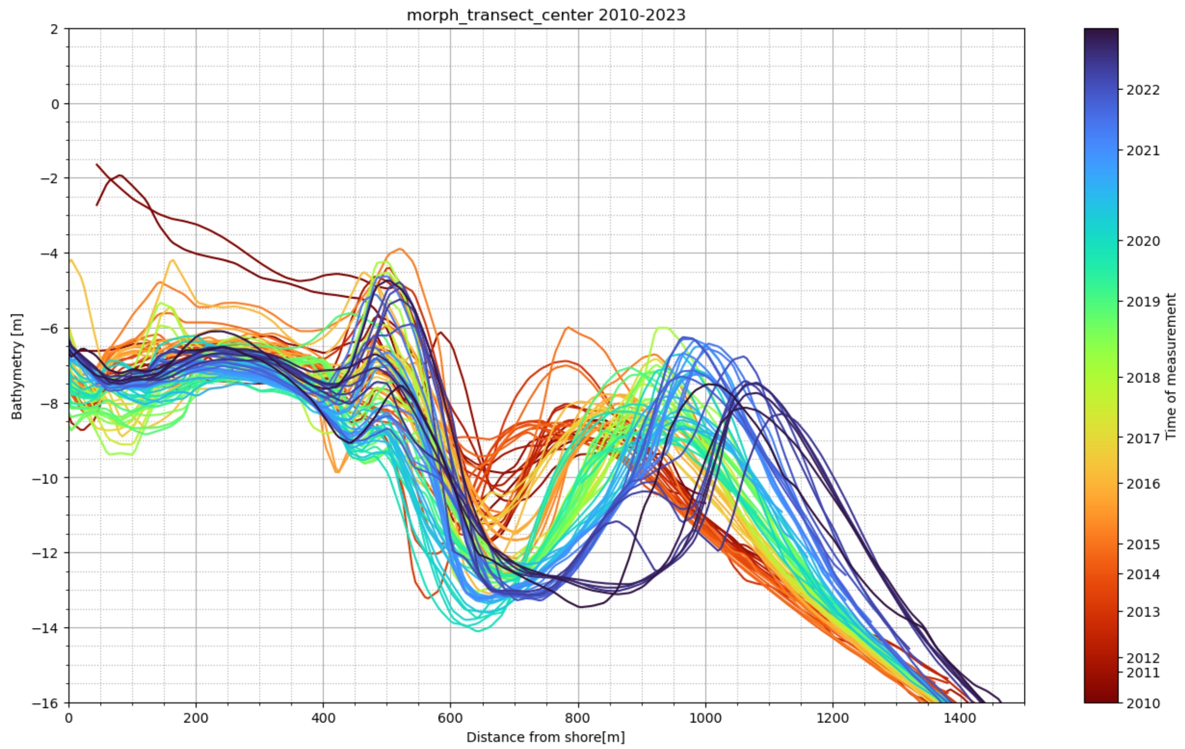
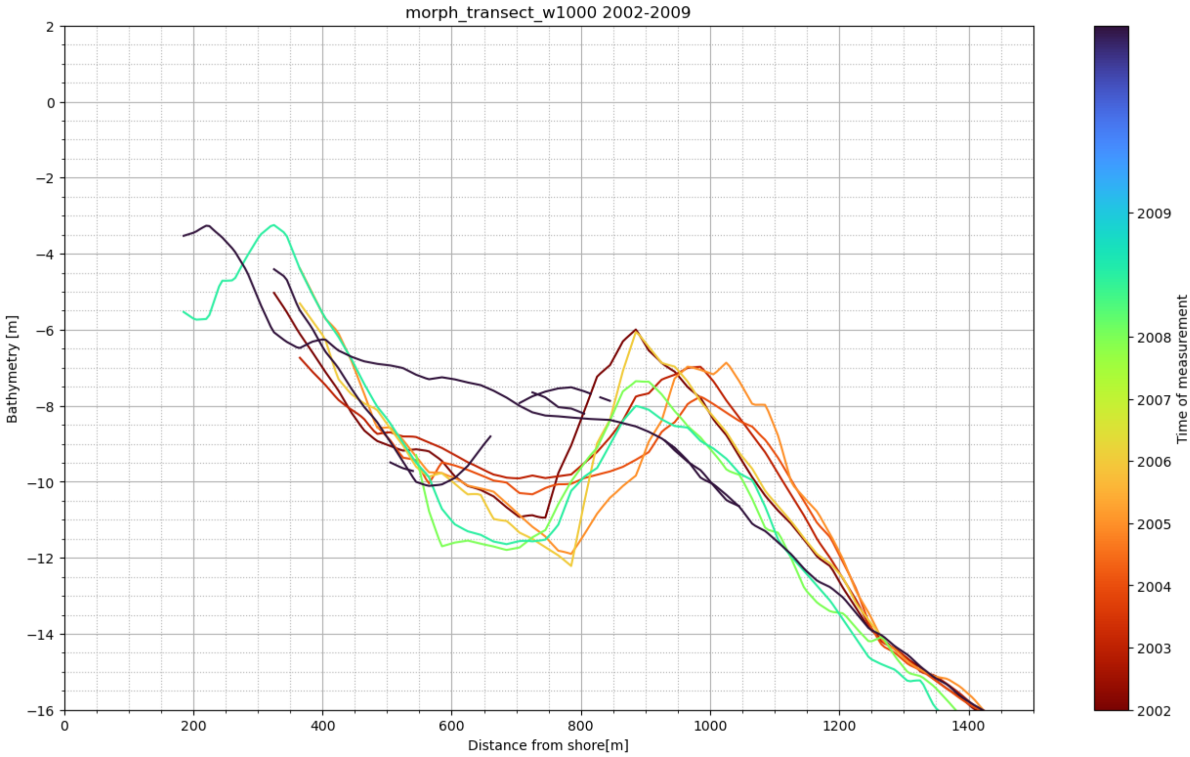


Figure 10. Measured bed profiles in the navigation channel. Top, measured bed profiles before construction (2002-2010) of Landeyjahöfn harbour. Bottom, measured bed profiles after constructions of Landeyjahöfn harbour (2010-2023). Bathymetry levels referenced to mean sea level (MSL).



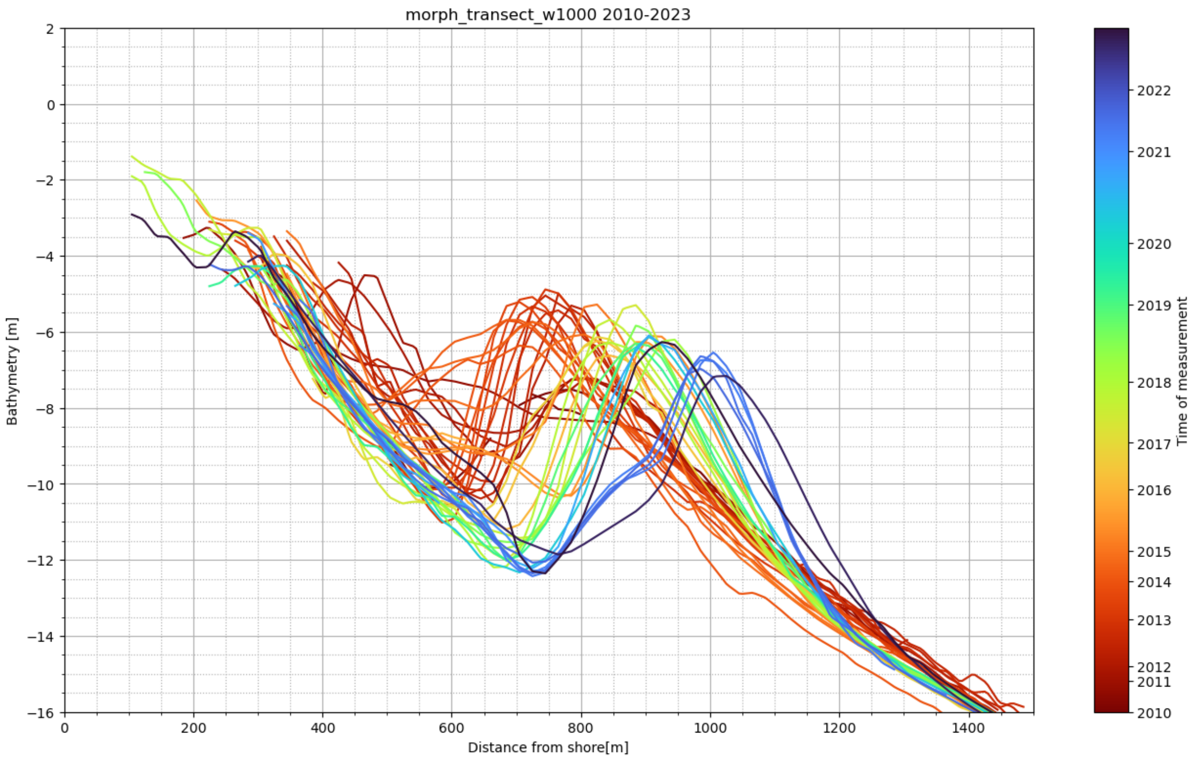


Figure 11. Measured bed profiles 1 km west of navigation channel. Top, measured bed profiles before construction (2002-2010) of Landeyjahöfn harbour. Bottom, measured bed profiles after constructions of Landeyjahöfn harbour (2010-2023). Bathymetry levels referenced to mean sea level (MSL).

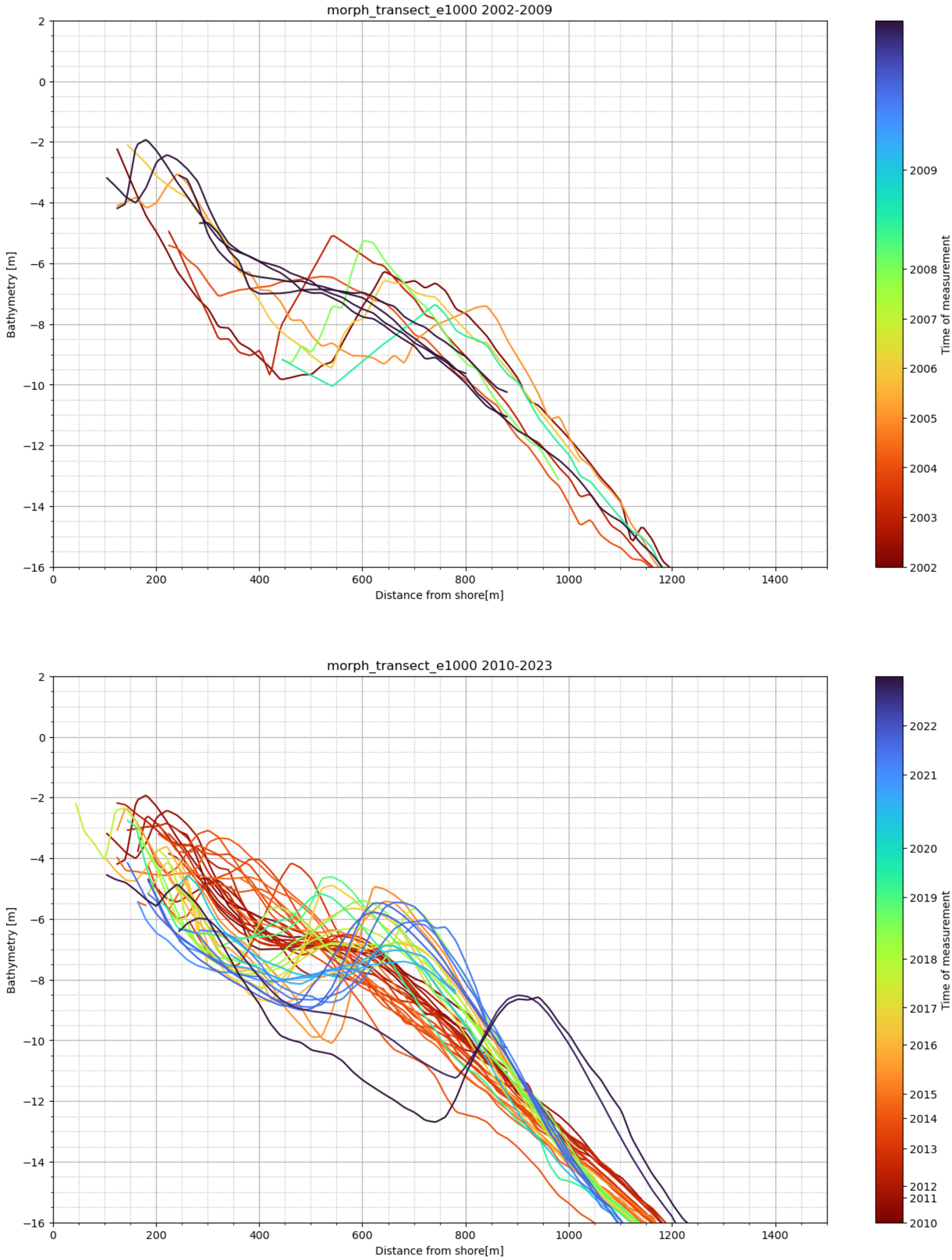


Figure 12. Measured bed profiles 1 km east of navigation channel. Top, measured bed profiles before construction (2002-2010) of Landeyjahöfn harbour. Bottom, measured bed profiles after constructions of Landeyjahöfn harbour (2010-2023). Bathymetry levels referenced to mean sea level (MSL).

Viggosson et al. (2005) presented seven sets of aerial photos from 1954 to 2000 and discussed the dynamic behaviour of the river mouth, Markarfljót River, east of Bakkafjara, where Landeyjahöfn harbour was planned at that time. The river mouth seemed to display a cyclic pattern in time, where in 1996 it returned to its position in 1954, after migrating to the west with its most westward point in early 1970s and then migrating eastwards to its former position (Figure 13). They further concluded that the migration of the river mouth affects the transport pattern and associated erosion and accumulation of material in the vicinity of the mouth.

DHI (2006) analyzed the long-term shoreline developments based on these seven aerial photos from 1954 to 2000. They concluded that the historical shoreline had been rather stable around the planned (at that time) harbour location, with shoreline variability up to 300 m to the east of the location and 100 m to the west of the location.

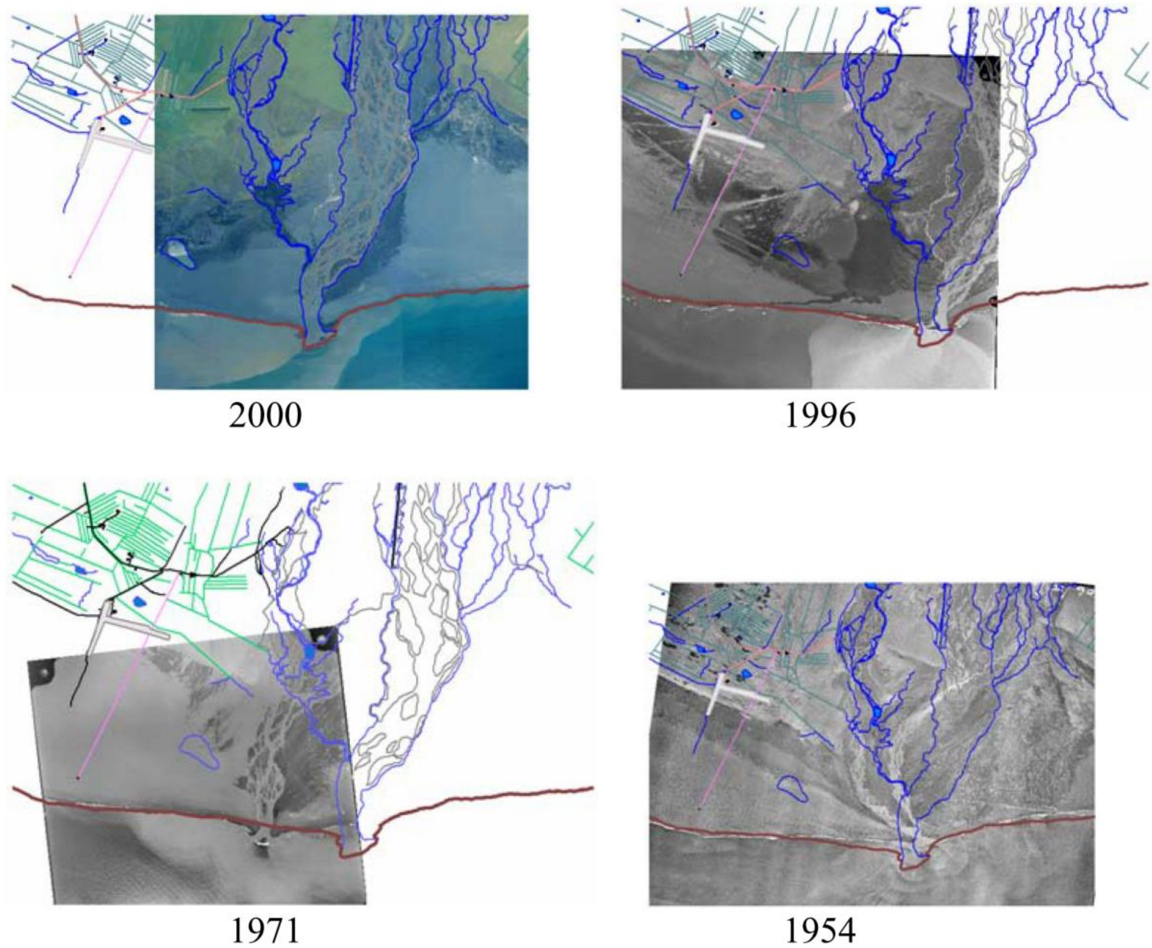


Figure 13. Aerial photos from the area around Bakkafjara (Viggosson, et al. 2005).

In Figure 14 aerial and satellite photos of Landeyjahöfn harbour are shown. The effects of the Eyjafjallajökull eruption in 2010 can clearly been seen on the east side of the harbour. The coastline east of the harbour has since then receded as can be observed from the aerial photos taken in 2022.

Aerial photos taken 2011 (Loftmyndir ehf)

Satellite photos taken 2013 (Google Maps)

Aerial photos taken 2017 (Loftmyndir ehf)

Aerial photos taken 2022 (Loftmyndir ehf)

Figure 14. Aerial and satellite photos of Landeyjahöfn harbour and coastlines in 2011, 2013, 2017 and 2022.

Wave climate has the most effect on morphological changes at the coastline where short-term wave conditions can have significant effect. During conditions with high waves coming to the shore at an angle to the shore normal, the outer bar is pushed offshore while in milder wave conditions waves push the outer bar to shore.

In Figure 15 wave conditions in 2015 are compared to measured bathymetry profiles from the same year at a transect located 1 km west of Landeyjahöfn harbour. In the top of the figure total weekly wave energy is shown, in the middle of the figure mean weakly wave angle from the shore normal is shown (+ waves from West and - from East) and in the bottom measured bathymetry profiles are shown. For the wave energy and angle, weekly values for all years in the calculated wave series are shown in the background for comparison. The wave climate in the beginning of 2015 was extreme compared to previous years which lead to the outer bar moving nearly 100 m just over the winter months (18. January – 7. May). During that period, especially in the first and second week of March high wave energy from the Southwest (>25° from shore normal) lead to this migration.

The behaviour is the opposite in 2016, with milder wave climate the outer bar is pushed ashore as measured profiles from January and April that year clearly show (Figure 16).

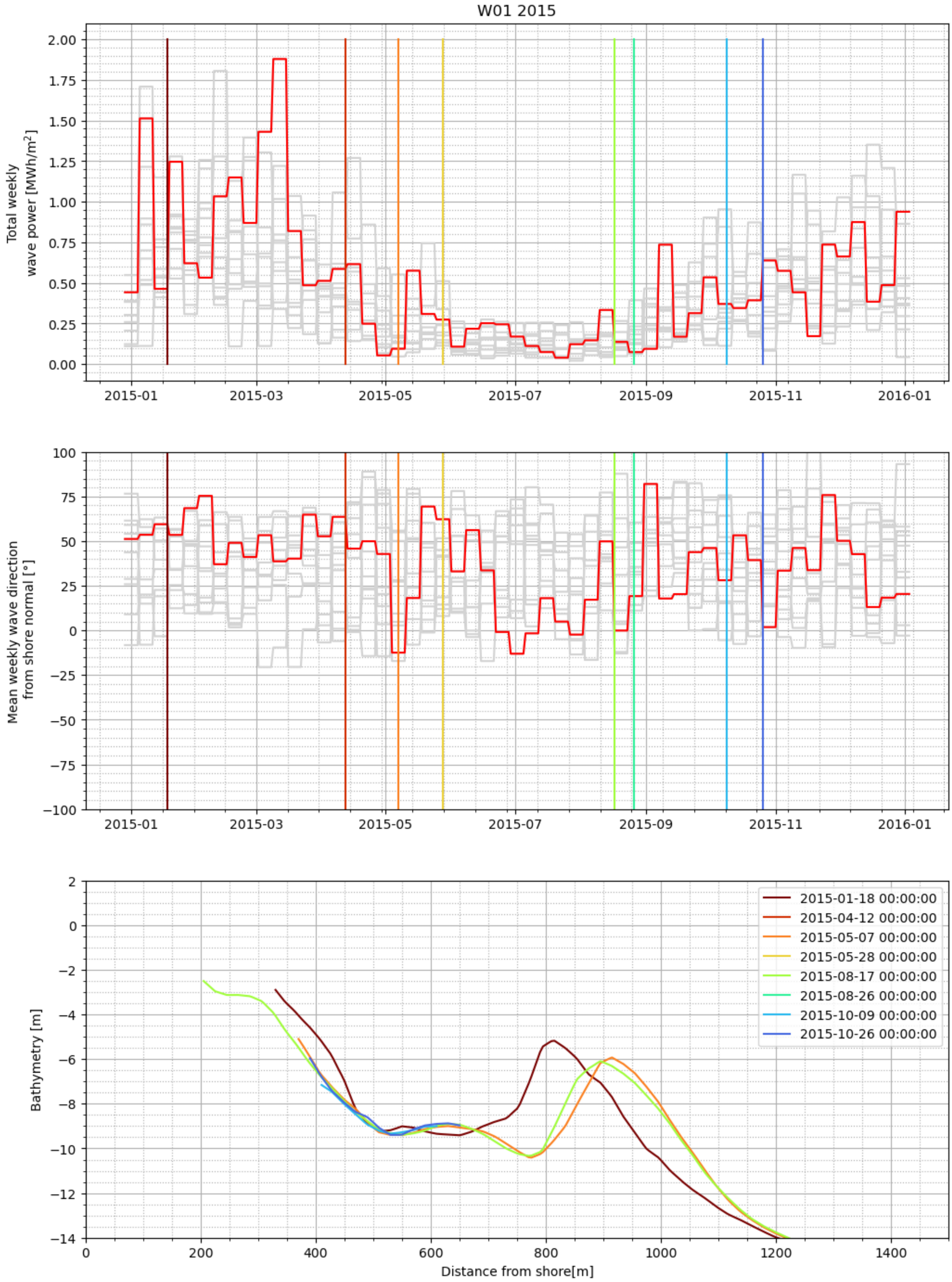


Figure 15. Mean weekly wave energy and wave angle from shore normal compared to bathymetry measurements transect located 1 km west of Landeyjahöfn harbour. Bathymetry measurements from 2015, calculated weekly wave energy and wave angle from shore normal shown for 2015 (red), gray lines in top and middle show annual calculations covering the period 2011 and 2020. Vertical lines in top and middle show time of bathymetry measurements.

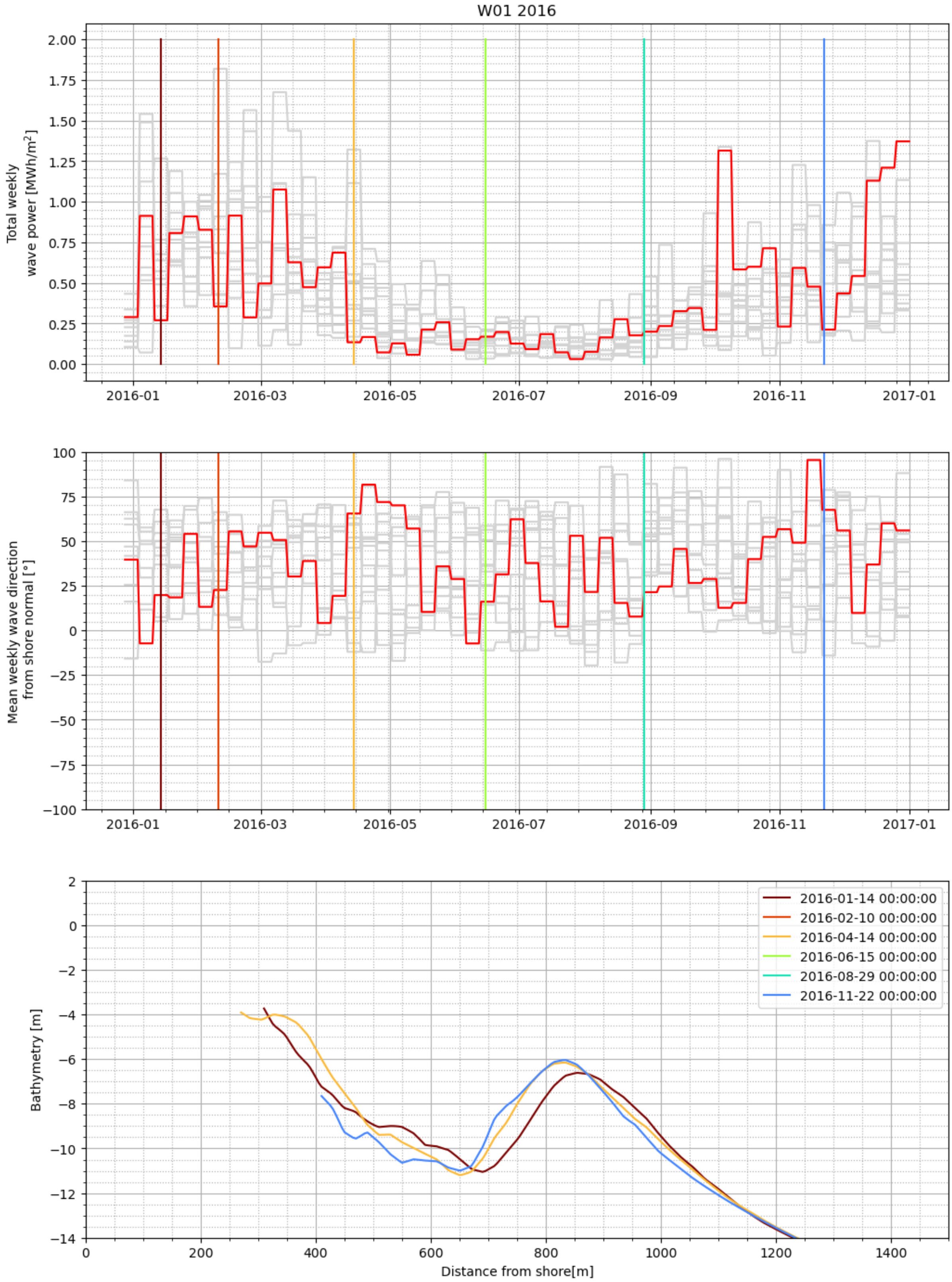


Figure 16. Mean weekly wave energy and wave angle from shore normal compared to bathymetry measurements transect located 1 km west of Landeyjahöfn harbour. Bathymetry measurements from 2016, calculated weekly wave energy and wave angle from shore normal shown for 2016 (red), gray lines in top and middle show annual calculations covering the period 2011 and 2020. Vertical lines in top and middle show time of bathymetry measurements.

The depth immediately seaward of the surf zone, where the wave forces can no longer produce a measurable change in bed elevation and thus in depth, is known as the closure depth of the morphological active zone (surf zone). The term 'measurable' should here be interpreted as being of the order of the survey accuracy (± 0.1 m). It does not mean that there is no sediment movement at the location of the closure depth, but the cross-shore gradient of the transport rates is too small to give measurable bed-level changes. Significant bed level changes may occur further onshore due to net migration of sand bars (breaker bars). The annual (value exceeded 12 hours per year) depth of closure is largely controlled by the position, volume, and migration of the outer bar.

The nearshore closure depth is related to the wave climate, the bottom slope, the sediment size, the time interval considered, and the criterion of depth change considered (fixed value <0.1 m). For example, the annual depth of closure (based on a fixed value of 6 cm depth change; sounding accuracy was 3 cm) at the Duck site (USA) varied between 5 and 8 m over a period of 12 years.

Quantitative estimates of the closure depth can be derived from Hallermeier (1981). He proposed a cross-shore zonation, consisting of three zones:

- Littoral zone extending to the seaward limit (depth = h_L) of intense bed activity caused by extreme near-breaking waves and currents.
- Shoal zone extending from depth h_L to depth h1 where the waves are likely to cause little or no sand transport.
- Offshore zone.

The littoral closure depth is annual value defined as the depth (below Mean Low Water Level) with minimum erosion (Hallermeier 1981 reports a value of less than 0.3 m) for extreme wave conditions (wave height exceeded 12 hours per year). Calculations based on the Hallermeier-Equation show that closure depth at the south coastline close to Landeyjahöfn is close to 19 m below MSL.

The Hallermeier-Equation represents a practical rather than a precise definition because it is not clear what is meant by minimum erosion. Another problem is the variation of storm intensity from year to year, which may result in large variation of the annual closure depth.

The closure depth can be seen as the seaward limit of the nearshore equilibrium profile. It gives an estimate of the seaward boundary for numerical coastal models and for sediment budget calculations.

3.5 Longshore sand transport

The LST-equation of Van Rijn (2014) was used to compute the longshore transport values (LST) around Landeyjahöfn. The LST-model has been used to compute the LST-components at 6 locations (Figure 3) on the west and east side of Landeyjahöfn harbour over the time period 2011 to 2020 (10 years). The basic characteristics of the locations are given in Table 2. The beach material consists of medium coarse black sand of volcanic origin as described in section 3.3.

Table 2. Characteristics of LST-locations.

Location	Distance to harbour (km)	Shore normal angle to North (degrees)	Offshore depth of wave data (m to MSL)	Median sediment size d_{50} (mm)	Beach and surf zone slope (tanβ) (-)
W20	20, West	46	21.5	0.4	0.02
W10	10, West	44	21.5	0.4	0.02
W01	1, West	5	21.5	0.4	0.02
E01	1, East	5	21.5	0.4	0.02
E10	10, East	5	21.5	0.4	0.02
E20	20, East	16	21.5	0.4	0.02

The wave data at these locations W20 to E20 are based on wave modelling described earlier (section 3.2). Analysis of those series, including wave roses were presented in section 3.2. The computed LST-components are given in Table 3 and shown in Figure 17 and Figure 18. The variation range of the annual net LST-values is quite large from 1 million m^3/year to the East at W20 in year 2020 to -1 million m^3/year to West at E01 in year 2019. The LST-components are maximum 1.5 million m^3/year to East and -1.2 million m^3/year to West.

Furthest west at location W20 the LST is highest 1 million m^3/year to East in year 2020 while the lowest calculated LST is -80,000 m^3/year to West in 2013. The long-term net LST is about 565,000 m^3/year to East. At location W10 the net LST is highest 420,000 m^3/year to East in 2020 while the lowest net LST is -155,000 m^3/year to West in y2019. The long-term net LST is about 110,000 m^3/year to East. Closest to the harbour at location W01 the net LST is highest 755,000 million m^3/year to East in year 2015 while the lowest net LST is -325,000 m^3/year to West in 2019. The long-term net LST is about 250,000 m^3/year to East.

East of Landeyjahöfn harbour at location E01 the net LST is highest -1 million m^3/year to West in year 2019 while the lowest net LST is -210,000 m^3/year to West in 2011. The long-term net LST is about -500,000 m^3/year to West. Further east at location E10 the net LST is highest 650,000 m^3/year to East in 2015 while the lowest net LST is -325,000 m^3/year to West in 2019. The long-term net LST is about 175,000 m^3/year to East. At location E20 the net LST is highest 650,000 m^3/year to East in 2015 while the net LST is lowest -675,000 m^3/year to West in 2019. The long-term net LST is about 30,000 m^3/year to East.

High annual LST-values to East are related to more waves from south-west in that year and vice versa. On the west side of the harbour, the net LST-value decreases from about 565,000 m^3/year to East at location W20 to about 250,000 m^3/year to East at location W01 (see Figure 19), which means a net deposition of about 300,000 m^3/year on the west side of the harbour.

On the east side of the harbour, the net LST is about 500,000 m^3/year to West at location E01 and in the range of 30,000-175,000 m^3/year to East at locations E10 and E20.

Table 3. Calculated annual longshore sand transport at specified locations for the years 2011 to 2020.

		Annual longshore sand transport (m³/year)										
		2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**Average**
W20	LST net	784000	635000	-82000	530000	956000	482000	477000	515000	313000	1026000	**563600**
	to East	1010000	800000	380000	734000	1304000	780000	703000	862000	643000	1252000	**846800**
	to West	-226000	-165000	-461000	-204000	-348000	-298000	-226000	-347000	-330000	-226000	**-283100**
W10	LST net	217000	247000	95000	94000	199000	-75000	93000	-14000	-155000	421000	**112200**
	to East	660000	557000	490000	502000	852000	475000	499000	615000	433000	860000	**594300**
	to West	-443000	-311000	-396000	-408000	-654000	-549000	-407000	-628000	-587000	-439000	**-482200**
W01	LST net	716000	344000	-22000	46000	756000	312000	139000	-170000	-326000	702000	**249700**
	to East	1226000	796000	706000	794000	1418000	979000	686000	820000	665000	1273000	**936300**
	to West	-511000	-453000	-727000	-748000	-663000	-667000	-547000	-989000	-991000	-571000	**-686700**
E01	LST net	-212000	-234000	-576000	-603000	-381000	-524000	-402000	-887000	-976000	-231000	**-502600**
	to East	456000	328000	295000	305000	523000	340000	303000	352000	249000	499000	**365000**
	to West	-668000	-561000	-871000	-907000	-903000	-863000	-704000	-1239000	-1225000	-729000	**-867000**
E10	LST net	546000	253000	-41000	-28000	653000	248000	96000	-196000	-325000	551000	**175700**
	to East	958000	621000	571000	622000	1173000	790000	549000	617000	520000	1024000	**744500**
	to West	-412000	-369000	-611000	-649000	-521000	-543000	-454000	-812000	-845000	-474000	**-569000**
E20	LST net	514000	206000	-253000	-231000	651000	99000	-33000	-526000	-676000	527000	**27800**
	to East	1137000	758000	692000	747000	1475000	940000	661000	735000	605000	1285000	**903500**
	to West	-624000	-552000	-945000	-977000	-824000	-842000	-694000	-1260000	-1281000	-759000	**-875800**

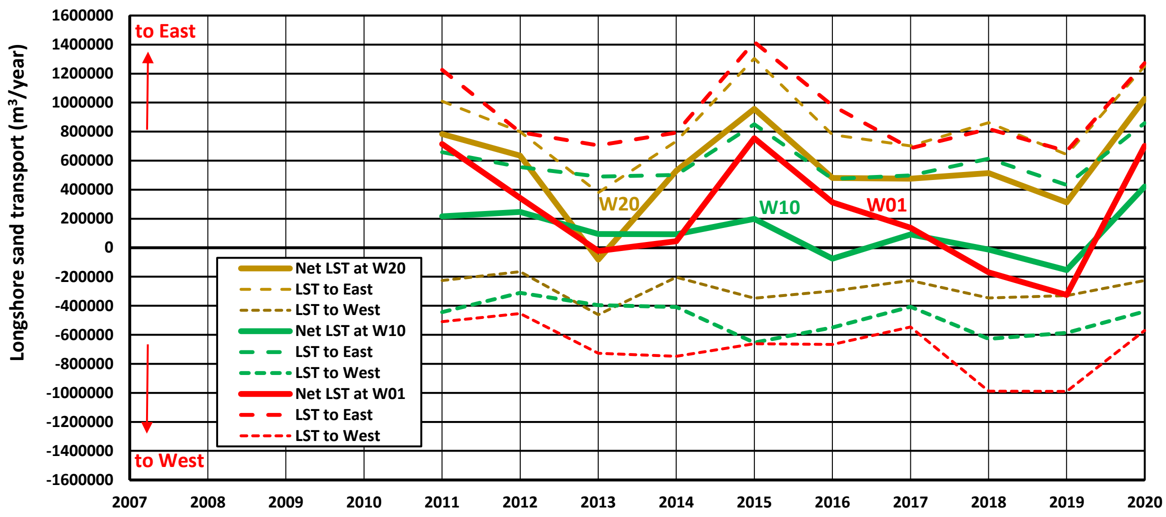


Figure 17. LST-components at locations W20, W10 and W01 in period 2011-2020.

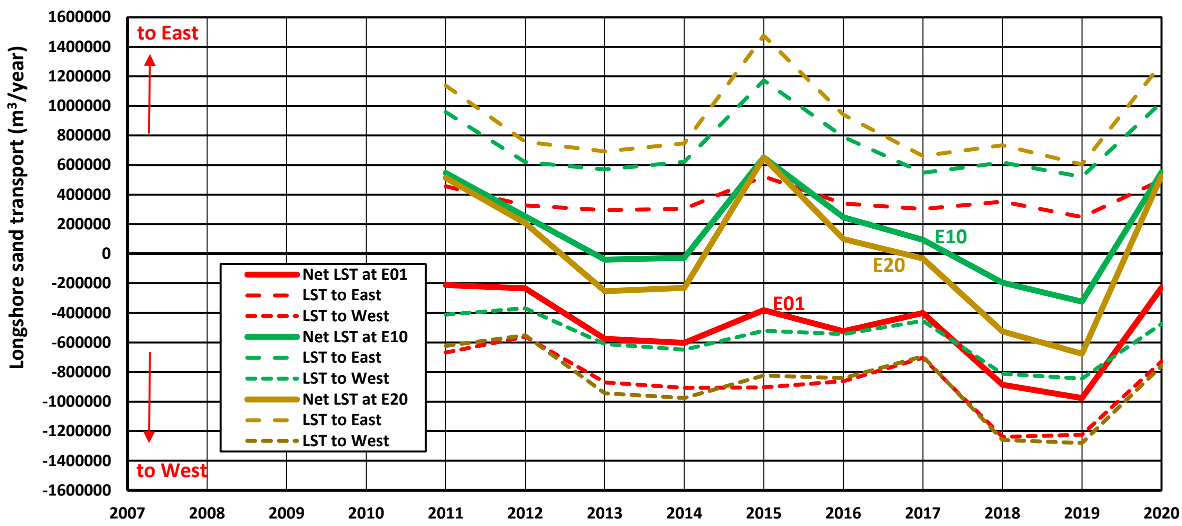


Figure 18. LST-components at locations E01, E10 and E20 in period 2011-2020.

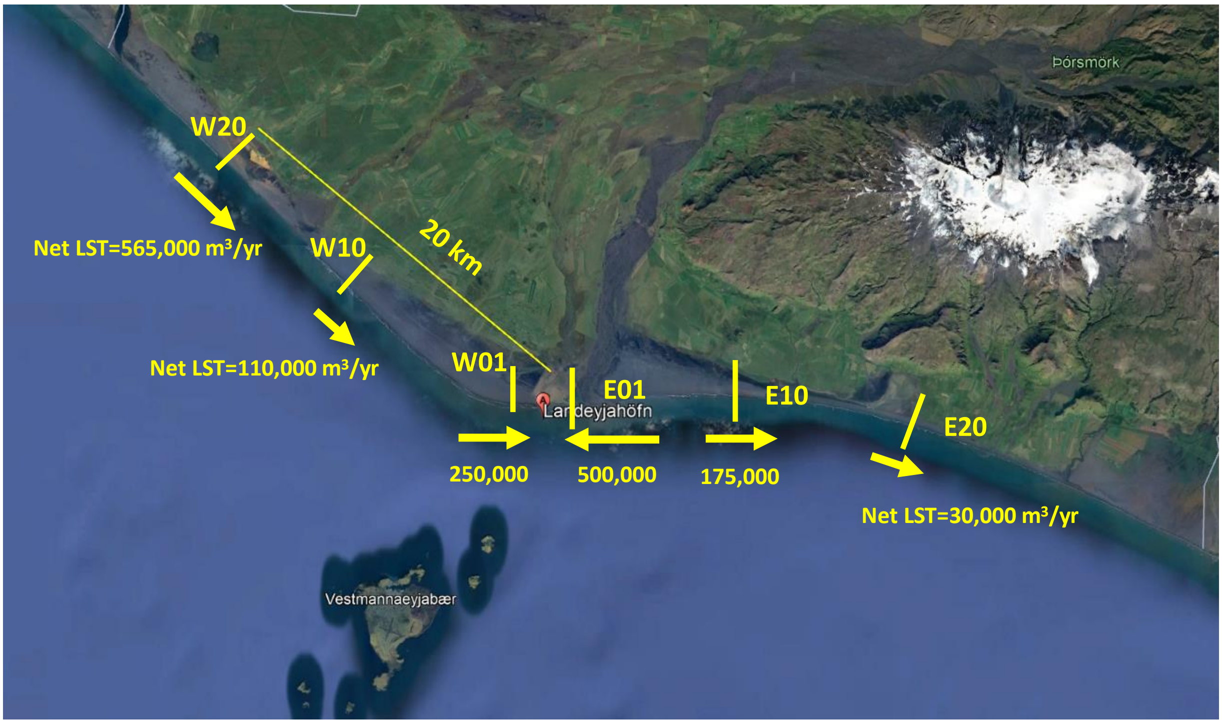


Figure 19. Locations of LST-computations and net LST values and direction of LST.

Coastline observations since the construction of the harbour in 2011 are shown in Figure 14 see also Figure 13. Some accretion is visible on the east side of the harbour, which is in qualitative agreement with the net LST of about 500,000 m^3/year to West at E01 (about 1 km east of harbour). Most of this net LST is carried along the harbour by longshore currents.

The shoreface zone is defined as the zone seaward of the -15 m depth contour. The accurate determination of the net annual longshore transport (LST) in this zone requires detailed modelling efforts beyond the scope of the present study. Tide-induced flows are minor and do not contribute much to LST in this zone. The highest contribution to LST is from wave-induced flow during storm events with waves > 2 m.

Herein, it is assumed that the LST in the shoreface zone is of the same order of magnitude as the net LST in the surf zone resulting in a value of the order of 500,000 m^3/year to East at W20.

4 Modelling wave climate and morphological changes

In the previous sections a general description of coastal processes, coastal sand mining concepts and guidelines as well as environmental conditions at the south coast has been provided. Based on that discussion, mining of sand is only feasible seaward of the surf zone. Preferably, mining of sand is performed only seaward of the depth of closure line, which is the -19 m depth contour (see section 3.4). The surf zone, landward of the outer bar crest, is a relatively narrow strip (width<1000 m) with inner and outer breaker bar which act as the first line of defence against wave attack and coastal erosion. Mining of sand in this zone is likely to lead to degeneration of the breaker bars and ultimately to a more severe wave attack at the beach.

This sets the stage for general goals in the modelling effort in order to assess the effects of the planned mining activities on the wave climate and possible morphological changes including land erosion.

Given the dynamic and complex environmental conditions at the south coast challenges in the modelling effort must be addressed, especially with regards to the morphology and the inter-relationship with the wave climate. The Vatnaskil-LVRS modelling suite for the south coast (Vatnaskil and LVRS, 2023) was applied to meet these challenges to address in particular the following:

1. Effects of morphological changes on wave climate.
2. Effects of short-term wave climates on morphological changes.
3. Effects of large-scale mining in areas landward of the outer bar on nearshore wave forcing.
4. Effects of large-scale mining in areas offshore of the outer bar on nearshore wave forcing.

The first two items allow for establishing the behaviour in the system without mining activities stressing the interrelationships of the wave climate and morphological changes. Furthermore, the latter two items focus on the mining activities and their potential effects, put into perspective of the pre-mining behaviour.

4.1 Effects of morphological changes on wave climate

In Section 3.4 the dynamic morphology at the south coast was discussed. A prevalent feature is the frequent and often rapid change in location of the outer bar, with the bar migrating offshore closest to Landeyjahöfn harbour in the past decade. The location of the outer bar and the height of its crest affect the wave forcings acting on the coastline.

A sensitivity analysis was performed with regards to outer bar location and the effects on the nearshore wave climate. For the analysis, two representative bathymetry measurements for different locations of the outer bar were selected, the outer bar being closest to shore in 2013 and furthest offshore in 2022. For each bathymetry the calculated wave series between 2011 and 2021 was applied, see Section 3.2.

The difference between the selected bathymetry measurements is shown in Figure 20, where positive values indicate higher bottom elevations in 2022. As the outer bar is pushed further offshore a trough is gradually forming and deepening landward of the outer bar. Also, the outer bar gradually lowers as it is being pushed offshore, see Section 3.4.

The effect of the location of the outer bar on significant wave height is shown in Figure 21, where positive values indicate higher significant wave height in 2022. Differences for 50% and 90% percentiles for significant wave height are shown for the selected bathymetries. Between 2013 and

2022, the outer bar is being pushed offshore while the crest of the outer bar is lowered leading to less effective sheltering of the bar and higher waves reaching the shoreline west of Landeyjahöfn. However, east of the harbour towards Markarfljót river, less difference is observed since both in 2013 and 2022 the bathymetry has limited effect on the waves reaching shore. This can be seen in Section 3.4 for the transect east of the harbour where in 2013 an outer bar cannot be observed and in 2022 the outer bar has travelled offshore to a depth of 8 m. Thus only the highest waves are affected and reduced close to shore as can be seen for the 90% percentile.

Likewise, in Figure 22 the difference for 50% and 90% percentiles of orbital velocity are shown. Orbital velocity is the velocity of the roller formed when a wave breaks. Orbital velocity can be considered as an indicator of sediment transport or erosion. With increased orbital velocity, increased suspension of sediment can be expected. As expected with decreased height of the outer bar crest, larger waves reach the shoreline west of the harbour leading to an increase in velocity. In the trough, the velocity is decreased in tandem with deepening of the trough. An increase in velocity is also observed just landward of the outer bar location in 2022.

The analysis shows how natural morphological changes can effectively alter the forces acting on the coastline forming a previously described morphological cycle, see Section 3.4, where an outer bar is formed close to the shore and being pushed offshore. As the outer bar is pushed further offshore it lowers leading to larger waves reaching the shoreline again forming a new outer bar.

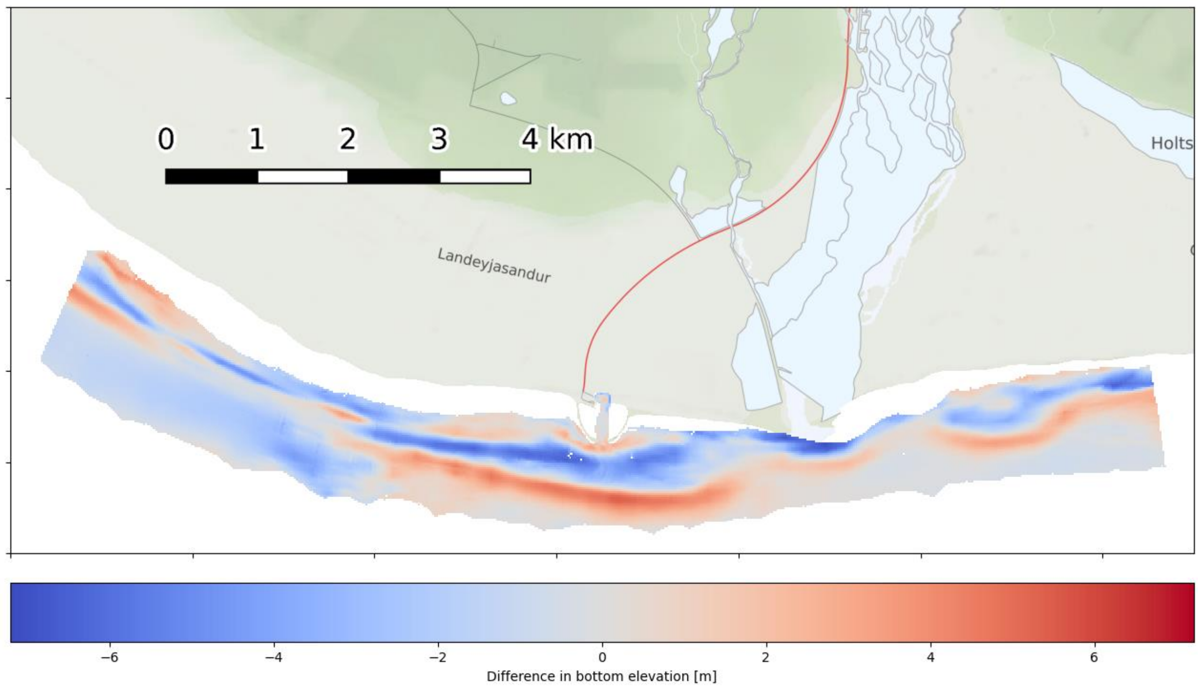


Figure 20. Difference of bathymetry measurements between 2013 and 2022 (2022-2013).

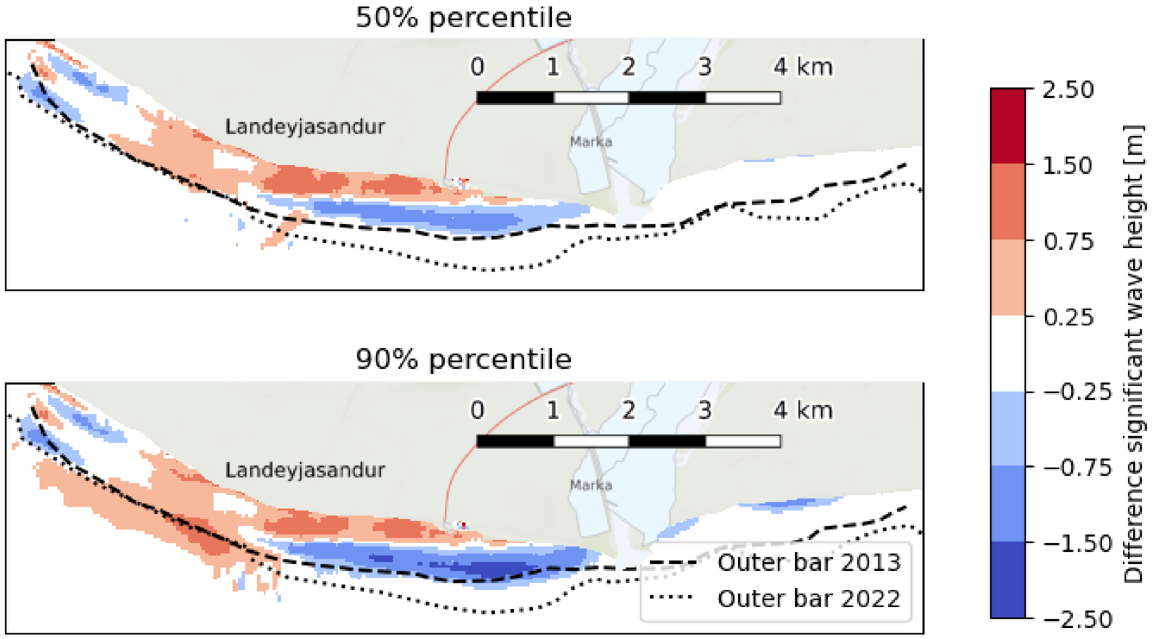


Figure 21. Difference of 50% (top) and 90% (bottom) percentiles of significant wave height. Calculations based on calculated wave climate between 2011 and 2021 for measured bathymetry of 2013 and 2022. Difference calculated as 2022 - 2013. Location of the outer bar shown as dashed (2013) and dotted lines (2022).

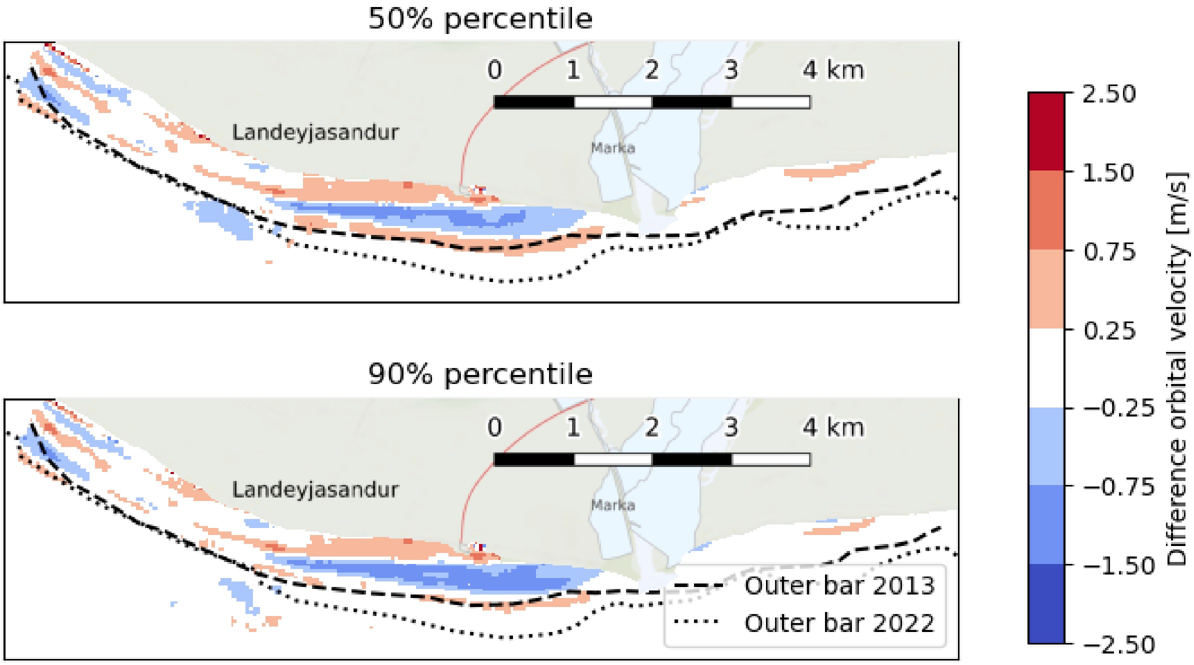


Figure 22. Difference of 50% (top) and 90% (bottom) percentiles of orbital velocity. Calculations based on calculated wave climate between 2011 and 2021 for measured bathymetry of 2013 and 2022. Difference calculated as 2022 - 2013. Location of the outer bar shown as dashed (2013) and dotted lines (2022).

4.2 Effects of short-term wave climate on morphological changes

For estimating the effects of variable short-term wave climate on sediment transport and morphology, two 15-day periods with significantly different wave climates were selected (Figure 23). Firstly, a calm summer period and secondly a relatively high energy winter period. For the computations, a common initial bathymetry from 2018 was used, assuming uniform grain size and unlimited bottom sediment thickness. This provides insights into the short-term effects on the morphology and the effect of morphological changes on the wave climate.

The bathymetry evolution in the simulated winter and summer events is shown in Figure 24 and figure 25 respectively. During summer minimal changes are observed while during winter, with powerful storms, the outer bar can move significantly. Dynamic and complex morphological behaviour of the outer bar can be observed in the winter simulation. The outer bar is pushed out in front of the harbour while it moves towards the coast on each side of the harbour. Further west in the model domain the bathymetry has a greater slope resulting in the bar moving outwards. The summer simulation captures the same general movements but on a much smaller scale.

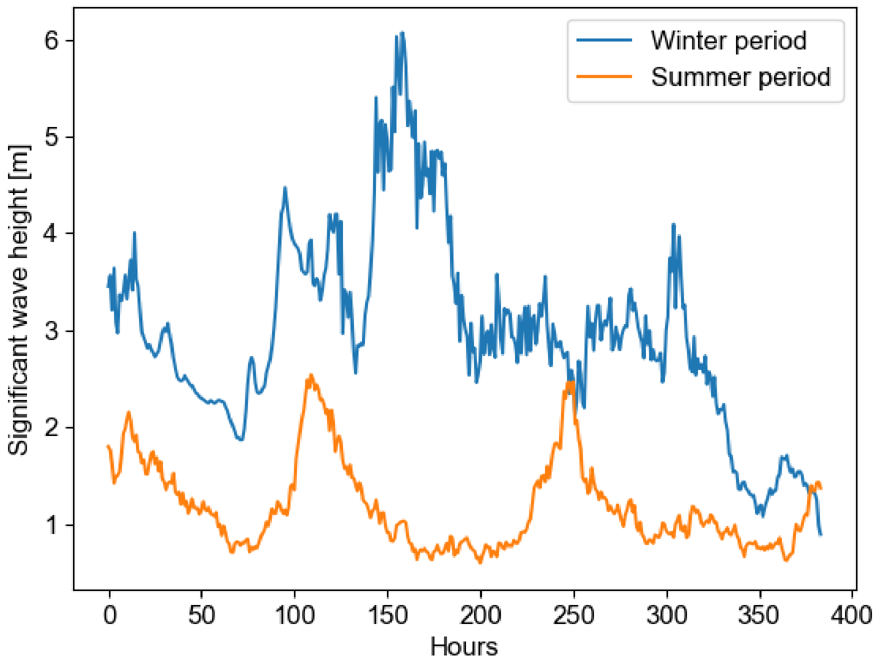


Figure 23. Wave height during the two wave periods used for the calculations.

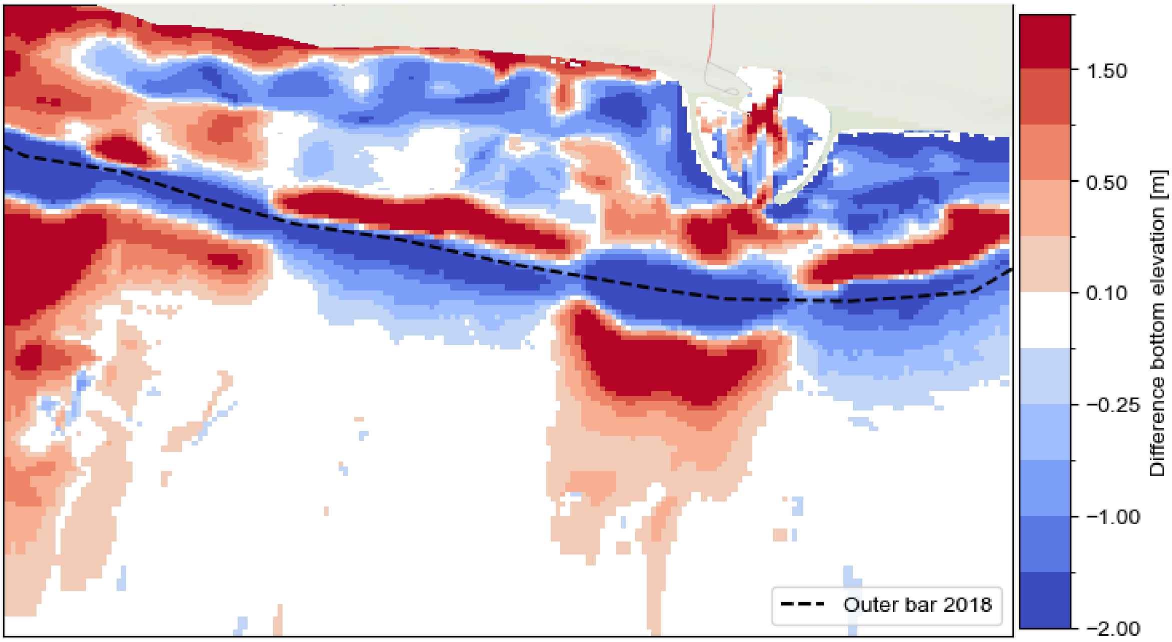


Figure 24. Bathymetry evolution over the winter period. Difference of bathymetry shown as the difference of inital bathymetry and the bathymetry after 15 days of runtime.

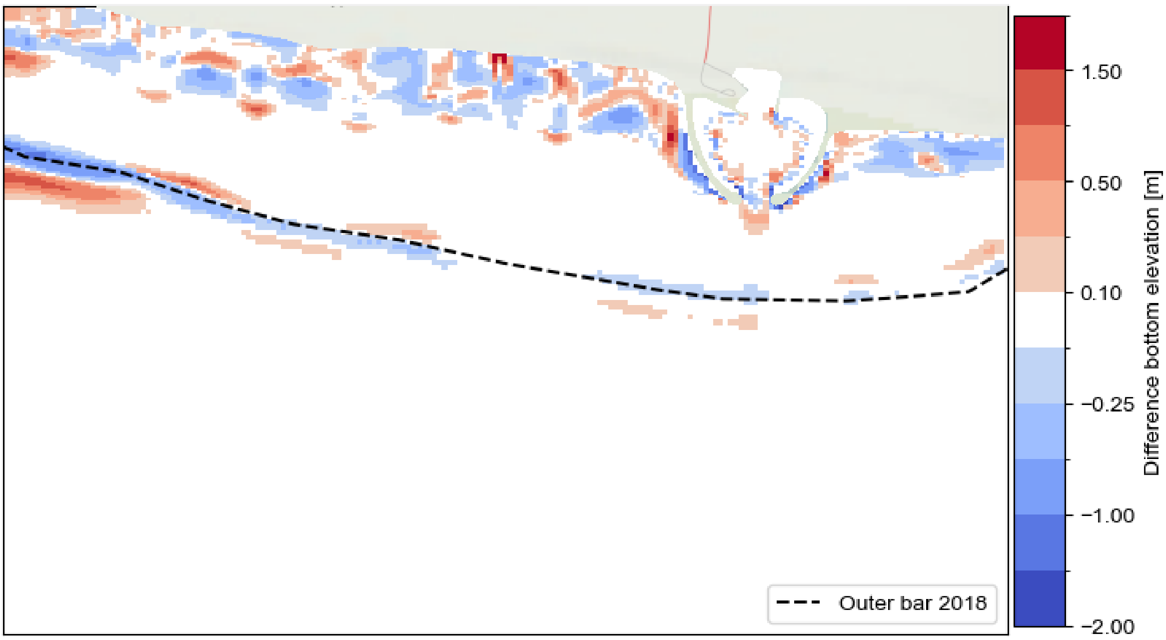


Figure 25. Bathymetry evolution over the summer period. Difference of bathymetry shown as the difference of inital bathymetry and the bathymetry after 15 days of runtime.

4.3 Effects of mining landward of the outer bar

As discussed earlier, mining of sand close to shore, landward of the closure depth, can have adverse effects on the morphology possibly leading to increased land erosion. To confirm and get a sense of the effects of nearshore mining on wave climate and morphology computations were performed to establish the sensitivity of various configurations of mining nearshore at the south coast, landward of the outer bar.

For sensitivity analysis of nearshore mining on long-term wave climate, two distinct mining strategy concepts were investigated. The mining strategies were compared to a baseline case where no mining had occurred.

The first scheme (scheme 1) assumes mining in 6-10 m depths on the coastal slope along most of the proposed mining area. This is a relatively narrow strip, approximately 120 m wide located approximately 300 m offshore, see Figure 26. A depth of half a meter is used, the corresponding volume is equivalent to one year of excavation (2 million cubic meters). The second scheme (scheme 2) assumes mining on 6-12 m depths on the coastal slope on four 2 km long and 250 m wide strips (Figure 27). A depth of 2 m is used, the volume is equivalent of the excavation of one year (2 million cubic meters).

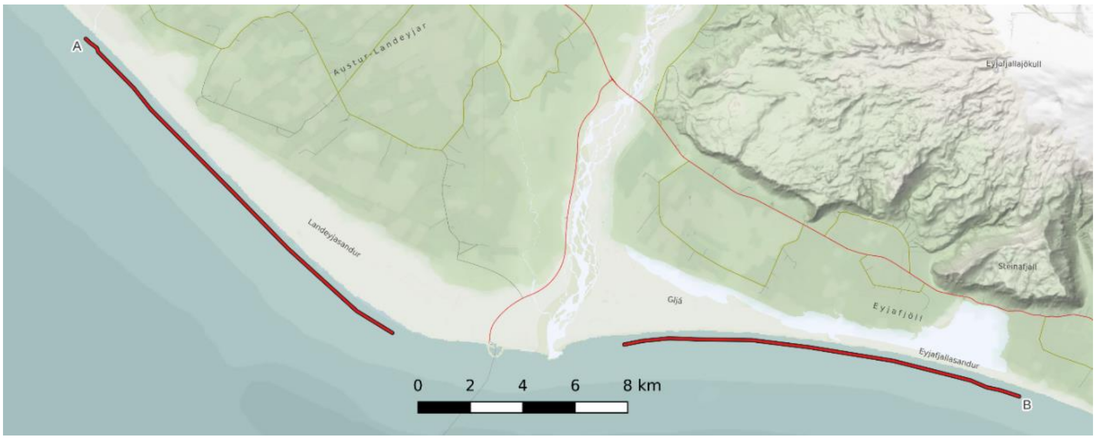


Figure 26. Near-shore mining areas, scheme 1, in Delft3D-SWAN calculations.

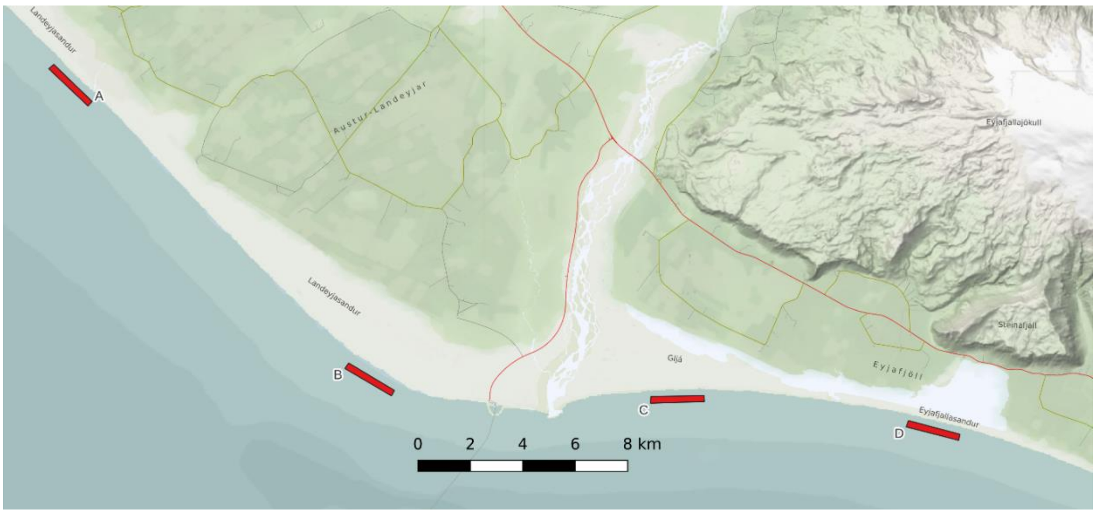


Figure 27. Near-shore mining areas, scheme 2, in Delft3D-SWAN calculations.

In Figure 28 difference in significant wave height for 50% and 90% percentiles is shown for the difference between mining according to scheme 1 and no mining. The results show as much as 0.2 m increase in significant wave height close to shore which is more than 3% relative difference which is above the 3% reference value of the IRCA for acceptable wave height changes nearshore of sand beaches (Section 2.2).

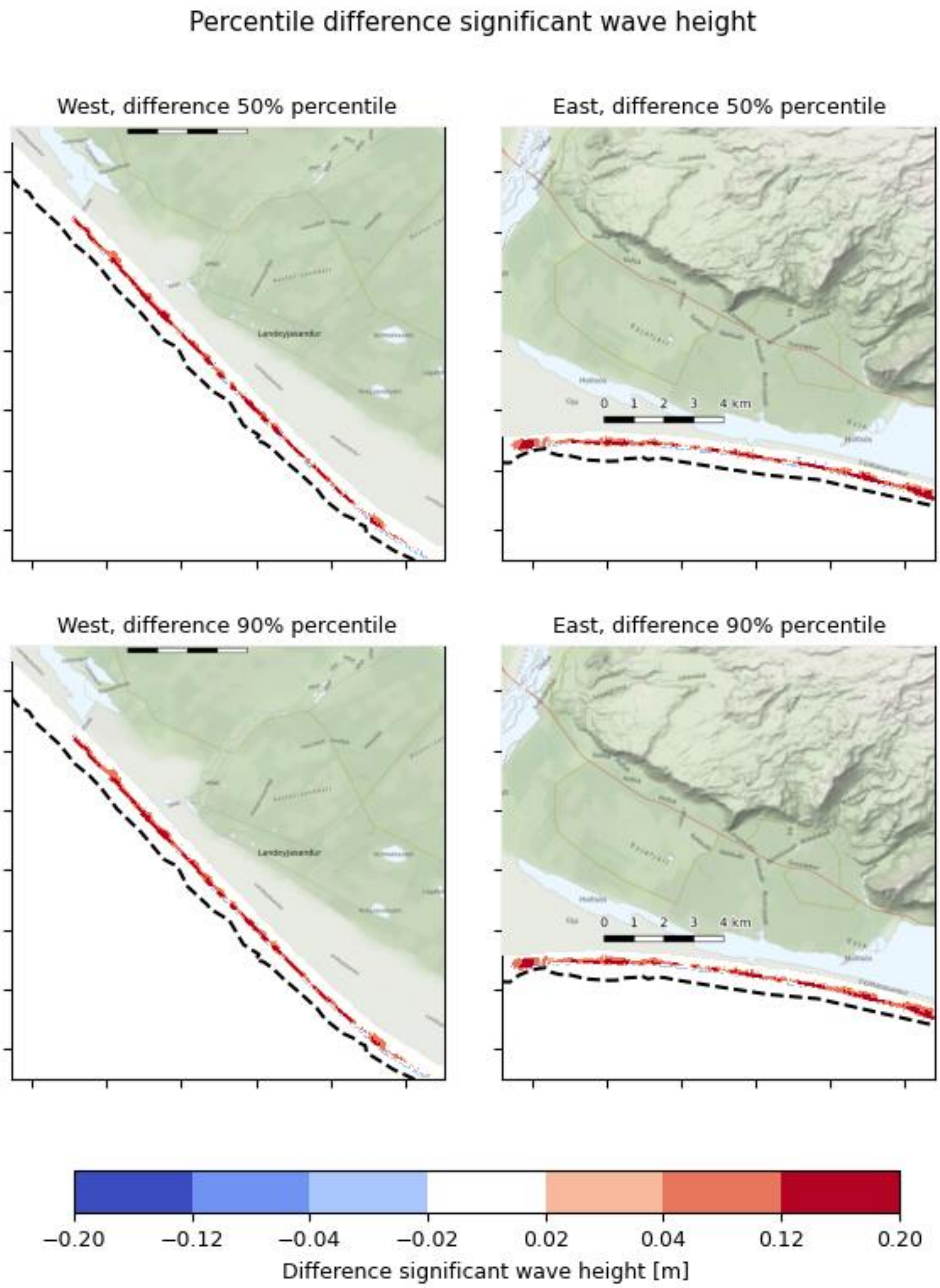


Figure 28. Difference in significant wave height, 50% and 90% percentile, between mining and no mining for scheme 1.

In Figure 29 the difference in wave height, 50% percentile, between mining and no mining (scheme 2) in areas A and B west of Landeyjahöfn harbour, and C and D east of the harbour is shown. The mining effects the significant wave height (difference > 0.8 m) in the nearest vicinity of the mining areas. The areas furthest east and west (A and D) from the harbour are more effected by the mining than those closer to the harbour (B and C). The relative difference (Figure 30) shows changes way above the 3% reference value of the IRCA for acceptable wave height changes nearshore of sand beaches (Section 2.2). The 90% percentile for the difference in wave height shows very similar results as the 50% percentile (Figure 31).

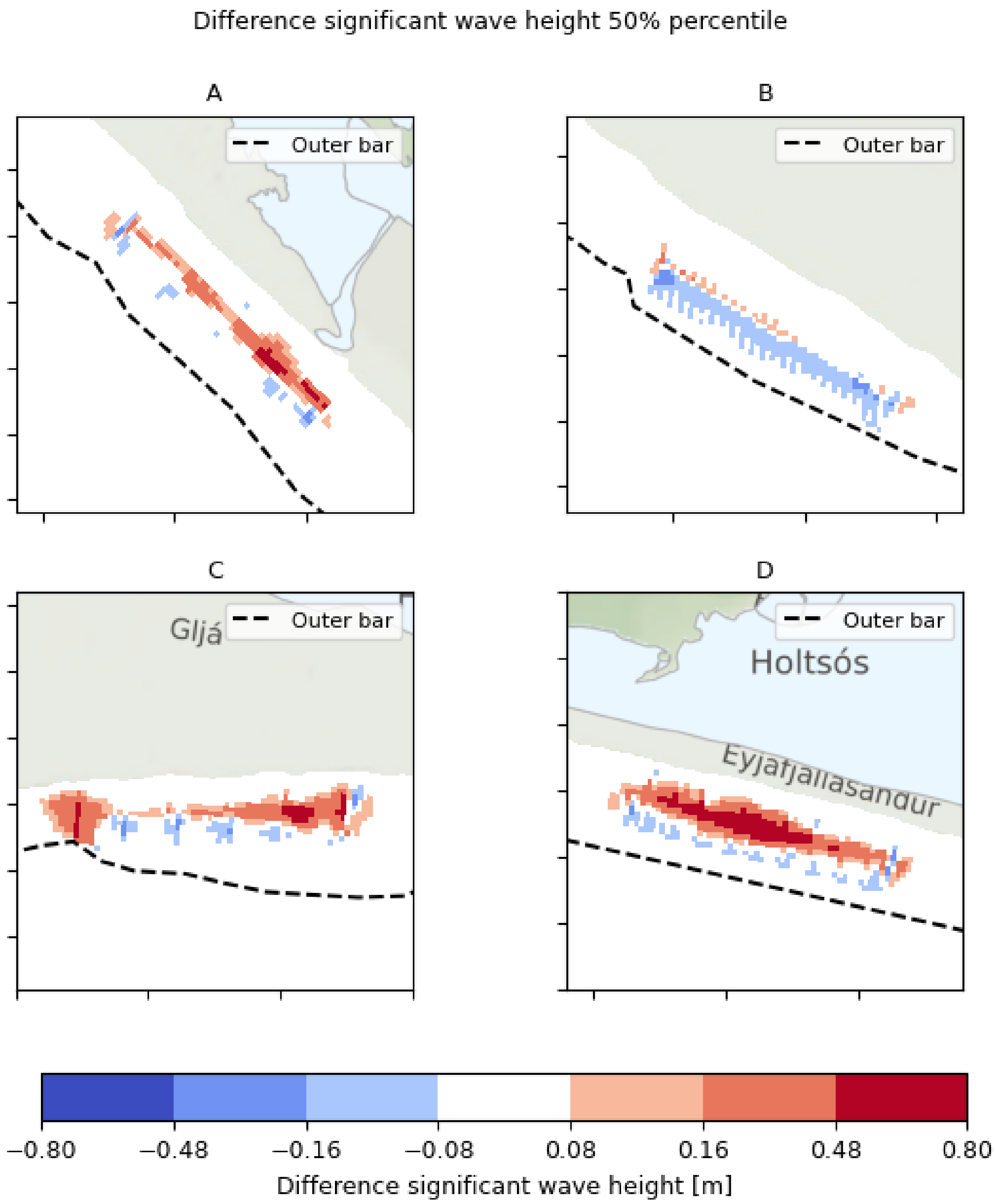


Figure 29. Difference in significant wave height, 50% percentile, between mining and no mining at specific areas; A and B west of Landeyjahöfn harbour, and C and D east of the harbour.

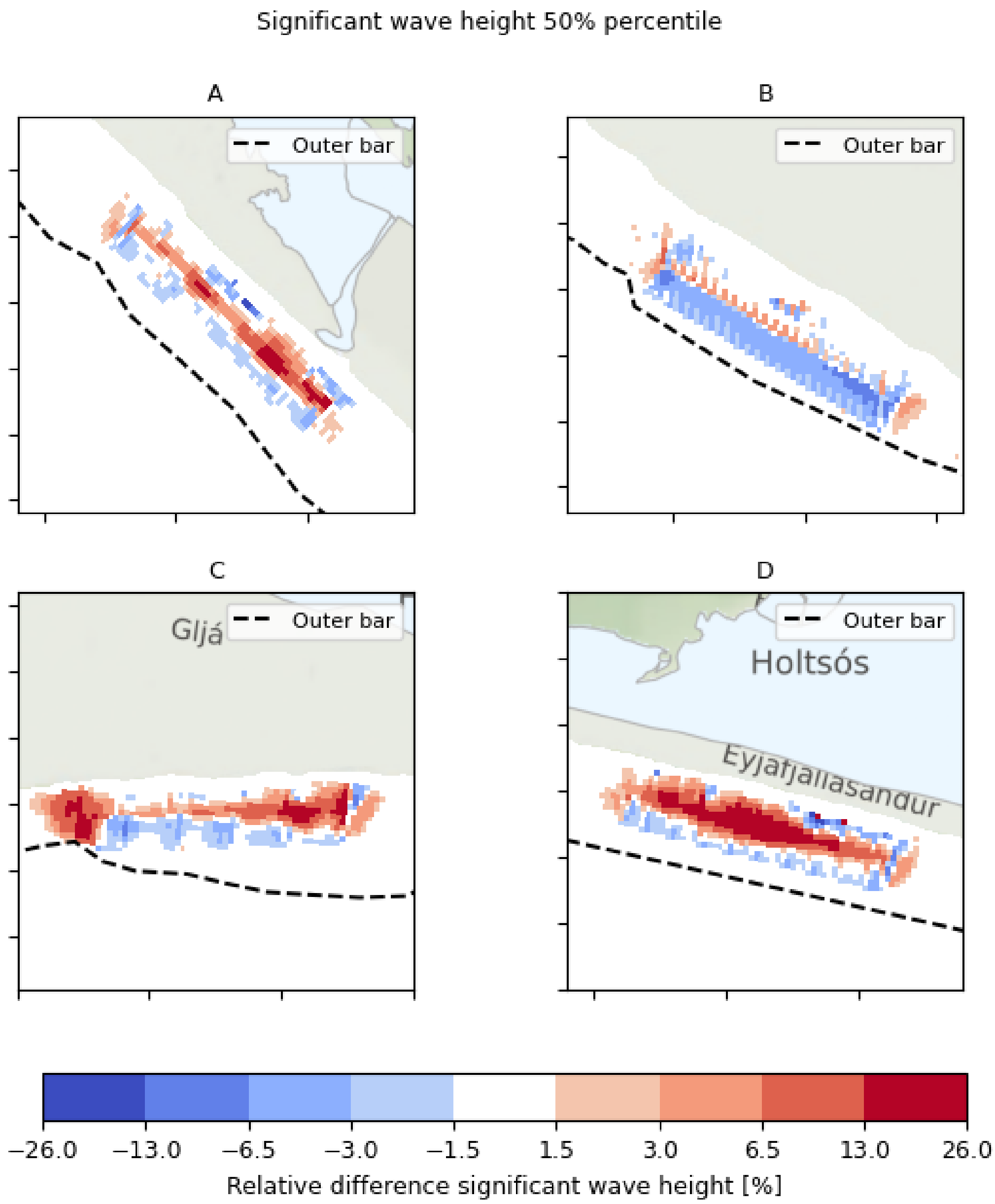


Figure 30. Relative difference (%) in significant wave height, 50% percentile, between mining and no mining at specific areas; A and B west of Landeyjahöfn harbour, and C and D east of the harbour.

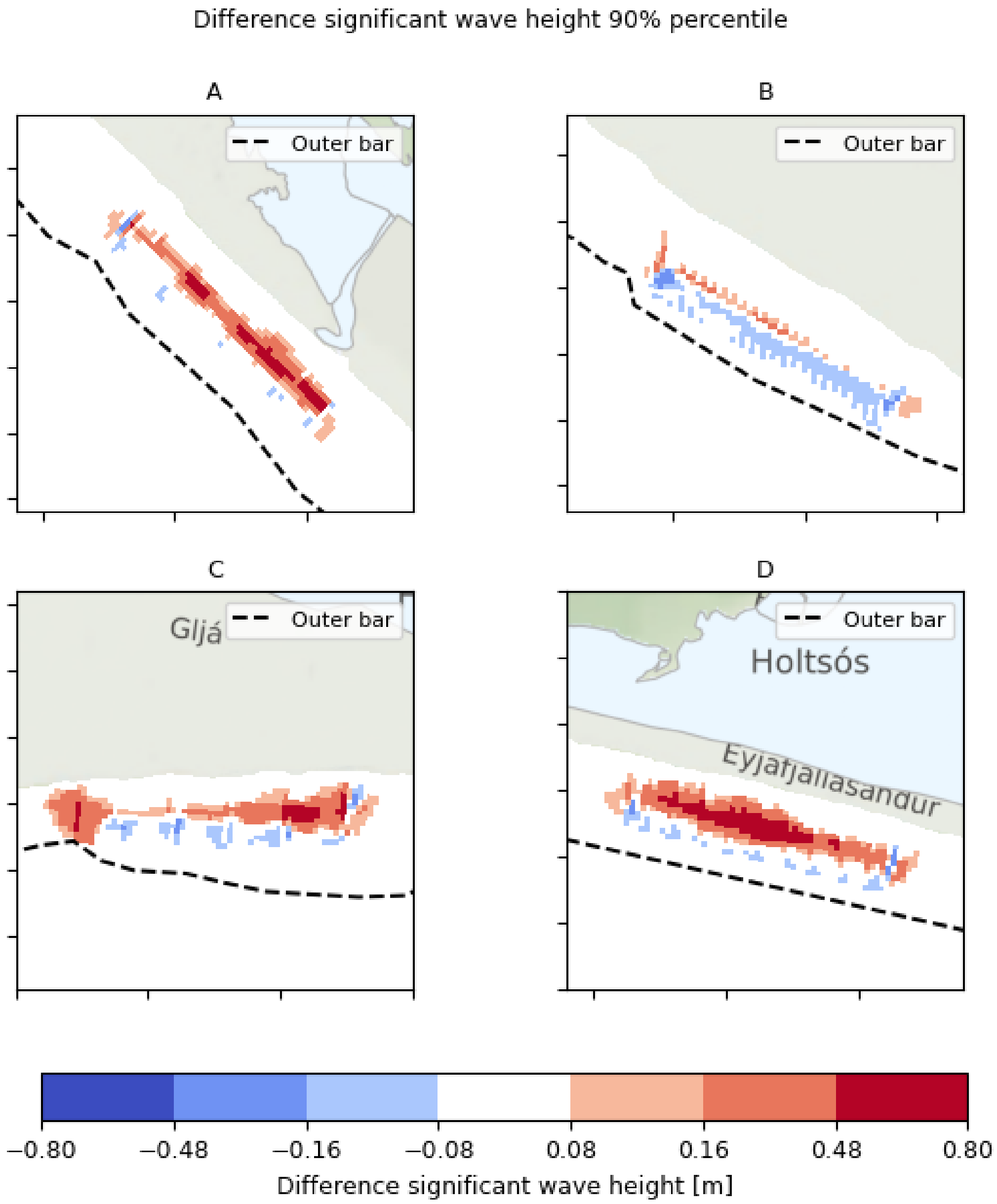


Figure 31. Difference in significant wave height, 90% percentile, between mining and no mining at specific areas; A and B west of Landeyjahöfn harbour, and C and D east of the harbour.

In Figure 32 the difference in orbital velocity is shown for the same mining areas east and west of the harbour. The difference in orbital velocity shows mostly lowered velocity due to increased depth in the mining area. Some increase in orbital velocity is however observed landward of the mining areas which is likely due to different refraction and shoaling patterns. This may impose a greater nearshore forcing following the mining activities.

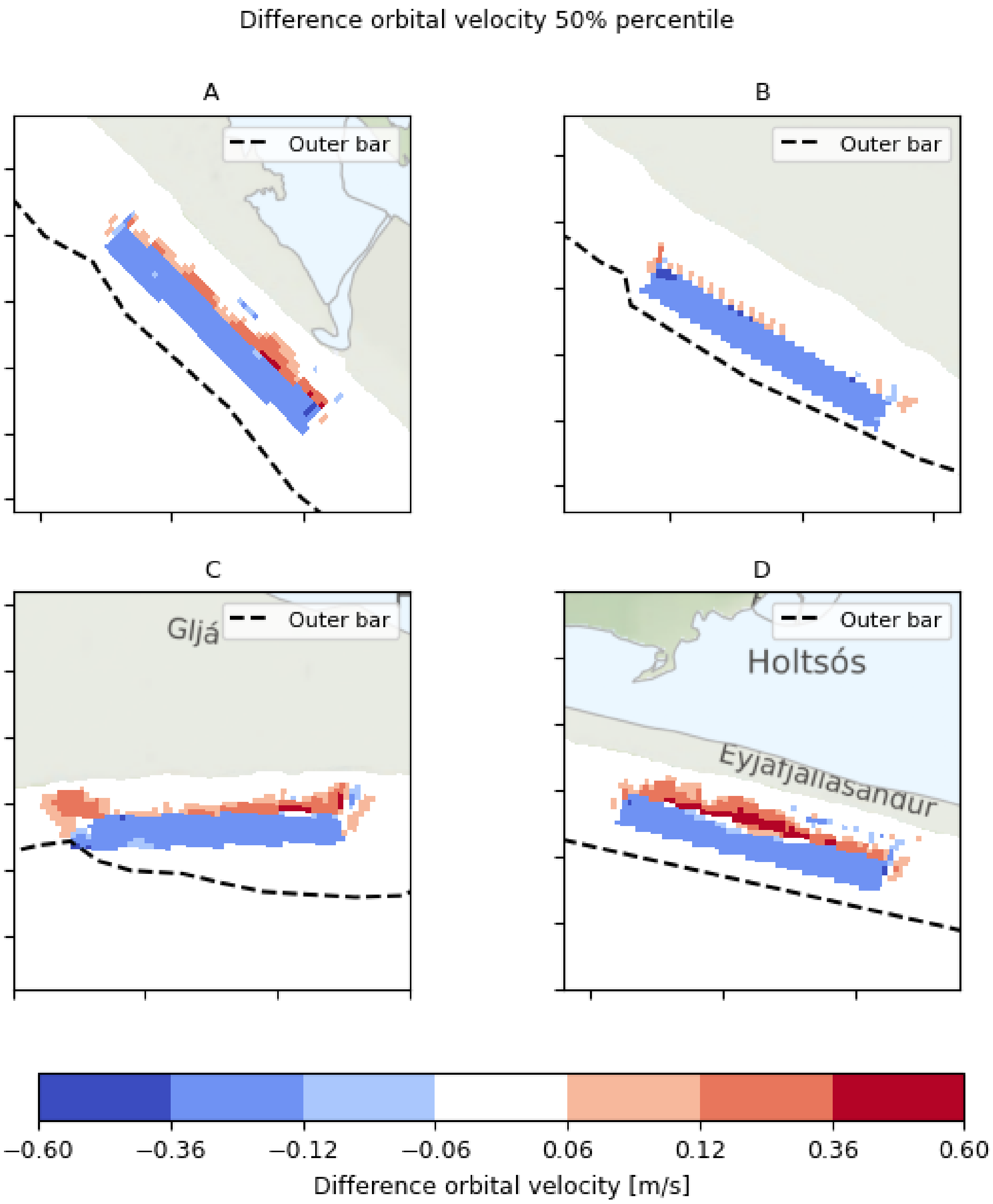


Figure 32. Difference in orbital velocity, 50% percentile, between mining and no mining at specific areas; A and B west of Landeyjahöfn harbour, and C and D east of the harbour.

The sensitivity of short-term effects of near shore mining on morphology was established using the two 15-day periods with significantly different wave climates (Figure 23). Firstly, a mining area located landward of the outer bar is defined as a rectangular area close to the shore, 2 km long, 250 m wide and 2 m deep. This mining area represents mining of 1 million m^3 of sand. In Figure 33 bathymetry evolution for the defined mining area is shown during wintertime. Additionally, the difference between simulation for the same period without mining and with mining is shown.

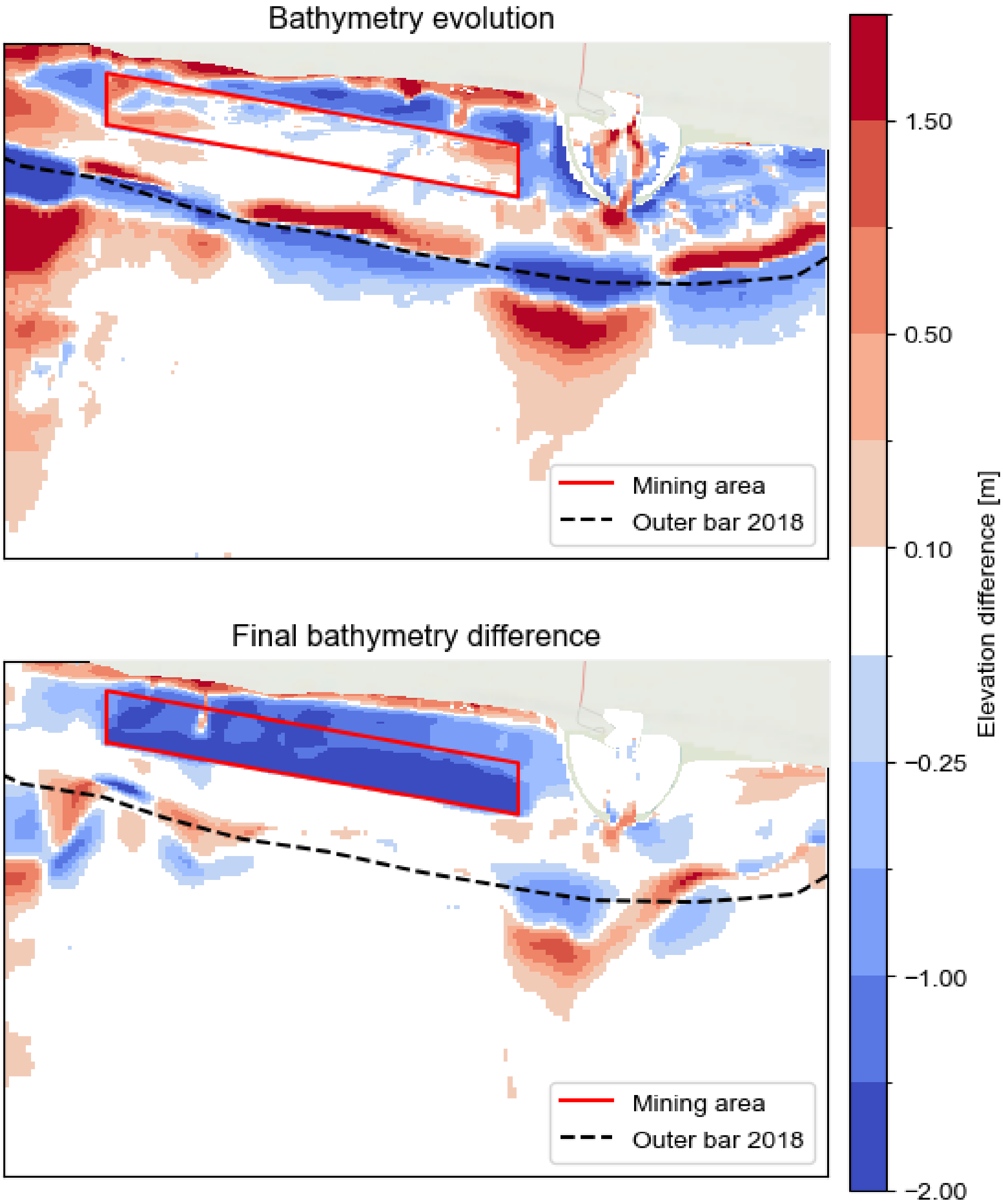


Figure 33. Bathymetry evolution of mining close to shore during winter simulation (15 days). Evolution of bathymetry over the simulation time shown above. Below, difference of final bathymetry for runs with and without mining.

The mining of sediment in the surf zone affects both the wave shoaling and the breaking processes. Waves landward of the mining area break further up the beach ashore with higher waves on the landward side of the mining area, leading to higher erosion in landward of the mining area. On either side of the mining area, sediments accumulate in the mining area due to the area outside the mining area being eroded and transported into the mining area. Some effects on the outer bar can be observed. While the bar generally moves in the same directions its movements are accelerated. An increase in sediment accumulation can be observed in the harbour mouth and also closest to shore.

In the simulated summer event, the effects on the outer bar are small, somewhat though towards the west (Figure 34). There is a build-up of materials on the beach that could be a result of the slightly higher wave changing the slope of the beach, pushing up materials, combined with sediments falling into the pit it which results in gradual erosion along the edge and enlargement of the pit.

Further computations, where the mining area was moved further offshore towards the outer bar, showed reduced erosion landward of the mining area and smaller effects on the outer bar.

There can be significant uncertainties in the numerical simulations of nearshore morphological changes as for the overall assessment of the effect of nearshore mining on the morphology. For those uncertainties to be reduced, the overall morphology at the coastline must be investigated even further. Nonetheless, the short-term simulations show that nearshore mining leads to erosion in the vicinity of the mining area and therefore can lead to changes to the nearshore environment beyond natural processes. To what extent that affects the long-term morphology is yet to be investigated.

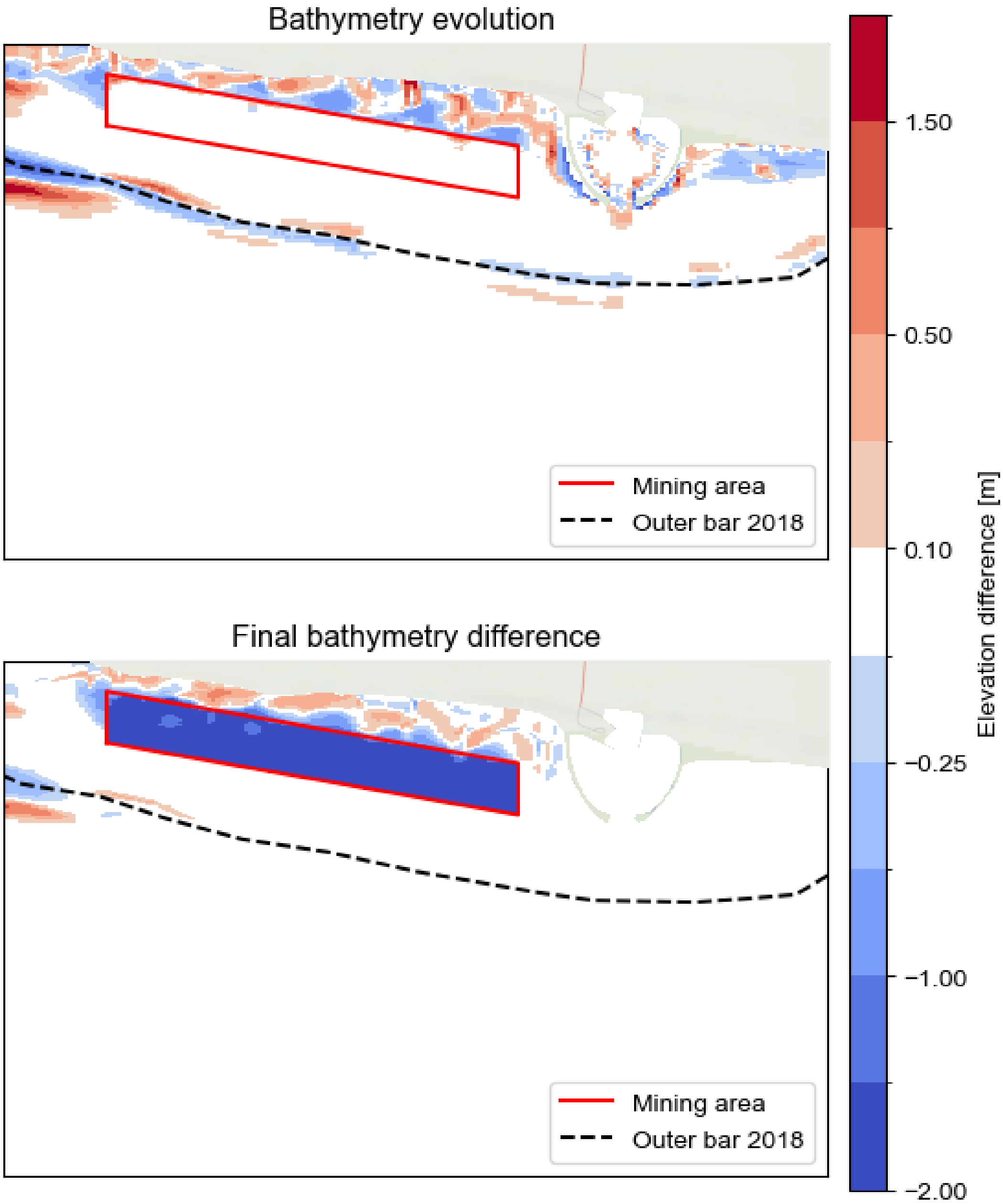


Figure 34. Bathymetry evolution of mining close to shore during summer simulation (15 days). Evolution of bathymetry over the simulation time shown above. Below, difference of final bathymetry for runs with and without mining.

4.4 Effects of mining offshore of the outer bar

As a basis for sensitivity analysis, two main zones for mining offshore of the outer bar are defined:

- Zone A, where a layer of 1 m is mined in the zone between the -15 m and -20 m CD depth contours (width of this zone is about 1 km).
- Zone B, where a layer of 2 m is mined in the zone between the -20 m and -35 m CD depth contours (width of this zone is about 1.5 km).

In these zones the mining volume per unit width is of the order of 3500 m^3/m. Given an alongshore length of 20 to 30 km, the potential mining volume is of the order of 70-100 million m^3 which is on the order of long-term planning activities. In Figure 35 the areas are shown, extending though along the entire stretch encompassing the investigation areas to allow for sensitivity assessment along the stretch.

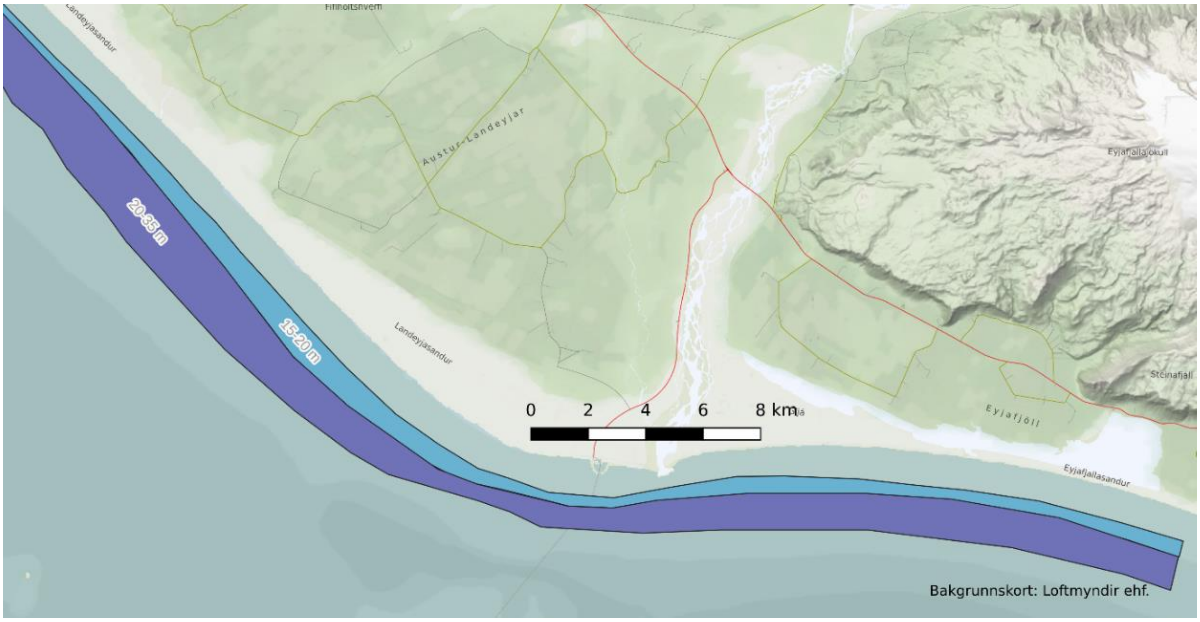


Figure 35. Offshore mining areas. Mining zones A at depth 15-20 m (blue) and B 20-35 m (purple).

As a first estimate of the possible effects of mining at zones A and B, a computation of cross-shore distribution of the wave heights and wave-driven longshore currents and sand transport rates for a series of (minor to major) storm events along a bed profile with and without mining area is utilized. A transect in the coastline was selected at about 10 km west of Landeyjahöfn (W01, Figure 3) which is assumed to be representative for this part of the coast. The mining area is situated between the -15 m and -35 m CD depth contours, relatively comparable to the combined mining zones A and B (Figure 35) at that transect; the depth of the mining area is 1 m between -15 m and -20 m CD and 2 m between the -20 and -35 m depth contours. Four storm events with minor to extreme wave conditions are defined, see Table 4.

The computed cross-shore distribution of wave height, longshore current and transport rates along the natural bed profile (without mining area) 10 km west of Landeyjahöfn (W10, see Figure 3) are shown in Figure 36. Waves can be observed breaking on the outer and inner bar with strong wave breaking on the outer bar for major and extreme storm events (H_s> 4.5 m). The maximum longshore current is up to 1.5 m/s at the inner bar crest for H_s=3 and 4.5 m while a maximum longshore current of about 2.3 m/s just landward of the outer bar crest can be observed for extreme wave conditions, for H_s= 9 m. The longshore and cross-shore sand transport rates are highest landward of the -15 m depth contour with maximum values occurring near the crest of the bars. The cross-shore transport is mainly in seaward direction during storm events resulting in beach and bar erosion, deposition in troughs between bars.

Table 4. Four storm events.

Storm event	H_s [m]	T_p [s]	wave angle to shore normal [°]	offshore depth [m]
Minor	3	10	30	50
Medium	4.5	12	30	50
Major	6	14	30	50
Extreme	9	16	30	50

Figure 37 shows the effect of the mining area seaward of the -15 m depth contour on the wave height, longshore current velocity and longshore/cross-shore sand transport for offshore wave cases $H_{s,o}$=6 and 9 m. The effects are negligibly small for offshore waves cases $H_{s,o}$=3 and 4.5 m (not shown). The effects of the mining area on the significant wave height and longshore current velocity at the outer bar crest (-6.3 m CD) and near the inner bar crest (at -2 m CD) are shown in Table 5. The effect on the width-integrated longshore sand transport LST (between -15 m and shore; between -6.3 m and shore) is also shown in Table 5.

Table 5. Wave height and longshore current velocity at -6.3 m (crest outer bar) and at -2 m depth (inner bar). Longshore sand transport landward of -15 m depth and -6.3 m depth. Bed profile with and without mining area.

Coastal parameters		Bed profile (no mining area)				Bed profile with mining area			
		$H_{s,0}$ = 3 m	4.5 m	6 m	9 m	3 m	4.5 m	6 m	9 m
Significant wave height (m)	at -2 m depth	2.54	2.95	3.20	3.58	2.54	2.95	3.20	3.58
	at -6.3 m crest outer bar	2.77	4.54	5.27	5.72	2.77	4.54	5.27	5.72
Longshore current velocity (m/s)	at -2 m depth	0.51	1.13	1.4	1.63	0.51	1.13	1.4	1.63
	at -6.3 m crest outer bar	0.01	0.57	1.16	2.19	0.01	0.57	1.17	2.21
LST (m^3/day)	Landward of -6.3 m outer bar crest	6450	30600	80000	385000	6450	31000	81500	392000
	Land ward of -15 m dept contour	6550	32200	91000	505000	6550	32500	92500	532000

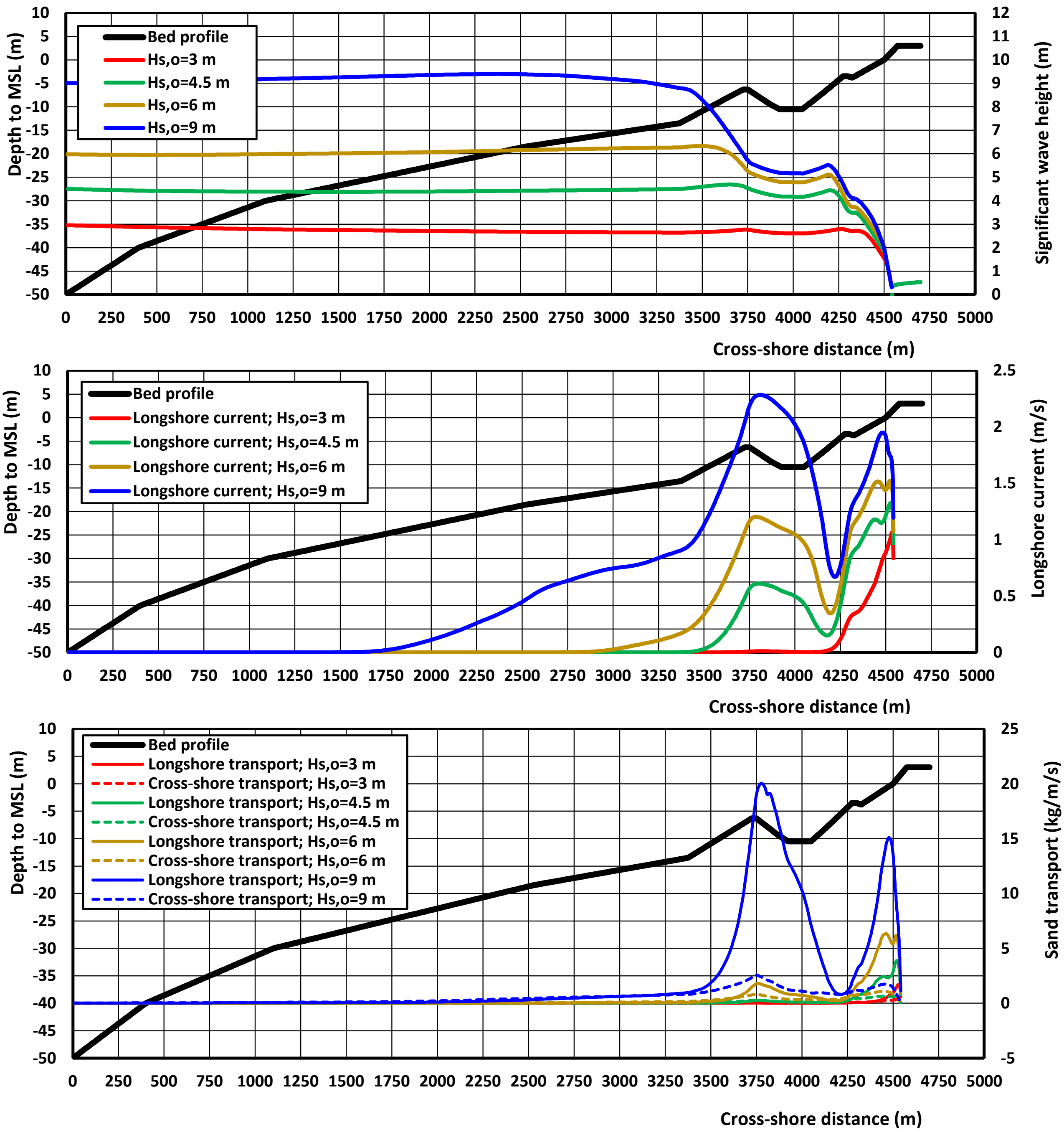


Figure 36. Cross-shore distribution of wave height, longshore current velocity, longshore and cross-shore sand transport for 4 storm events; bed profile 10 km west of Landeyjahöfn (W10).

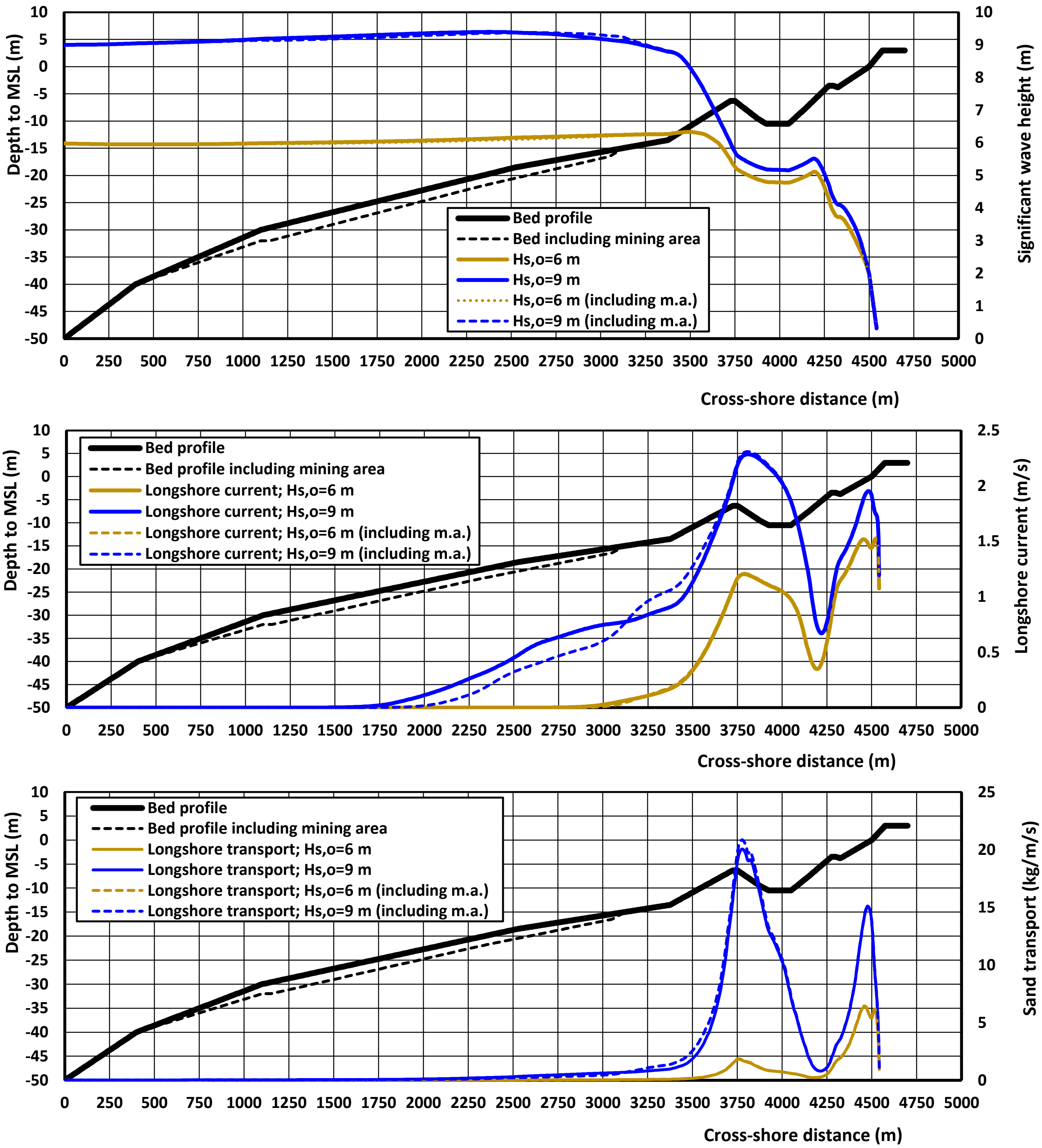


Figure 37. Cross-shore distribution of wave height, longshore current velocity, longshore and cross-shore sand transport for 4 storm events; bed profile 10 km west of Landeyjahöfn (W10) including the mining area.

For the analysis of the effect on wave climate, a hypothetical bathymetry where all this area has been mined and as if no recharge of materials into the mining area has occurred, is used as bottom topography. Comparing results from these cases against the previously established baseline case provide insights into the potential effects of mining on wave climate nearshore.

In Figure 38 the calculated difference in orbital velocity and significant wave height between mining offshore of the outer bar and no mining is shown for the coastline west of Landeyjahöfn harbour. The mining offshore of the outer bar has relatively little effect on the waves and associated orbital velocities magnitudes. The relative difference in wave height (Figure 39) is within the 0-3% limits set by the IRCA for sand beaches but stretches up to 3% at the outer bar and offshore. The relative difference is as high as 12% offshore of the outer bar for orbital velocity. This is likely due to different shoaling and refraction patterns caused by change in bathymetry. An increase in wave height along the shoreline is not observed in any cases. East of the harbour similar results can be observed.

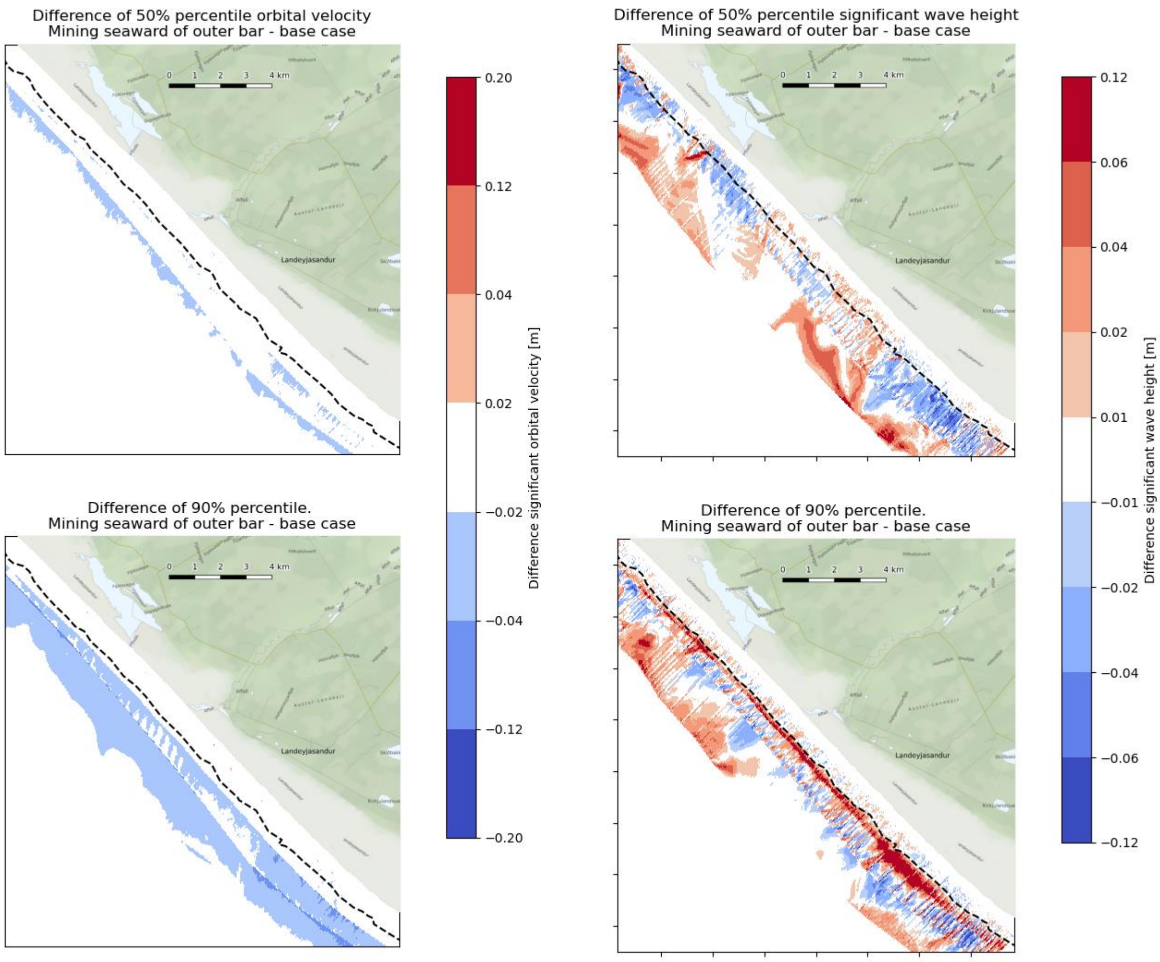


Figure 38. Mining offshore of outer bar. Difference from base case for 50% and 90% percentiles of orbital velocity (left) and significant wave height (right), west of Landeyjahöfn harbour.

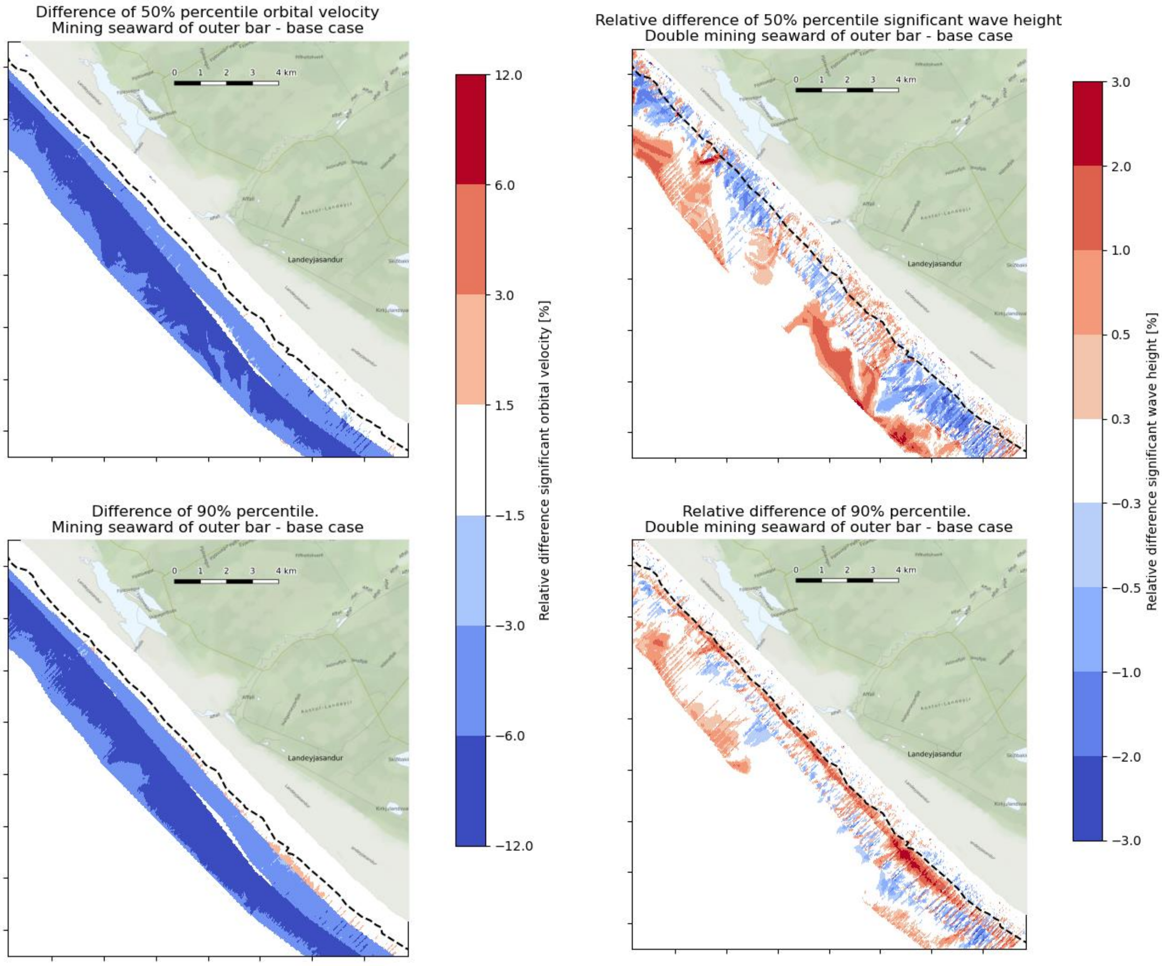


Figure 39. Mining offshore of outer bar. Relative difference from base case for 50% and 90% percentiles of orbital velocity (left) and significant wave height (right), west of Landeyjahöfn harbour.

Computation on short-term sand transport and morphological changes reflect to a large extent these limited effects on the wave climate imposed by the mining activities offshore of the outer bar. In Figure 40 the bathymetry evolution during a 15-day wintertime simulation is shown for the mining in Zones A and B. In the top of the figure the bathymetry evolution is shown over the simulation time. As in the case with no mining, some changes occur on the outer bar and close to shore. In the bottom of the figure the difference between the bathymetry evolution with and without mining offshore of the outer bar is shown. Mining offshore of the outer bar seems to have relatively small effects on the nearshore morphology, with changes occurring primarily in the vicinity of the harbour. This may be somewhat resulting from modified shoaling and refraction patterns in that area. Some differences can be observed at the outer bar, perhaps leading to more rapid evolution of the bar movement. The difference at the outer bar may also be related to changes in shoaling and refraction patterns caused by the mining area.

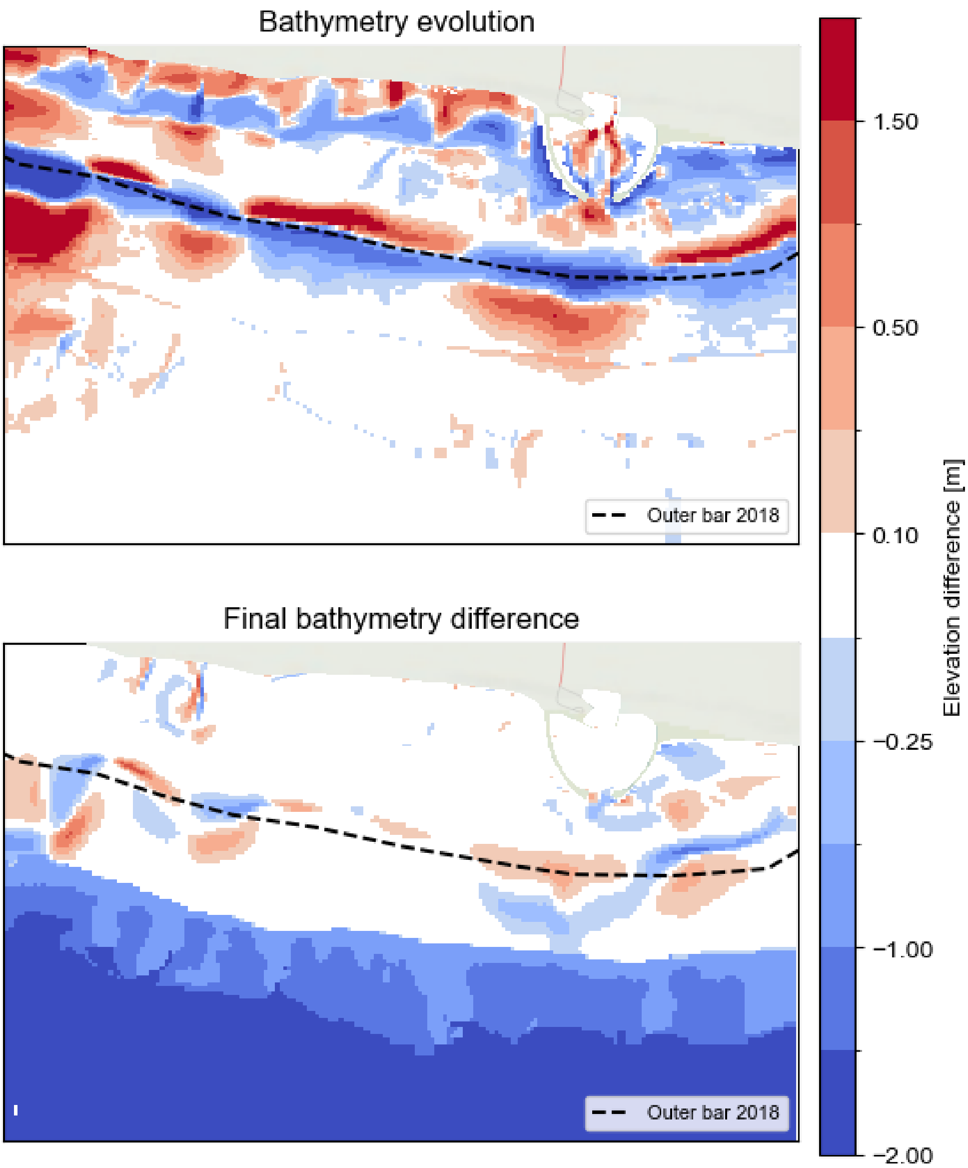


Figure 40. Bathymetry evolution of mining offshore of outer bar winter simulation (15 days). Evolution of bathymetry over the simulation time shown above. Below, difference of final bathymetry for runs with and without mining.

5 Summary and main conclusions

5.1 The planned mining activities

- HeidelbergCement Pozzolonic Materials (HPM) plans to mine up to 2 million cubic meters of sand from the coastal bottom near Landeyjahöfn harbour in Southern Iceland.
- In this report, the general concept of mining operations within the investigation area is addressed and the possible effects to the nearshore wave climate and coastal morphology.
- Three primary factors set the planned mining operations apart from previous mining of seabed materials in Iceland: The planned amount of bottom material to be mined; The extent of the potential area to be mined; and the characteristics of the mining area.
- The mining activities are to be performed along the exposed, sandy Southern Iceland coast, within approximately 2-4 km from shore. The black basalt sand coast experiences severe weather conditions with very high waves, resulting in significant sand transport and dynamic conditions.

5.2 The assessment approach

- Guidelines for mining activities are limited in Icelandic legislation and regulations with respect to suitable physical characteristics for mining sites. Such sites can though be subject to numerous limitations and even protective measures.
- In the present assessment an integrative approach is taken, led by a comprehensive background to account for coastal processes, the concept of coastal sand mining and the morphological behaviour of mining pits, as well as some of the guidelines internationally available for nearshore mining parallel to Icelandic guidelines.
- This background sets the stage for the primary environmental conditions and site characteristics to be described for the investigation area in question. The modelling performed to support the overall assessment of the mining activities draws from the environmental conditions and the challenges they impose on the investigation.

5.3 The concept of coastal sandmining and its effects

- The mining of sea sand will affect both the ecology and morphology of the coastal system. The focus of the present investigation is on the morphology and related processes.
- The morphology is affected in the sense that locally the bed level is lowered substantially in the front of an extraction area, pit (or channel), which may influence the local flow and wave fields and hence the sand transport rates. Waves fields are modified by shoaling, refraction, and reflection processes (interception of onshore sand transport). The pit area (slopes) may migrate towards the shore over time and/or may act as a sink (trapping) for sediments from the nearshore system (beach drawdown).
- On long term the area of influence may extend well outside the original mining area. Furthermore, the small-scale and large-scale bed forms (from mega-ripples to sand waves) may be destroyed locally, which may also have an effect on the hydrodynamic system (less friction and turbulence).

- Large-scale mining pits may have a significant impact on the near-field and far-field (up to the coast) flow and wave patterns; the flow velocities inside the mining area may be lower and the wave heights may also be lower, depending on the depth of the mining area. Consequently, the sand transport capacity inside the mining area will decrease and sediments will settle in the mining area, resulting in deposition. Thus, the mining area can act as a sink for sediments originating from the surrounding areas and depending on the local flow and wave patterns.
- Erosion of the sea floor may take place in the (immediate) surrounding of the mining area. This may lead to a direct loss of sediment from the nearshore zone (beaches).
- Indirect effects result from the modification of the waves moving and refracting over the excavation area (pit), which may lead to modification of the nearshore wave conditions (wave breaking) and hence longshore currents and sediment transport gradients and thus to shoreline variations.
- In the case of massive mining of sand, typically the mining areas need to be situated in the offshore shoreface zone to minimise the effects of nearshore coastal erosion.

5.4 Coastal processes and morphological features

- Characteristic morphological features occurring on the shoreface are breaker bars in the nearshore zone and large sand banks, ridges or shoals on the middle and lower shorefaces, which are at some places connected to the shore. Small-scale bed forms may be superimposed on these large-scale features ranging from wave-induced micro ripples to mega-ripples.
- The effects of a nearshore mining area on the shoreline can be broken down into four main effects: beach drawdown, interception of onshore sand transport, modification of offshore sand banks, and generation of alongshore transport gradients.
- The effect of mining area on the shoreline strongly depends on the distance to the shore. Nearshore mining of sand in depths < 8 m will immediately have negative effects, but offshore mining pits (depths> 20 m) generally have much smaller direct effects. Even when the immediate direct effects on the shoreline are negligible some negative effects may be realised in the long term after the mining area has migrated to the shore. The migration rates often vary roughly between 0.2 m/year at the 20 m depth contour to about 1.5 m/year at the 10 m depth contour.

5.5 Site characteristics

- The south coastline of Iceland is characterized by black beach sands (basalt sand) and high offshore waves.
- During neap tide the tide is about 1 m and the peak tidal current is about 0.2 m/s while during spring tide the tide is almost 3 m and the peak tidal currents above 0.5 m/s.
- Sand is found to be finer (0.15 mm) offshore of the outer sand bar and in the trough and coarser (0.3 to 0.45 mm) on the bar crest and near the beach. The mean grain size varies between 0.15 mm to 0.45 mm. The average size is 0.25 mm.
- The bathymetry at Landeyjahöfn harbour location consists of a bar-trough system at the west side of the harbour with local bar depressions for outflow of rip-currents located at the

harbour location and east of it where the ever-meandering spit formation from the river delta of the Markarfljót river takes over.

- The outer bar system may be interrupted locally (depression) due to the generation of local rip currents. Such an interruption is often present at the harbour location, where a major outgoing flow pattern may occur as part of flow passing around the river delta.
- The Markarfljót river mouth seemed to display a cyclic pattern in time, where in 1996 it returned to its position in 1954, after migrating to the west with its most westward point in early 1970s and then migrating eastwards to its former position. Migration of the river mouth affects the transport pattern and associated erosion and accumulation of material in the vicinity of the mouth.
- Historical shoreline was rather stable around the Landeyjahöfn harbour location, prior to its construction, with shoreline variability up to 300 m to the east of the location and 100 m to the west of the location. Similar analysis after the construction of the harbour has not been performed.
- Wave climate has the most effect on morphological changes at the coastline where short-term wave conditions can have significant effect. During conditions with high waves coming to the shore at an angle to the shore normal, the outer bar is pushed offshore while in milder wave conditions waves push the outer bar to shore.
- Calculations based on the Hallermeier-Equation show that closure depth at the south coastline close to Landeyjahöfn is close to 19 m below MSL. The closure depth can be seen as the seaward limit of the nearshore equilibrium profile.
- Longshore sand transport along the coastline was estimated at various locations over a distance of 20 km on the west side (W20) and east side (E20) of the harbour in the period between 2011 and 2020. The net annual LST is about 600,000 m^3/year to East at W20 and 30,000 m^3/year to East at E20. Overall, the sediment budget in the surf zone of this area is positive with more sand entering at W20 than leaving at E20. Most likely, this is also valid for the sediment budget in the shore face zone seaward of the -15 m depth contour.

5.6 Modelling

The general description of coastal processes, coastal sand mining concepts and guidelines as well as environmental conditions at the south coast sets the stage for general goals in the modelling effort in order to assess the effects of the planned mining activities on the wave climate and possible morphological changes including land erosion.

The modelling approached addressed in particular the following:

- Effects of morphological changes on wave climate.
- Effects of short-term wave climates on morphological changes.
- Effects of large-scale mining in areas landward of the outer bar on nearshore wave forcing.
- Effects of large-scale mining in areas offshore of the outer bar on nearshore wave forcing.

The first two items allow for establishing the behaviour in the system without mining activities stressing the interrelationships of the wave climate and morphological changes. Furthermore, the latter two items focus on the mining activities and their potential effects, put into perspective of the pre-mining behaviour.

5.6.1 Underlying conditions without mining activities

- Natural morphological changes can effectively alter the forces acting on the coastline forming a morphological cycle, where an outer bar is formed close to the shore and being pushed offshore. As the outer bar is pushed further offshore it lowers, leading to larger waves reaching the shoreline again forming a new outer bar.
- During harsh winter conditions, significant morphological changes can be expected with dynamic and complex behaviour of the outer bar and alterations of the nearshore bathymetry. During mild summer conditions, however, much smaller response in the system is observed although qualitatively general movements are somewhat similar. The short-term morphological changes in response to short-term variability in the wave climate may therefore have a significance to the longer-term coastal morphology.

5.6.2 Mining landward of the outer bar

- Mining of sand close to shore, landward of the closure depth, can have adverse effects on the morphology possibly leading to increased land erosion. Modelling computations investigating mining nearshore, landward of the outer bar, show simulated mining activities near shore leading to increased wave height above the limit (<3%) set in the guidelines of the IRCA in Iceland.
- The sensitivity of short-term effects of near shore mining on morphology was established utilizing variable short-term wave climates indicating winter and summer conditions. Such mining activities in the surf zone affect both the wave shoaling and wave breaking processes, particularly during winter conditions. Landward of the mining area waves break further up the beach ashore with higher waves on the landward side of the mining area, leading to higher erosion landward of the mining area. On either side of the mining area, sediments accumulate in the mining area due to the area outside the mining area being eroded and transported into the mining area. The outer bar generally moves in the same directions but with accelerated movements. This may have significance to the longer-term effects of the mining.
- Moving the mining area further offshore towards the outer bar reduces the erosion landward of the mining area and results in smaller effects on the outer bar.
- The short-term simulations show that nearshore mining leads to erosion in the vicinity of the mining area and therefore can lead to changes to the nearshore environment beyond natural processes. To what extent that affects the long-term morphology is yet to be investigated, but it is likely that the nearshore bathymetry can be modified significantly.

5.6.3 Mining offshore of the outer bar

- The investigations on the effects of mining offshore of the outer bar presumed that the order of mining is in accordance with planned long-term mining activities.
- The mining offshore of the outer bar, near and beyond the region of closure depth, appears to have relatively little effects on the nearshore wave climate.

- Similarly, computation on short-term sand transport and morphological changes largely reflect these limited effects on the wave climate imposed by the mining activities offshore of the outer bar. However, as in the case with no mining, some changes may occur on the outer bar and close to shore, particularly in vicinity of the harbour. This may be somewhat resulting from modified shoaling and refraction patterns in that area. The observed differences at the outer bar may lead to more rapid evolution of the bar movement. The difference at the outer bar may also be related to changes in shoaling and refraction patterns caused by the mining area.
- In any case, the research of the area in preparation for mining activities should investigate this further and put into context of safe distance from shore and safe depth with respect to established closure depth.

5.7 Concluding remarks

The surf zone landward of the outer bar crest is a relatively narrow strip (width<1000 m) with inner and outer breaker bar which act as the first line of defence against wave attack and coastal erosion. Mining of sand in this zone could lead to degeneration of the breaker bars and ultimately to a more severe wave attack at the beach, which should be prevented to avoid land erosion.

Integrating information from literature, available experience elsewhere and the modelling results presented here suggest that mining landward of the outer bar may have severe negative effect on the coastal morphology and hydrodynamics of the system.

By securing the mining activities far enough offshore, however, at least beyond a depth that would be chosen in close agreement with the closure depth, Icelandic guidelines on wave climate modifications and some of the goals addressed in international guidelines and regulations may be met, including those from Great Britain and The Netherlands:

- The beach should not be affected from drawdown into the dredged area (no permanent trapping of beach sediments into dredged area).
- The supply of sediments to the coastline should not be affected.
- Bars and banks providing protection to the coast from wave attack should not be damaged/affected.
- Significant changes in wave refraction patterns altering nearshore waves and hence the alongshore transport of sediment should not occur.

Further analysis following the preparation and research of the mining activities are needed to ensure that the selected distance offshore and appropriate depths help in minimizing the potential effects on the outer bar, a feature that the southern coast strongly relies on for its ongoing balance.

For the modelling work an example was taken with offshore mining of 1 m layer in the zone between the -15 m and -20 m CD depth contours (width of this zone is about 1 km) and of 2 m layer of in the zone between the -20 m and -35 m CD depth contours (width of this zone is about 1.5 km). The mining volume per unit width is of the order of 3500 m^3/m and may therefore support the long-term mining activities along a stretch of approximately 20 – 30 km.

This overall concept of long-term offshore mining arrangement can be kept as indicative at the onset of further research and investigations in the area; however, the modelling results suggest that most likely the mining must occur at somewhat greater depths, beyond the closure depth.

Drawing from the analysis of the available bathymetric data and the results of the morphological modelling it may be concluded that further analysis can be made on the deeper range of the bathymetry combined with deep-range longshore transport and morphological computations. This may support the research and preparations for the proposed mining activities, to help in determining secure depth ranges at each location along the expected mining area. Furthermore, to address potential recovering periods of the mining sections, both for supporting the longevity of the operations and for assessment of temporal impact ranges of the project.

At the onset of the proposed mining, monitoring must include frequent bathymetry measurements, including regular large-scale campaigns. Furthermore, frequent detailed land elevation mapping on the shoreline at low tide levels will be needed along with aerial photography. These data allow for detailed analysis of the morphological changes and by comparison with older bathymetric data, potential effects of the mining activities should be inferred. In addition to this monitoring the change in sediment grain sizes in and around the excavation areas help in evaluating long-term changes.

A review of mining activities and monitoring data incorporating detailed analysis and suitable modelling should be carried out on regular basis throughout the project lifetime. This is of great importance as morphological changes resulting from the mining activities may take some time to come forth and thus may be difficult to distinguish from natural morphological changes without such measures.

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Appendix A - Morphology, additional data

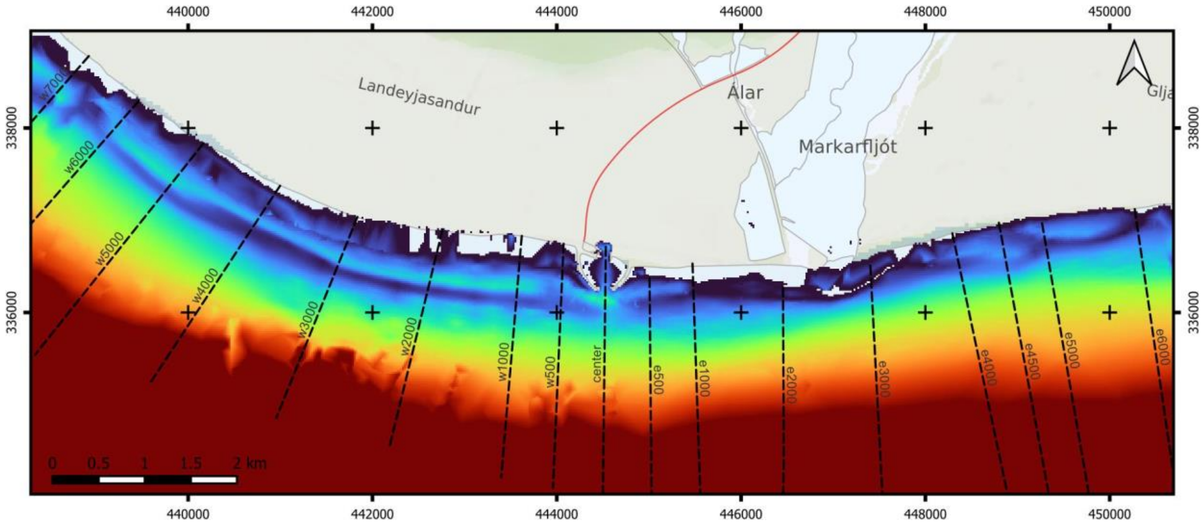


Figure A.1. Overview of cross-shore profiles defined for bathymetry profiles.

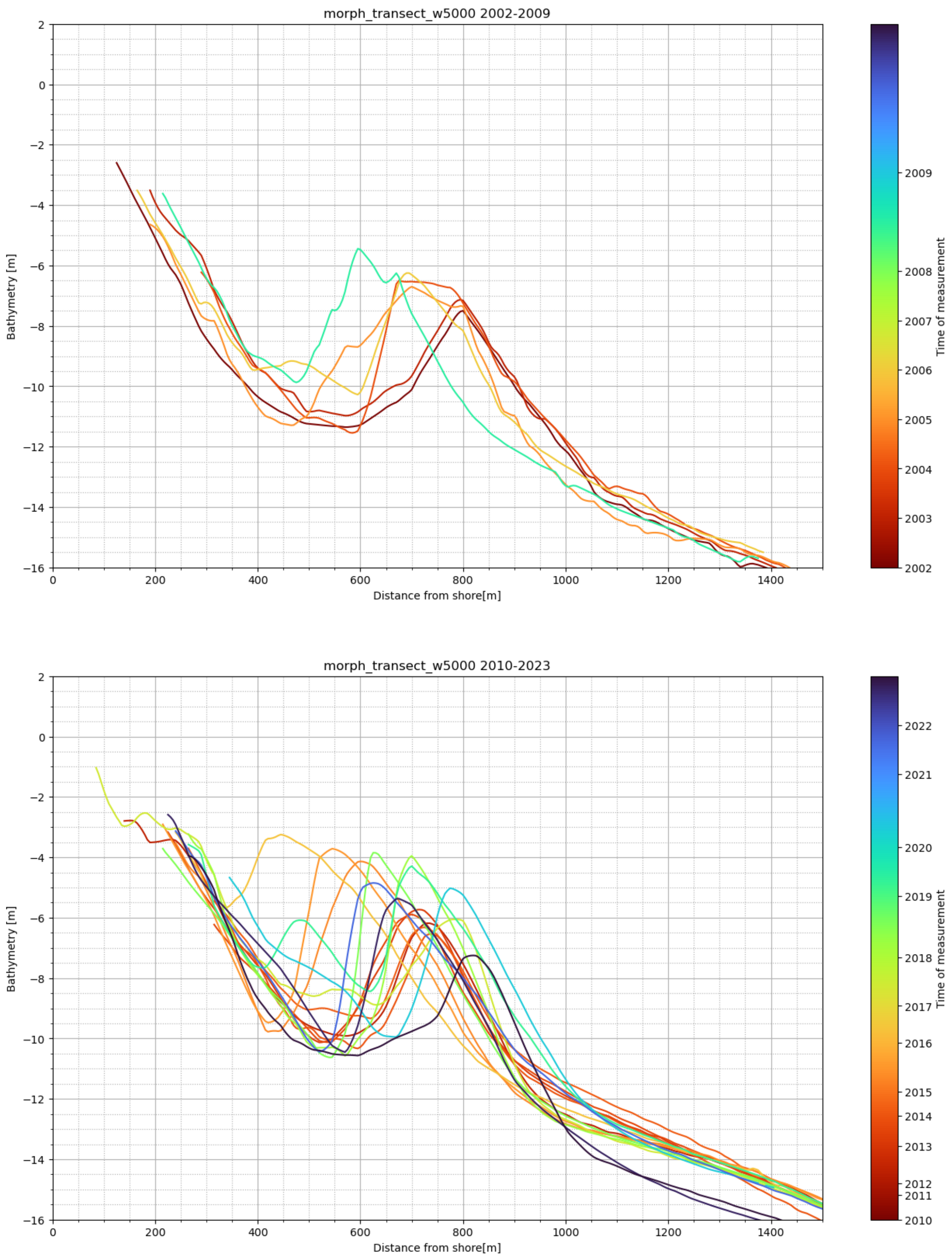
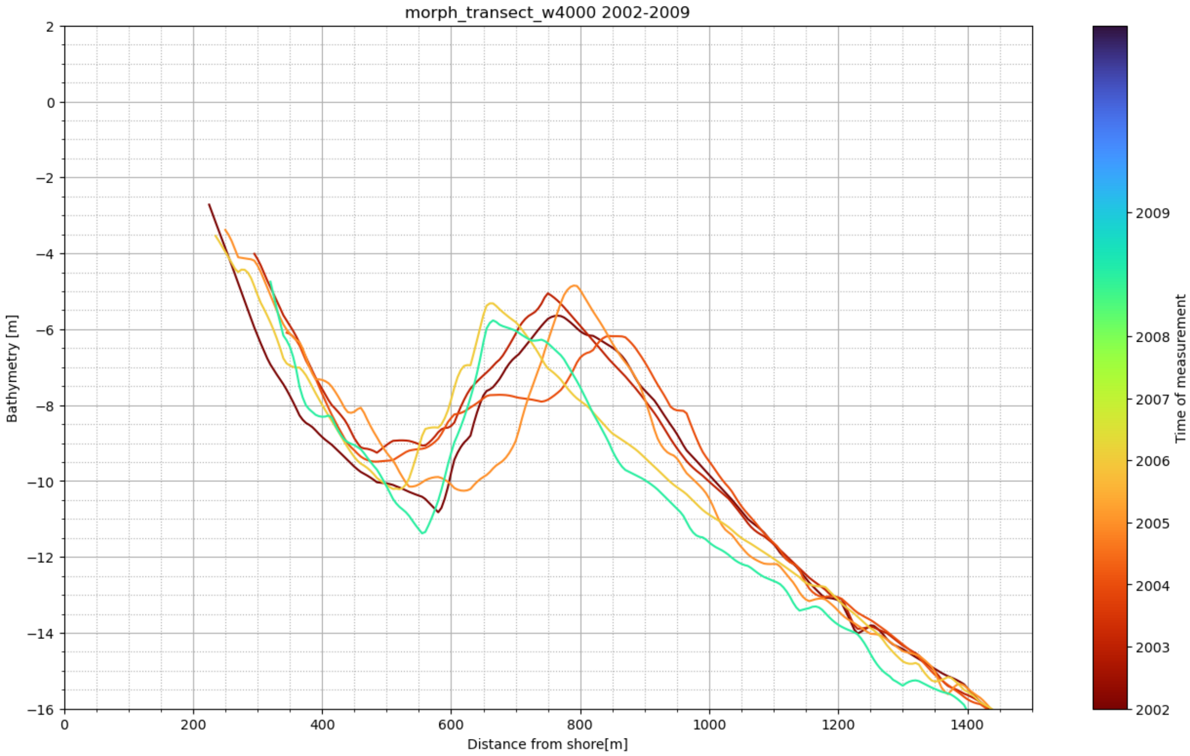


Figure A.2. Measured bed profiles 5 km west of navigation channel. Top, measured bed profiles before construction (2002-2010) of Landeyjahöfn harbour. Bottom, measured bed profiles after constructions of Landeyjahöfn harbour (2010-2023). Bathymetry elevation shown with respect to mean sea level. Mean sea level 1.33 m above CD.



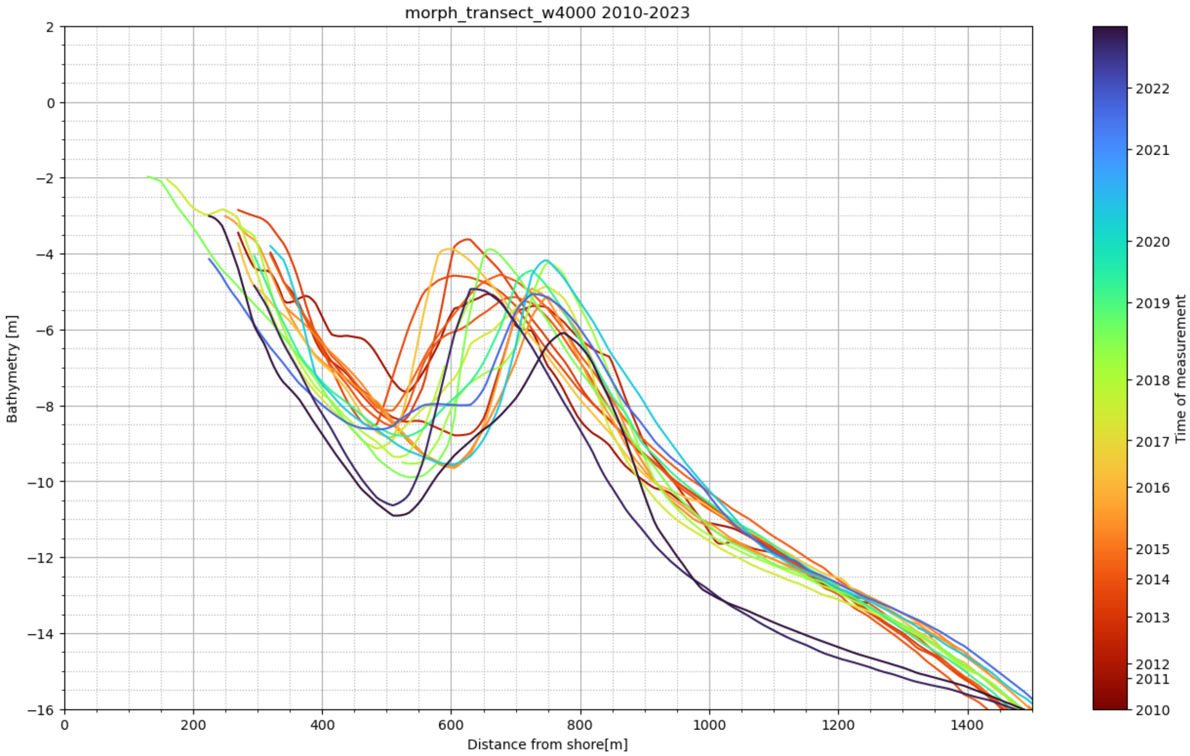


Figure A.3. Measured bed profiles 4 km west of navigation channel. Top, measured bed profiles before construction (2002-2010) of Landeyjahöfn harbour. Bottom, measured bed profiles after constructions of Landeyjahöfn harbour (2010-2023). Bathymetry elevation shown with respect to mean sea level. Mean sea level 1.33 m above CD.

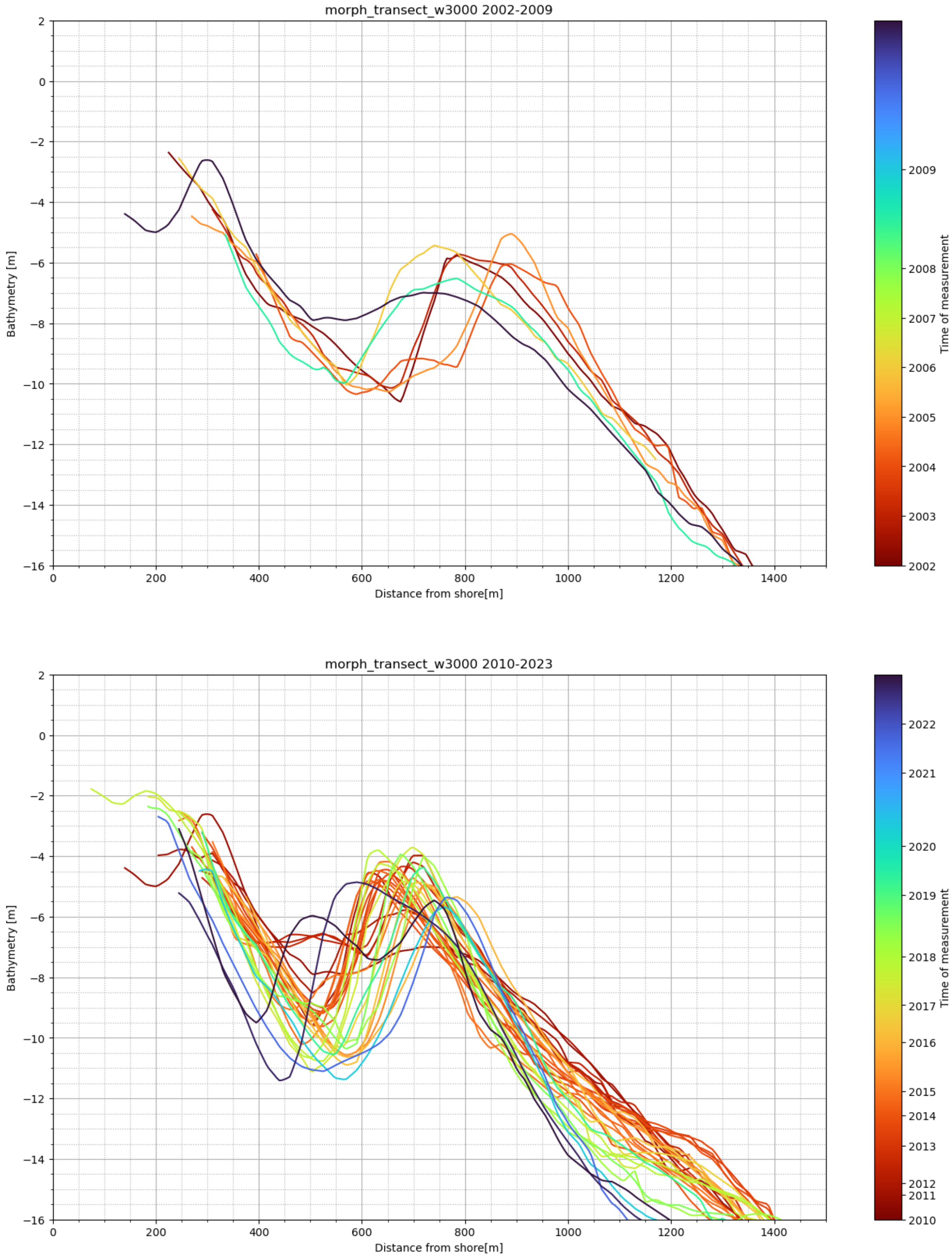


Figure A.4. Measured bed profiles 3 km west of navigation channel. Top, measured bed profiles before construction (2002-2010) of Landeyjahöfn harbour. Bottom, measured bed profiles after constructions of Landeyjahöfn harbour (2010-2023). Bathymetry elevation shown with respect to mean sea level. Mean sea level 1.33 m above CD.

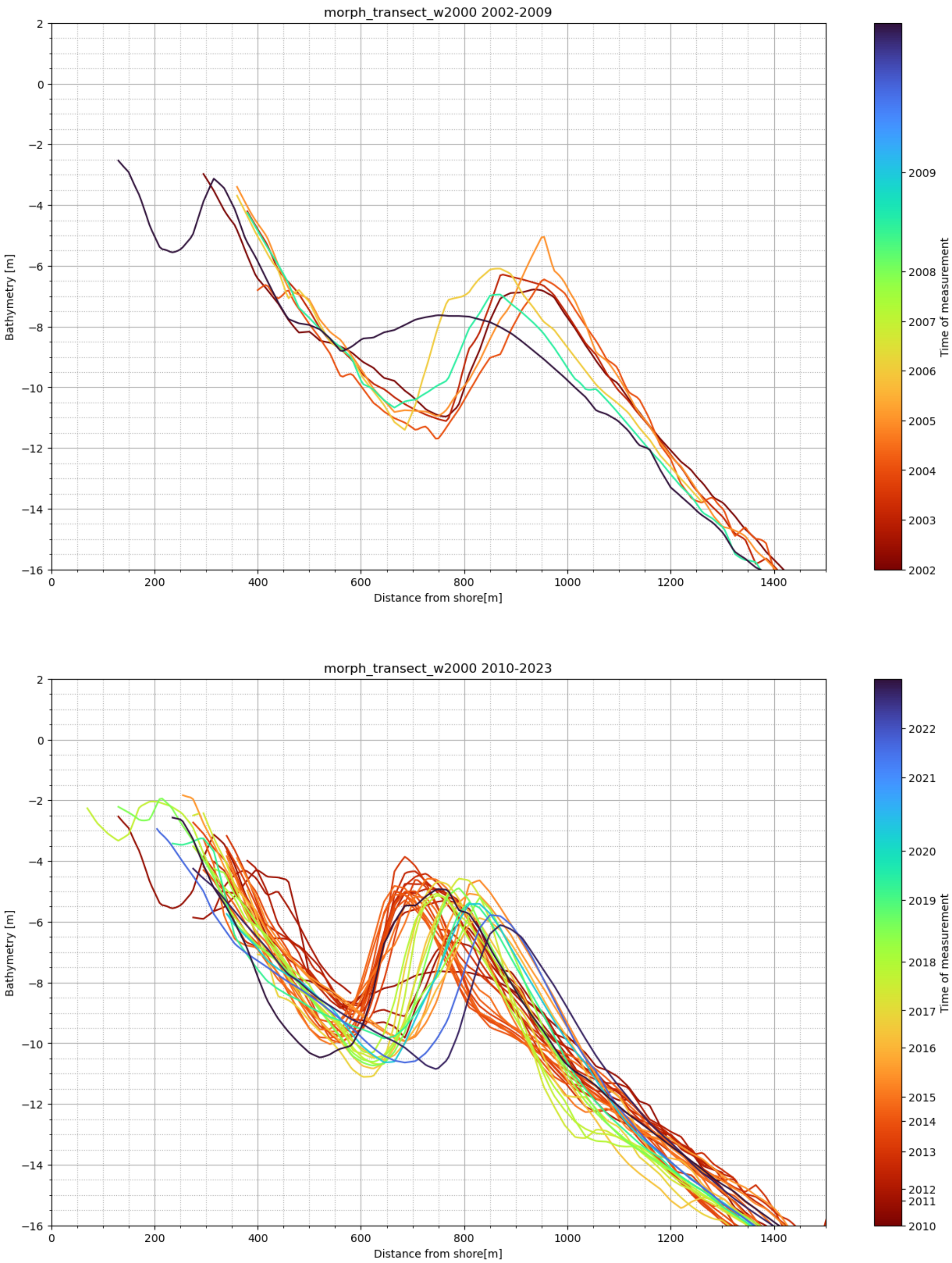
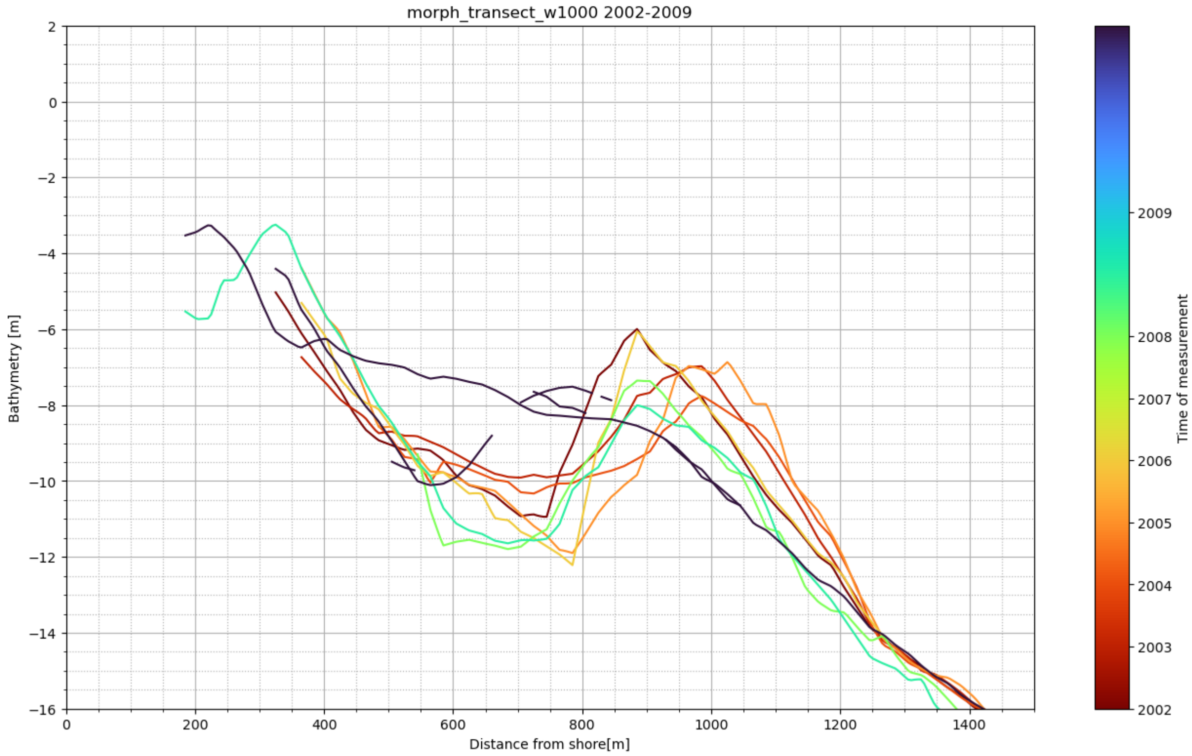


Figure A.5. Measured bed profiles 2 km west of navigation channel. Top, measured bed profiles before construction (2002-2010) of Landeyjahöfn harbour. Bottom, measured bed profiles after constructions of Landeyjahöfn harbour (2010-2023). Bathymetry elevation shown with respect to mean sea level. Mean sea level 1.33 m above CD.



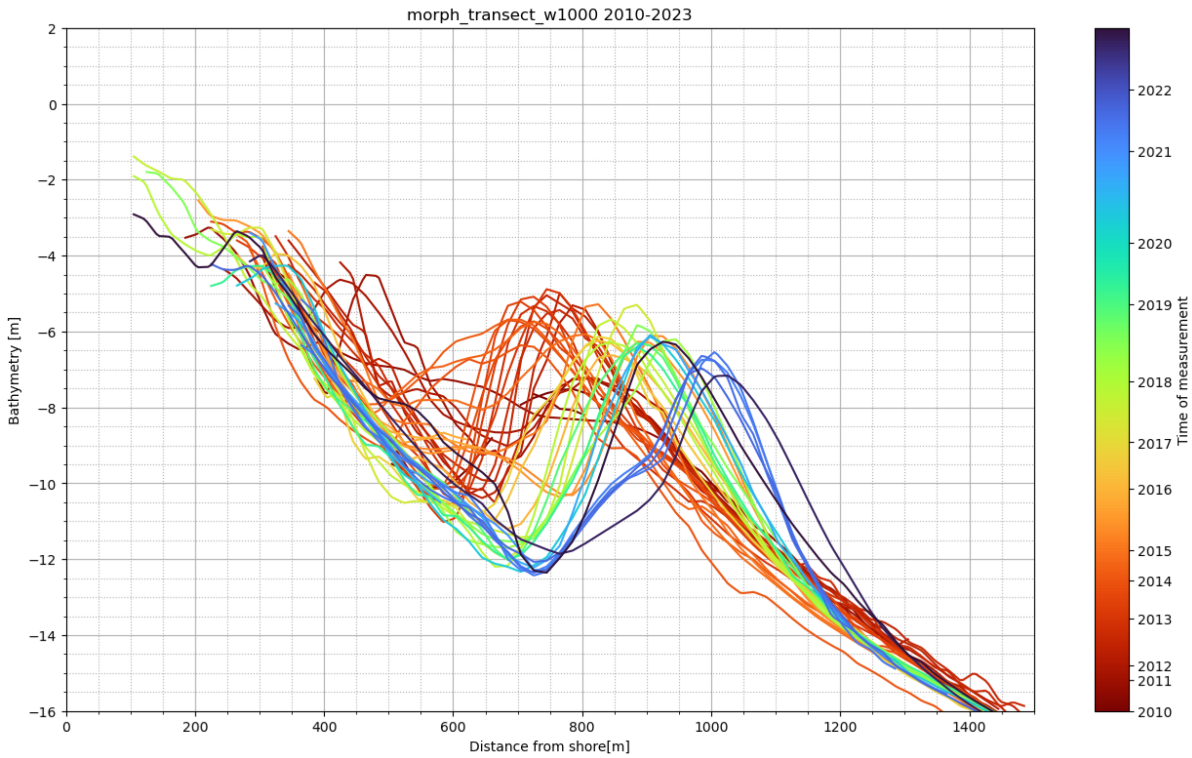
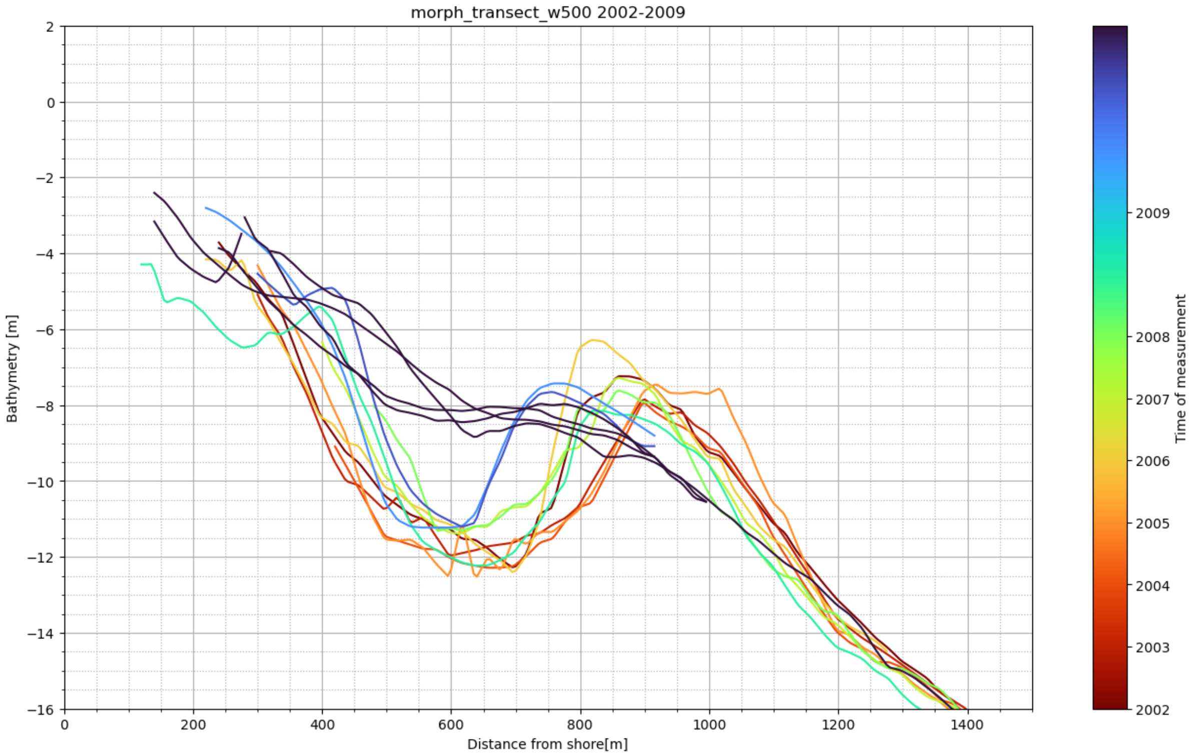


Figure A.6. Measured bed profiles 1 km west of navigation channel. Top, measured bed profiles before construction (2002-2010) of Landeyjahöfn harbour. Bottom, measured bed profiles after constructions of Landeyjahöfn harbour (2010-2023). Bathymetry elevation shown with respect to mean sea level. Mean sea level 1.33 m above CD.



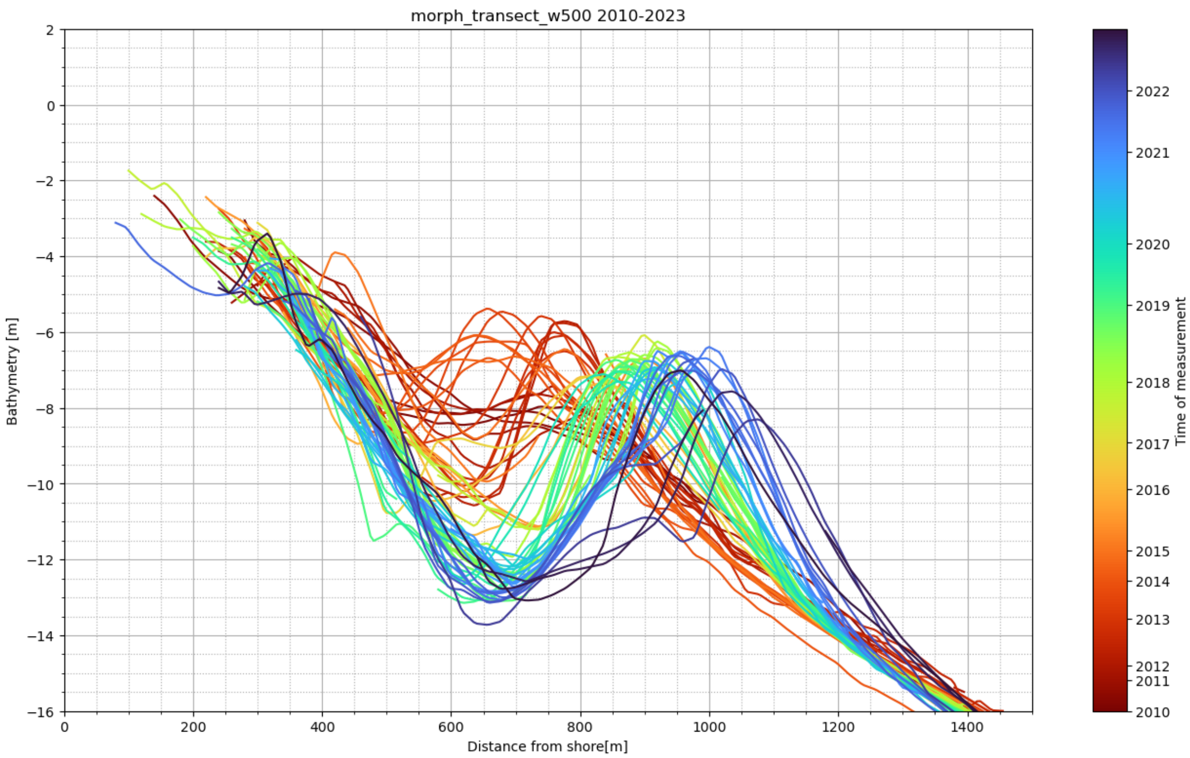
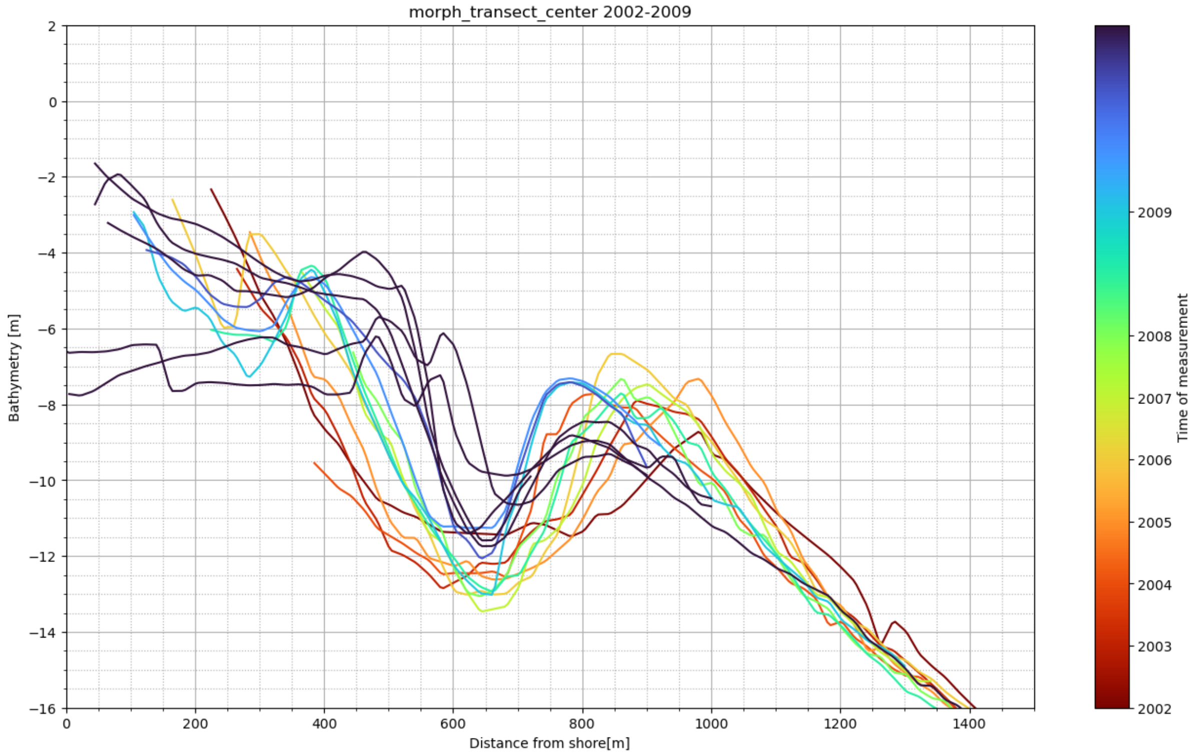


Figure A.7. Measured bed profiles 500 m west of navigation channel. Top, measured bed profiles before construction (2002-2010) of Landeyjahöfn harbour. Bottom, measured bed profiles after constructions of Landeyjahöfn harbour (2010-2023). Bathymetry elevation shown with respect to mean sea level. Mean sea level 1.33 m above CD.



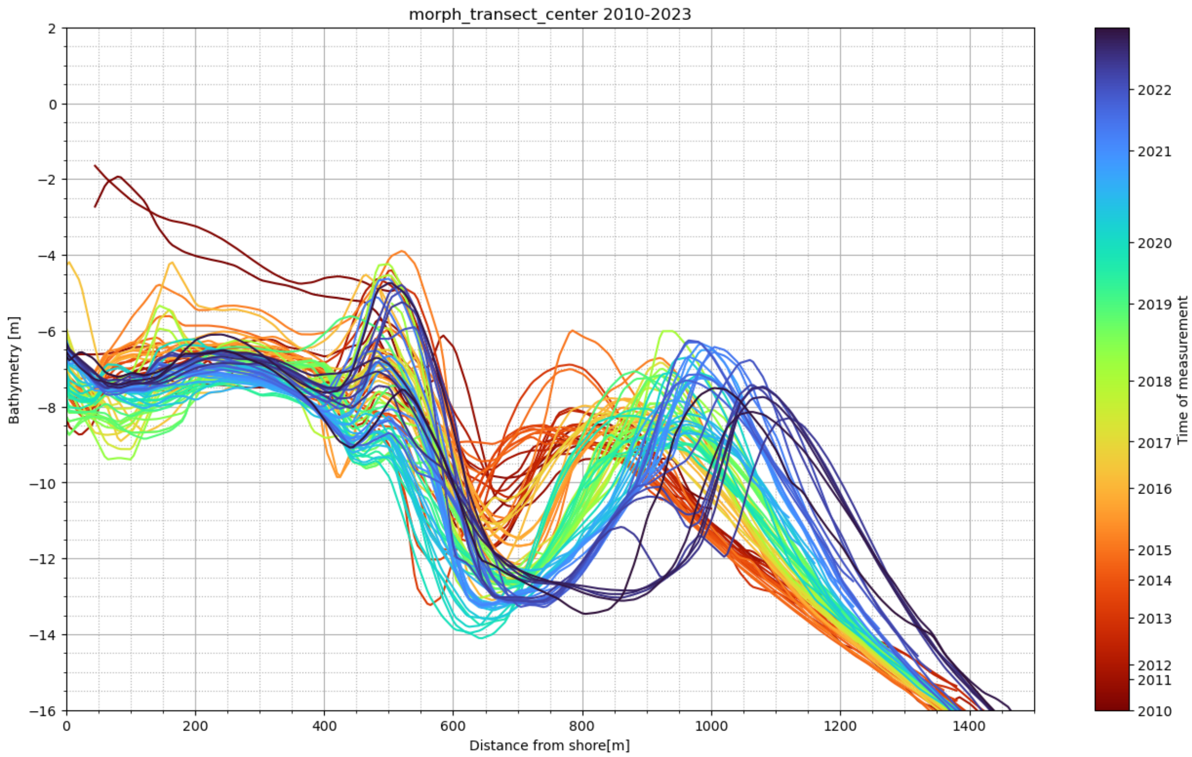


Figure A.8. Measured bed profiles along the center of the navigation channel. Top, measured bed profiles before construction (2002-2010) of Landeyjahöfn harbour. Bottom, measured bed profiles after constructions of Landeyjahöfn harbour (2010-2023). Bathymetry elevation shown with respect to mean sea level. Mean sea level 1.33 m above CD.

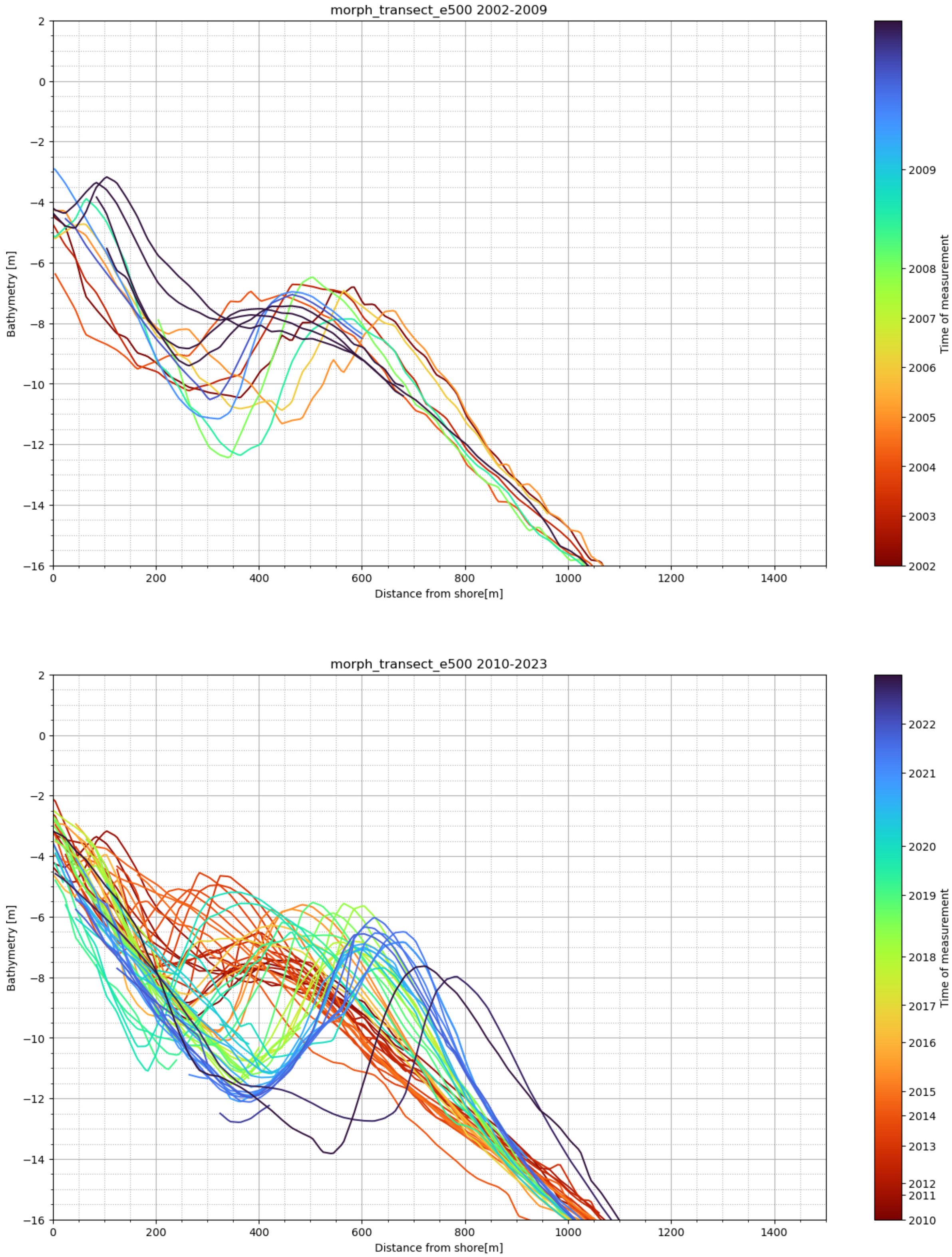
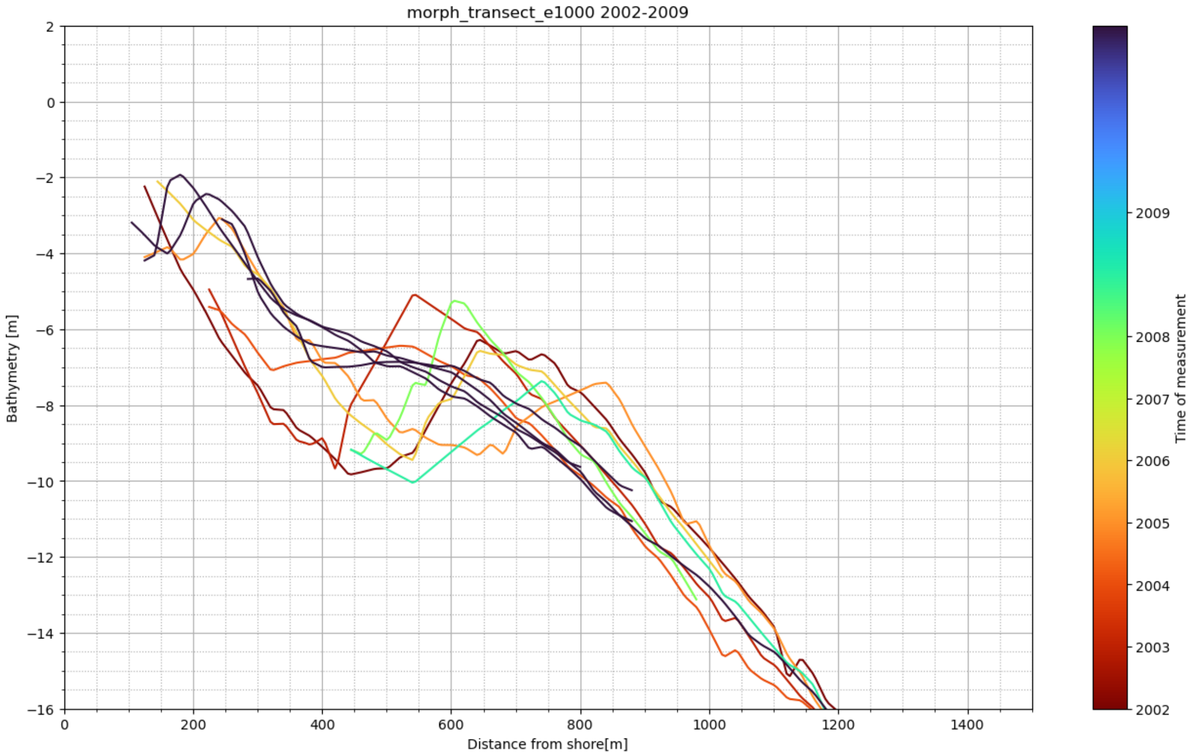


Figure A.9. Measured bed profiles 500 m east of navigation channel. Top, measured bed profiles before construction (2002-2010) of Landeyjahöfn harbour. Bottom, measured bed profiles after constructions of Landeyjahöfn harbour (2010-2023). Bathymetry elevation shown with respect to mean sea level. Mean sea level 1.33 m above CD.



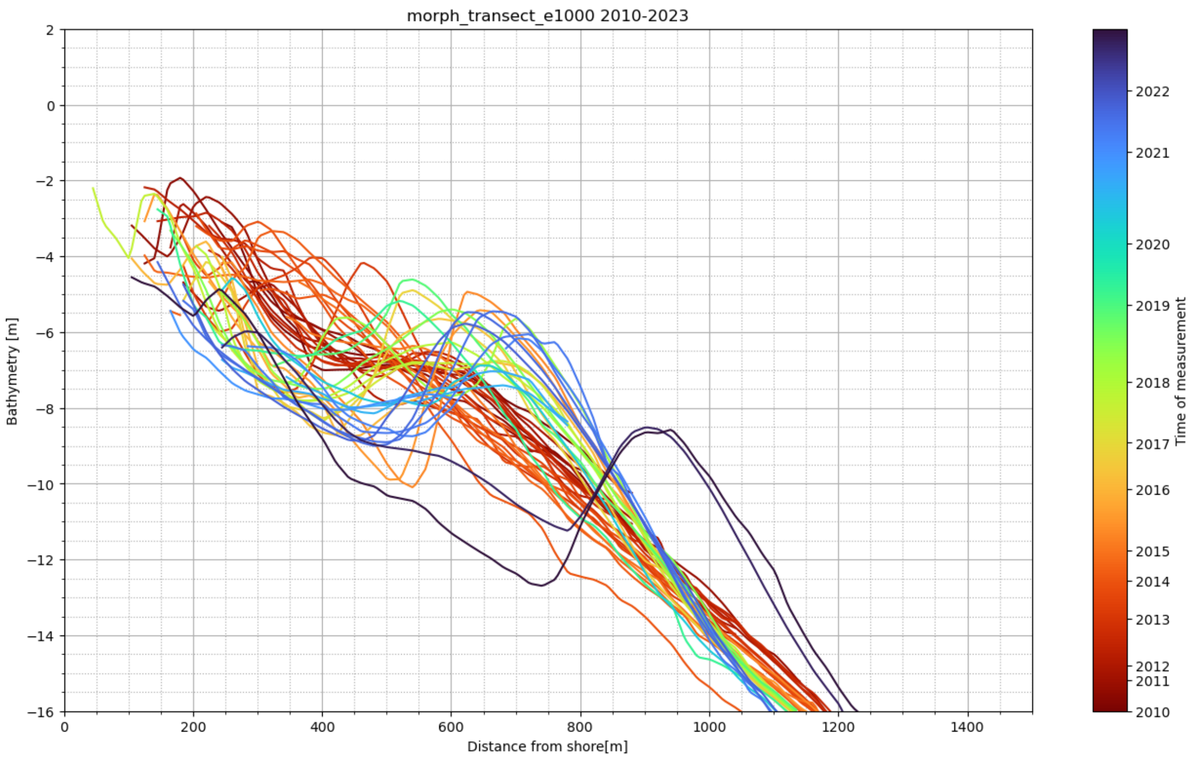
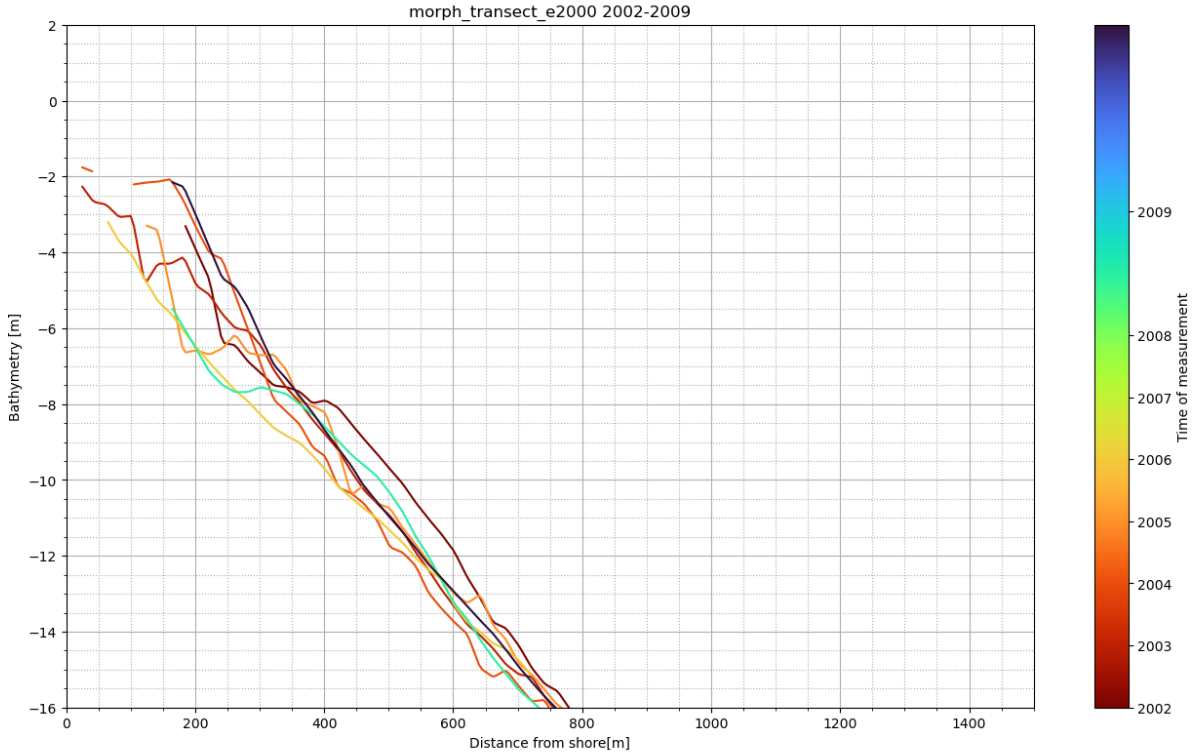


Figure A.10. Measured bed profiles 1 km east of navigation channel. Top, measured bed profiles before construction (2002-2010) of Landeyjahöfn harbour. Bottom, measured bed profiles after constructions of Landeyjahöfn harbour (2010-2023). Bathymetry elevation shown with respect to mean sea level. Mean sea level 1.33 m above CD.



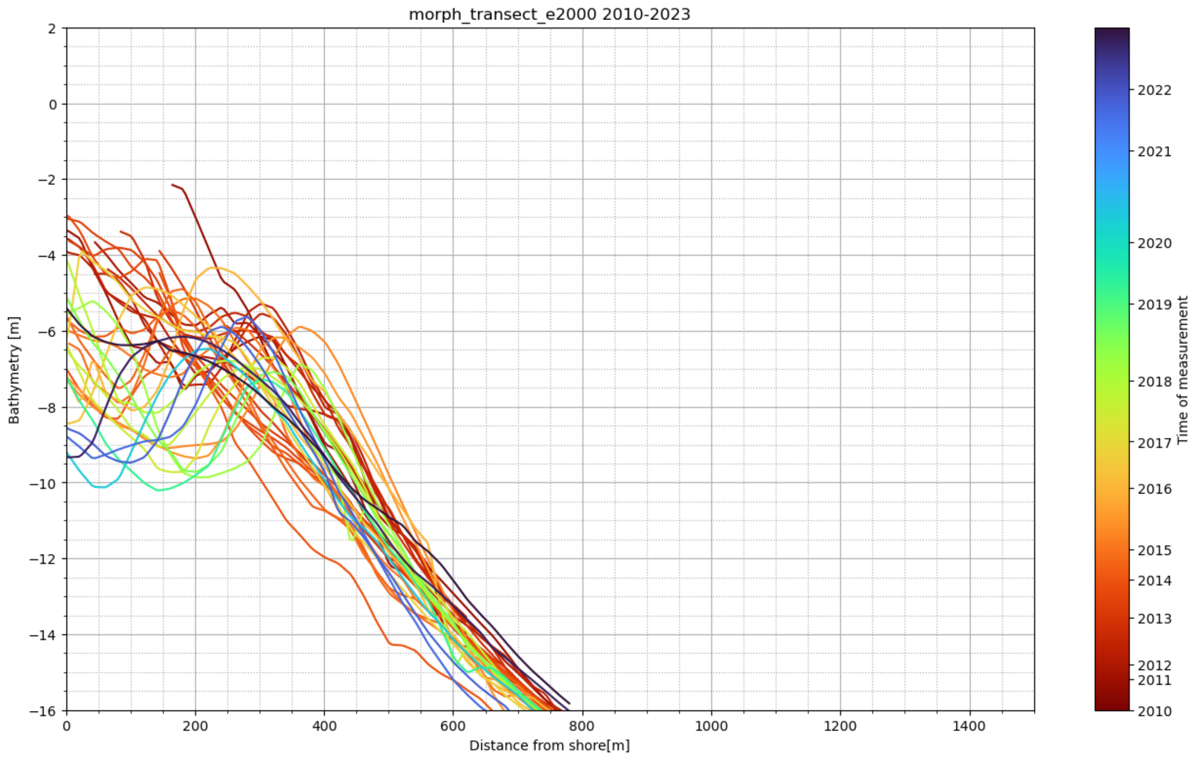


Figure A.11. Measured bed profiles 2 km east of navigation channel. Top, measured bed profiles before construction (2002-2010) of Landeyjahöfn harbour. Bottom, measured bed profiles after constructions of Landeyjahöfn harbour (2010-2023). Bathymetry elevation shown with respect to mean sea level. Mean sea level 1.33 m above CD.

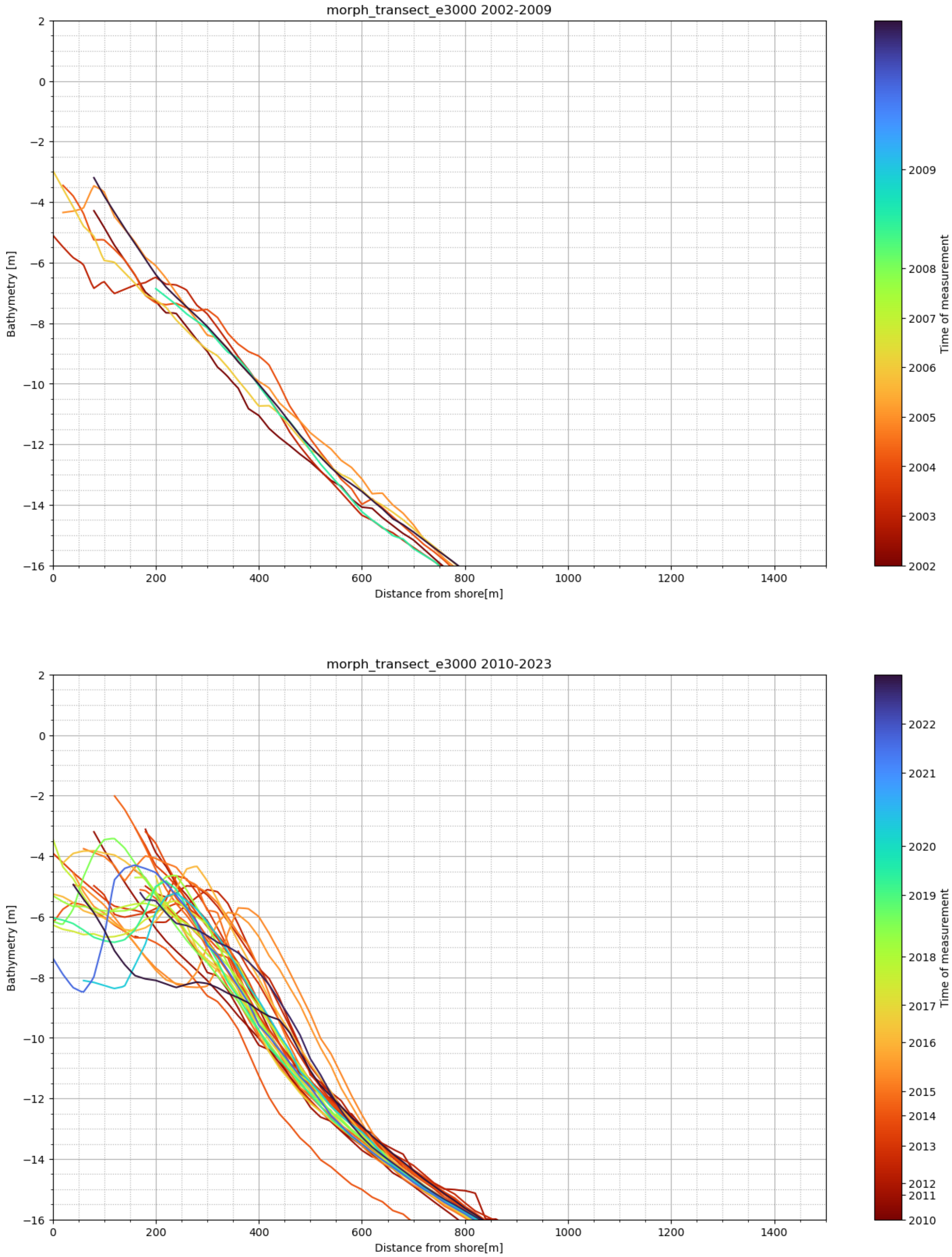
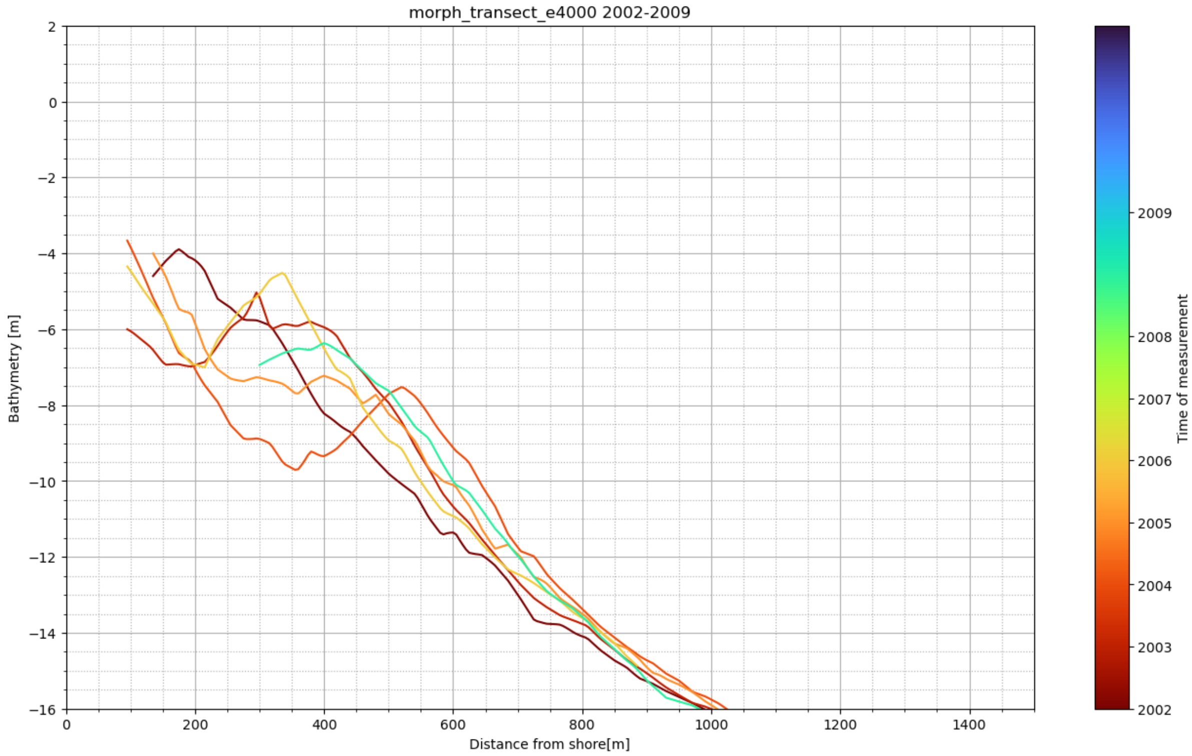


Figure A.12. Measured bed profiles 3 km east of navigation channel. Top, measured bed profiles before construction (2002-2010) of Landeyjahöfn harbour. Bottom, measured bed profiles after constructions of Landeyjahöfn harbour (2010-2023). Bathymetry elevation shown with respect to mean sea level. Mean sea level 1.33 m above CD.



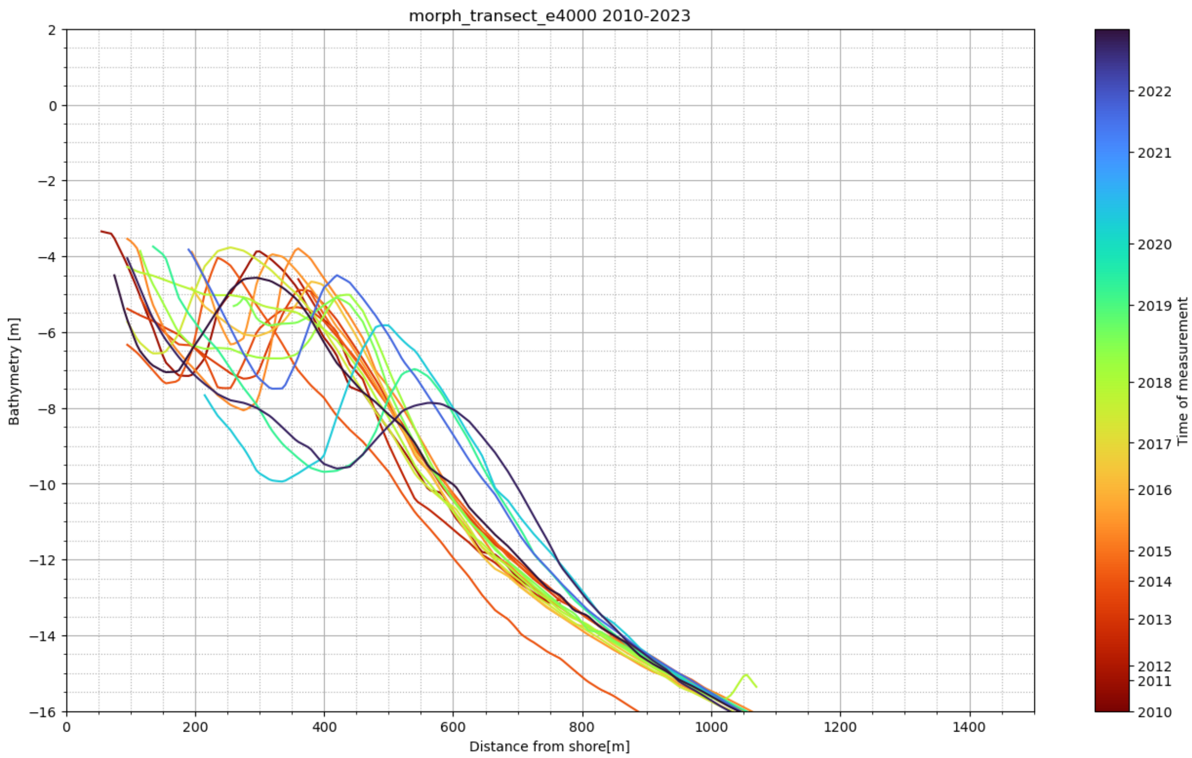
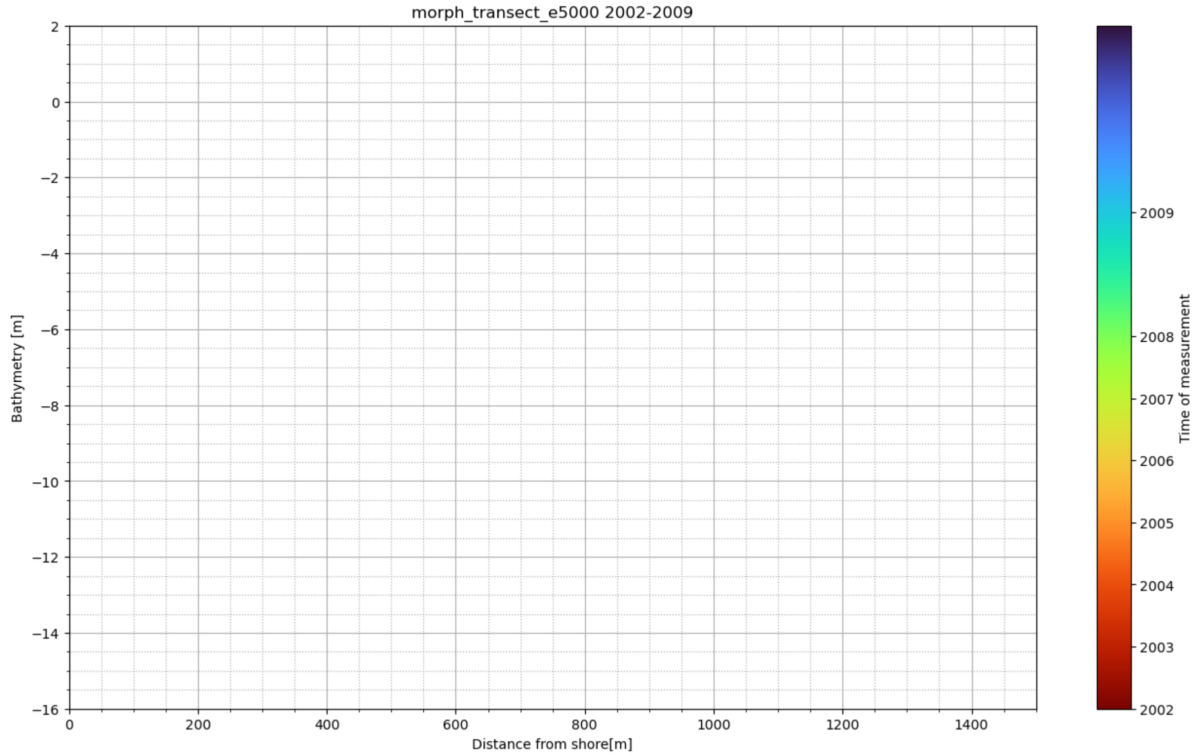


Figure A.13. Measured bed profiles 4 km east of navigation channel. Top, measured bed profiles before construction (2002-2010) of Landeyjahöfn harbour. Bottom, measured bed profiles after constructions of Landeyjahöfn harbour (2010-2023). Bathymetry elevation shown with respect to mean sea level. Mean sea level 1.33 m above CD.



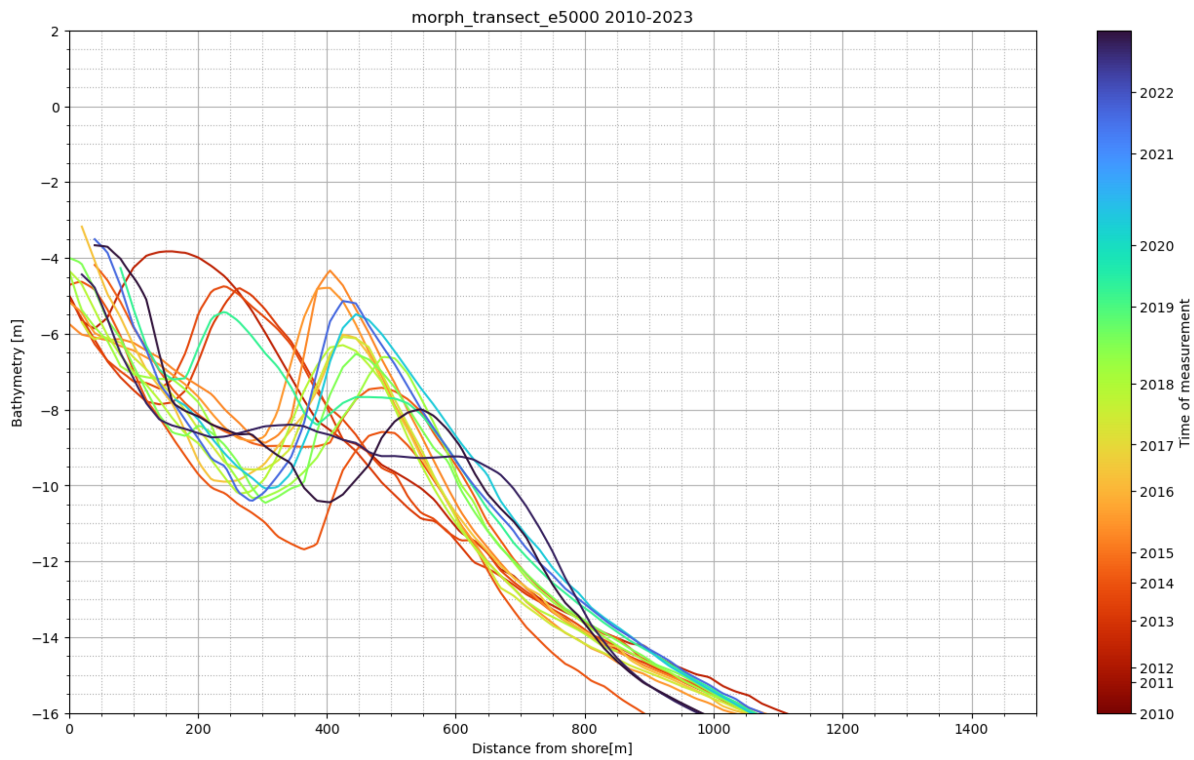


Figure A.14. Measured bed profiles 5 km east of navigation channel. Top, measured bed profiles before construction (2002-2010) of Landeyjahöfn harbour. Bottom, measured bed profiles after constructions of Landeyjahöfn harbour (2010-2023). Bathymetry elevation shown with respect to mean sea level. Mean sea level 1.33 m above CD.

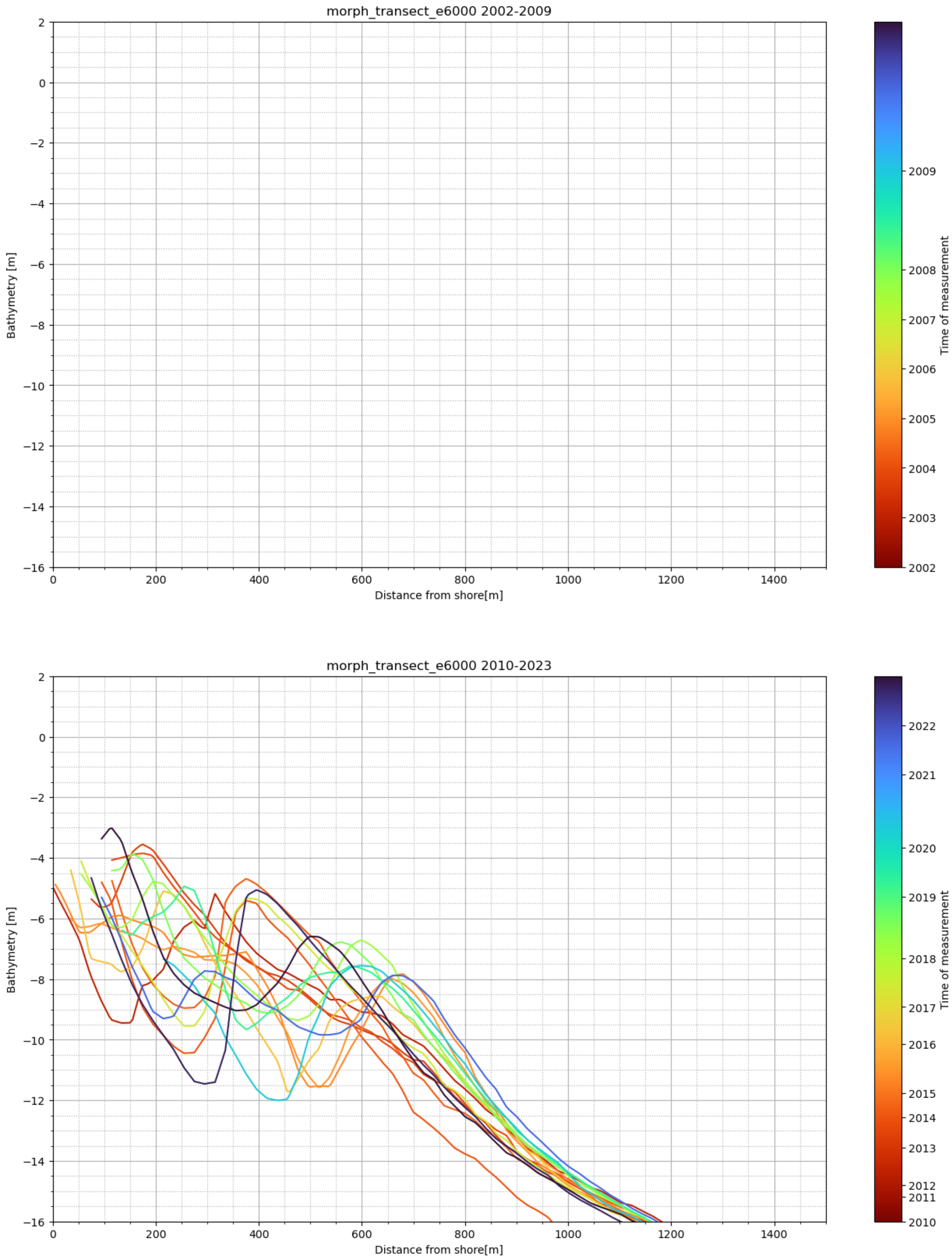


Figure A.15. Measured bed profiles 6 km east of navigation channel. Top, measured bed profiles before construction (2002-2010) of Landeyjahöfn harbour. Bottom, measured bed profiles after constructions of Landeyjahöfn harbour (2010-2023). Bathymetry elevation shown with respect to mean sea level. Mean sea level 1.33 m above CD.