SEDIMENT TRANSPORT AND BATHYMETRIC CHANGE AT HONRAFJÖRÐUR TIDAL INLET

SEDIMENTTRANSPORT OCH BATYMETRISK FÖRÄNDRING VID HORNAFJÖRÐURS TIDVATTENINLOPP

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Abstract
The relatively calm area behind barrier island are favored locations for harbors even though the navigation through the inlet itself can be challenging. Different measures like dredging or coastal structures might be necessary to ensure the desired water depth to maintain a safe navigation. Iceland as an island country depends strongly on reliable navigational routes connecting harbors to the ocean to ensure its economic wealth. The port of Höfn at the Hornafjörður inlet in southeastern Iceland is the main navigational link for the commercial fishing in this area.The interactions between longshore sediment transport and sediment transport induces by the inlet flow and waves are complex and led to navigational limitations in history. A deeper understanding of local transport patterns is needed to ensure a reliable navigation at the Hornafjörður inlet and limit economic losses in future. Regarding the complexity of the situation around the inlet and the limited data on local hydrodynamics, mathematical modeling must be used to simulate local currents. This article focuses on the research performed and model results gained in connection with the master thesis project "Sediment transport and bathymetric change at Hornafjörður tidal inlet – Field data analysis and mathematical modeling" (Klante, 2018).

Keywords: hydrodynamic modelling; Iceland; tidal inlet; morphology; sediment transport; TELEMAC

Sammanfattning
Det relativt lugna området bakom barriärö är en fördelaktig plats för hamn trots att navigationen genom själva inloppet kan vara utmanande. Olika åtgärder såsom muddring eller kuststrukturer kan vara nödvändiga för att säkerställa det önskade vattendjupet för en säker navigering. Island som är en önation är beroende av tillförlitliga navigeringsvägar som förbinder hamnar med havet. Detta för att säkerställa sitt ekonomiska välstånd. Hamnen vid Hornafjörður inloppet på sydöstra Island är den viktigaste navigeringslänken för det kommersiella fisket i detta område. Samspelet mellan kustströmmarnas sedimenttransport och sedimenttransporter som orsakas av inloppsflöde och vågor i området är komplexa och har historiskt sett lett till navigerigingsbegränsningar. En bättre förståelse av det lokala transportmönstret behövs för att säkerställa en pålitlig navigering vid Hornafjörðurs inlopp och begränsa ekonomiska förluster i framtiden. När det gäller komplexiteten i situationen kring inloppet och de begränsade data som finns om lokal hydrodynamik, måste matematisk modellering användas för att simulera de lokala strömmarna. Denna artikel fokuserar på den forskningen som utförts och modellresultatet som uppnåtts i samband med masterprojektet "Sedimenttransport och badymetrisk förändring vid Hornafjördur tidvatteninlopp – Fältdataanalys och matematisk modellering" (Klante, 2018).

1. Introduction

The interest in tidal inlets has been strong throughout history, since they have been used for shipping in commercial as well as in recreational way. The relatively protected area behind the barrier islands and a quite calm sea are preferred for the location of harbors. Moreover, the water quality inside lagoons is higher through the water exchange with the ocean. Therefore, tidal inlets gained a high economic importance due to the increase of industries relying on shipping as well as the increase of non-commercial boating usage (Van de Kreeke and Brouwer, 2017).

Iceland as an island country is depended on harbors, not only for the import and export of goods, but also for the national economy. With a GDP of 6.3 %, fishing is the third biggest industry and holds a high value for the country (Íslandsstofa Promote Iceland, 2018). The port of Höfn located at the Hornafjörður inlet in southeast Iceland is one important harbor for the Icelandic fishing industry and is affected by navigational problems caused through sediment accumulation in the inlet area.

The community Hornafjörður is a municipality at the southeastern coast of Iceland with ca. 2200 inhabitants. The town of Höfn located at the Hornafjörður inlet is the main harbor of this region (see Figure 1a and Figure 1b). The tidal inlet located south of Höfn connects the two fjords Hornafjöður and Skardsfjörður as well as Höfn's port with the Atlantic Ocean. Fishing and agriculture are the main industries for the region, with fishing being the larger one. Three fishing companies are located in Höfn, among these Skinney-Þinganes is the largest company in the eastern region of Iceland (Hróðmar and Sædís, 2018).

1.1. The Hornafjöður inlet

The south coast of Iceland is one of the most exposed coastlines in the world with yearly significant wave height exceeding 10 m. It is about 400 km long sandy shoreline fed by glacial rivers. As such, it experiences heavy littoral drift both to west and east depending on the wave direction.

The intensity of the littoral transport, defined as the gross transport, is approximately constant along the coast, being of the order 1-2 million m^3 per year. The net transport varies, being strong and east-going along the western sections and much smaller around the inlet to Hornafjörður (Deigaard and Brøker, 2016).

The Hornafjörður tidal inlet is easterly on the south coast. The inlet has a rock headland on its west side and several rock reefs about 2 km south of it shelter the inlet from southerly waves. It has two bays or fjords, Hornafjörður and Skarðsfjörður with an area on high tide of about 40 and 33 km^2, respectively. As the fjords are shallow the low tide

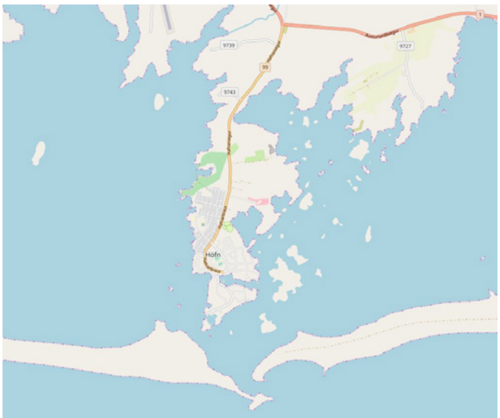

Figure 1a. *Overview of the Hornafjördur Area (OpenStreetMap Contributors, 2019)*

Figure 1b. *Aerial overview of the Hornafjördur inlet (photographer: Ásgeir Núpan Ágústsson)*

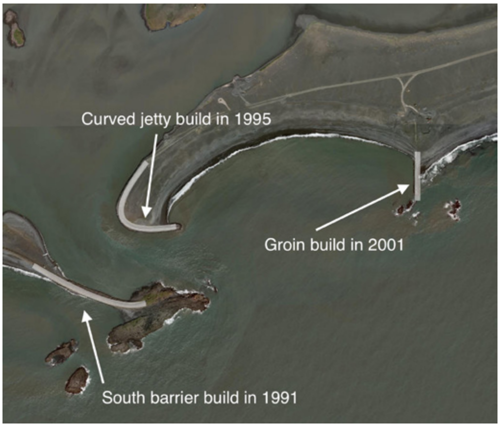

Figure 2. *Coastal protection structures at the Hornafjödur coastal inlet (NASA Landsat, 2018)*

area is considerably smaller. With a spring tidal difference of about 2 m, the tidal prism of about 63 million m^3 is the driving force to keep the inlet open. On spring tide the maximum discharge through the inlet is in the range of 3,400 to 4,400 m^3/s. Other inlets in the area that do not have large bay areas are often closed by wave action during the winter time (Viggosson et al., 1998).

The combination of high waves and course sediments result in a rather narrow inlet width which causes unusual high current velocities (Brunn et al., 1991). The maximum velocity is about 2.7 m/s on ebb tide and about 2.0 m/s on flood tide.

During the last century the location of the tidal inlet has been quite stable, however, heavy shoaling occurred in the entrance at 10 to 15 years interval, resulting in insufficient water depth and navigational limitations, which led to economic losses in the fishing sector.

Different structures (see Figure 2), which should help to stabilize the tidal inlet and minimize the sedimentation of it have been implemented during the last decades. After a breach of the South Barrier at the rock headland Hvanney in 1990 a rubble mound shore protection was constructed in 1991 to restore and reinforce the barrier. After a thorough study including both numerical and hydraulic models a curved jetty was constructed at the end of the East Barrier in 1995. To prevent littoral drift to the inlet from east a groyne was constructed about 1.2 km east of the inlet in 2001. These structures have successfully stabilized the inlet itself. On the other hand they do not influence the longshore sediment transport over the ebb shoal in front of the inlet, and do therefore not secure the required navigational depth of -8.0 m over the shoal that must be kept at all times (Viggosson, Sigurdarson and Jónsdóttir, 2005) .

1.2. Classification of the Hornafjörður inlet

The tidal prism and sediment transports induced by acting waves define shape and size of pathways through barrier islands and are unique for each coastal inlet. Even though sediment transport rates are quite large and different measures like dredging or coastal structures have to be taken to ensure a safe navigation along the inlet channel, the regions behind barrier islands are preferred locations for harbors. Figure 3 shows the three main components which define the morphological categorization of a coastal inlet and mainly influence the unique shape of each single inlet (Van de Kreeke and Brouwer, 2017).

The Hornafjörður inlet shows a characteristic curve with the opening facing to the east along the coastline (see Figure 4). The accumulation of sediment seawards the inlet is called ebb delta. In the case of the Hornafjörður inlet, the ebb delta is located along the eastern barrier with the consequence that the main ebb channel stretches along the coast and the terminal lobe shows a club like shape from west to east. The sediment accumulation on the inside of the inlet is called flood delta and usually shows a horseshoe shape (Hayes and FitzGerald, 2013). At the Hornafjörður inlet the flood delta is located between the channels to the two fjords. The aggregation of sediment along the southern barrier could be regarded as a part of the flood delta.

Each inlet shows a unique shape and properties regarding the mentioned three main morphological features. To understand the specifics of an inlet, different researchers have compared the characteristics and developed classification. This helps to estimate if the sediment transport at an inlet is mainly driven by wave energy or the tidal prism.

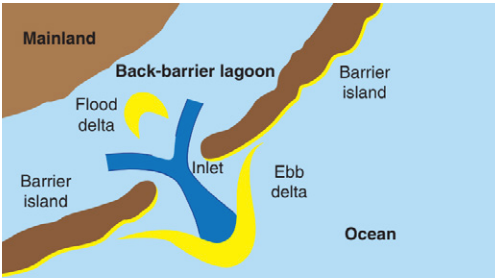

Figure 3. *Components of a typical coastal inlet (Van de Kreeke and Brouwer, 2017)*

Figure 4. *Aerial view of the Hornafjördur Inlet (NASA Landsat, 2018)*

Omarsson (2015) made an extensive study about the Hornafjörður inlet and its classification. Omarsson used the three different classifications after De Vriend et al. (2002), Hayes (1979) and Thuy et al, (2014). De Vriend et al. (2002) classifies inlets by its specific shape while Hayes (1979) and Thuy et al., (2014) compare the different strength of tidal prism and wave energy to classify an inlet. He concluded that the inlet is a wave dominated inlet with strong tidal influence. That means that the wave energy causing sedimentary movement at the inlet is slightly higher than the energy originating from the tidal prism.

1.3. Research problematic

As the coastline at the Hornafjörður inlet is specifically shaped and the orientation facing alongside the coast, hydrodynamic processes are complex and the information about specific sediment transport patterns is limited. The southern coast of Iceland is dominated by strong longshore sediment transport, which result in significant bathymetric changes and hydrodynamic interactions with the inlet flow and can cause navigational problems through the inlet. Seasonal variations play an important role, since waves tend to be larger during winter time and are able to transport larger sediment masses, which result in water depth variations between -6.0 m and -8.0 m at the ebb shoal. An additional uncertainty regarding the tidal prism is the present glacial rebound which resulted in a land uplift of ca. 22 mm during the last two decades. A further uplift has been estimated with a total amount of up to 1.0 m until 2050, which could result in a significant decrease of the tidal prism and could lead to further navigational problems.

A better understanding of the morphological evolution is needed to draw conclusions about specific transport patterns and to ensure a safe navigation through the Hornafjörður inlet in the future. Regarding the complexity of the interactions between wave currents and tidal prism it has been decided to use mathematical modeling to simulate the bathymetric processes along the inlet. Open TELEMAC-MASCARET is a model capable of simulating these interactions and has been chosen in order to gain the needed knowledge.

2. Methods

As the Hornafjörður inlet is an important navigational link, several measurements including extensive bathymetric surveys have been performed to allow safe navigation of different sized vessels through the inlet. To increase the understanding of the morphological patterns and its causes, analytical reviews of these measurements have been performed. The resulting data has been used to set up and run a 2D hydrodynamic model including sediment transports. This present paper focuses on the model properties and results rather than on the analytical reviews.

2.1. TELEMAC-MASCARET model suite

Open TELEMAC-MASCARET is an open source system of integrated solvers for simulating free-surface flow problems with help of finite element method. Different companies from France, United Kingdom and Germany with a broad knowledge in fluid dynamics in research and engineering manner have been developing this software since the early 1990s. Its wide approach can be used for many applications regarding free-surface flow and the software has been divided into several modules to ensure a reliable and fast computation of each specific case (TELEMAC-MASCARET Consortium, 2019). For this present research, three of the existing seven modules have been used: TELEMAC-2D to simulate two-dimensional hydrodynamics, TOMAWAC to simulate wave propagation and SISYPHE to provide information about the sedimentary movement.

The modules TELEMAC-2D, TOMAWAC and SISYPHE

The two-dimensional free surface flows in the horizontal space are calculated by TELEMAC-2D through the shallow water equations while using the water depth and velocity as unknown parameters. The software allows the user to assign different physical parameters to the model (e.g. water density). If no specific values are set by the user, the system uses common values (Ata, 2016). For the model used in the present research the Strickler value kst = 25 has been set for the whole area and the water density is defined with 1025 kg/m^3 as the whole area consists of salt water. Minor influences as for example brackish water inside the lagoons can be expected when looking at a tidal inlet. However, this fact has been neglected.

The TOMAWAC module is able to simulate wave propagation in ocean domains and coastal areas and solves the non-linear stationary wave theory (Awk, 2016). In general with decreasing water depth the interaction between bathymetry, wave increases and waves begin to break. Different theories are available to choose from when using TOMAWAC, in this present research the theory by Battjes and Janssen has been applied.

To gain information of the morphological development the SISYPHE module was used, which is able to simulate complex processes in different environments like rivers, estuaries and coastal areas. Different flow and sediment properties can be set by the user (Tassi, 2016). Since Iceland has a specific geological history and the sediments at the Hornafjörður inlet mainly consists of basalt, the typical density had to be changed to 2850 kg/m^3 to ensure a good representation of the present conditions. Next to the mentioned bathymetric measurements, various sediment measurements have been made, among other settings the grain size has been set to d_{50}=0.35 mm. Even though minor changes in grain size are present along the eastern barrier, a simplified approach has been used, which assigns the same grain size in the whole area.

All the above mentioned parameters are defined by the user in a simple text file, which is called steering file. Each module uses its own steering file, which makes it easier to apply changes if needed.

2.2. Model Set-Up

For any TELEMAC model the same standards apply when setting up a model, which are the following:

1. Generation of a triangle mesh
2. Define the boundary conditions
3. Steering file creation
4. Run the model
5. Post-Processing

The triangle mesh describes the three dimensional object of the areas bathymetry with help of points, vertices and faces. In this specific case, the mesh creation software Blue Kenue™ from the National Research Council Canada has been used to create the resulting mesh shown in Figure 5. To ensure a sufficient simulation, the main mesh density has been set to 500 m with a higher density at the inlet of minimum 15 m node distance. The bathymetry assigned to the mesh is the result of interpolation from different measurements performed at the tidal entrance with a grid of 10 m x 10 m.

The model boundaries where set according to local circumstances. A necessary assumption made, is that the whole model boundaries are impermeable except the specific river area and the southern part of the model. This might not represent reality, but a big enough total model area ensures that no boundary effects are present at the area of interest. Furthermore, the whole coastline has been

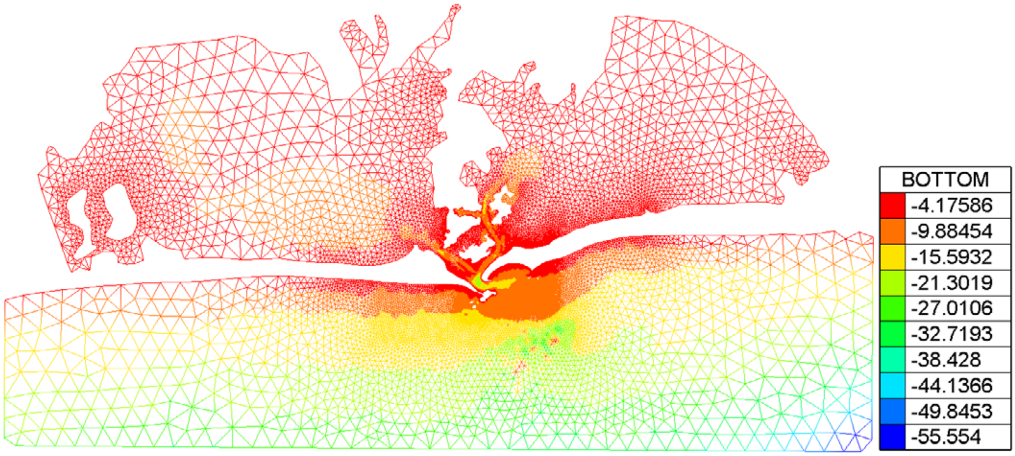

Figure 5. *Three dimensional mesh with bathymetry of the modelled area.*

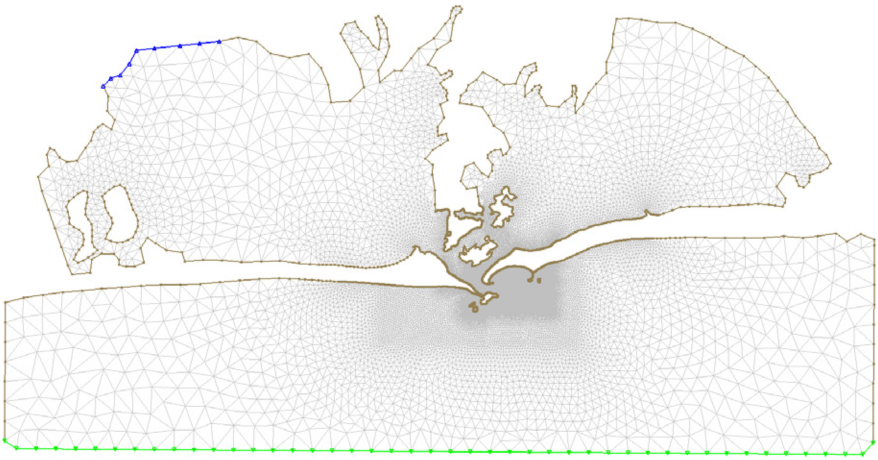

Figure 6. *Mesh of the model including set boundaries. Blue represents the river boundary and green the southern boundary.*

assigned with a height of -0.5 m to ensure that the investigated area is always covered with water.

In the northeastern part of the Hornafjördur fjord, the glacial river Austurflód enters the lagoon with a flow of ca. 100 m³/s (Sigurdarson, 2016). Although this river transports sediments into the lagoon this facts has been neglected in the model due to missing measurements. This river has been set as a boundary with prescribed flow. The southern boundary of the model has been set to be depended on the water level. This makes it possible to enter the tidal variance as well as specific wave conditions into the model. Specific locations inside the used mesh can be seen in Figure 6.

2.3. Calibration

To ensure the reliability of a model, calibration is an essential process. For the presented research it has been decided to only calibrate the hydrodynamic model, since a calibration of the wave model would not be feasible as parts of data are created through a Mike21 model from DHI.

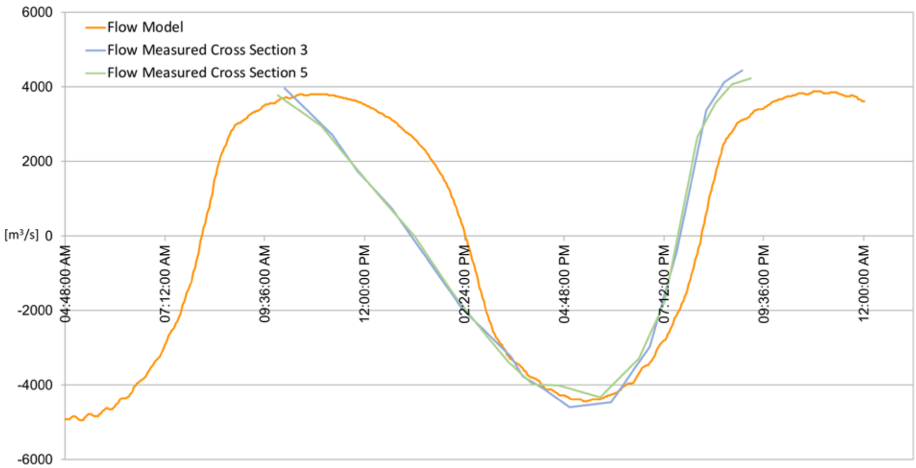

Figure 7. *Comparison of modeled flow against measurements*

A fair amount of measurements exist at the Hornfjörður inlet, though not all of them are usable for calibration purposes, since the time frames varies too much. Two cross sections along the inlet, where the total flow was measured, have been used to confirm the calibration of the model.

The calibration resulted in an R^2=0.93 for the maximum observed flow through the inlet. A plot of the model results compared with the measurements can be seen in Figure 7. The absolute error resulted in 2.1 % and 3.7 % for its specific location. From Figure 7 one can clearly see a time lag between model and reality, which is not present at the peak flow. This time lag could not be eliminated, but since the peak flow gained sufficient results in time, volume and current the model is expected to gain satisfactory results.

3. Simulation and Results

3.1. Simulated Events

The highest sediment transport rates, which will consequently result in navigational restrictions, have been noticed during high energy events. Consequently, it has been decided to simulate recurring high energy events to gain a better understanding about the general sedimentary movement at the Hornfjörður inlet.

As mentioned earlier, the main input into the model is the water level, which is determined by the tide and the acting waves. The southern area of Iceland follows a lunar semidiurnal tidal schedule, which results in a high tide and a low tide during approximately 25 h. The highest high tide is called spring tide and occurs on full moons and the lowest low tide is called neap tide and occurs on quarter moons (National Oceanic and Atmospheric Administration, 2017). For representation of a demanded high energy event a full moon event at the 7th August 2017 and the quarter moon event at the 30th July 2017 have been selected.

Different approaches exist when implementing waves into hydrodynamic models. To create a model with the real wave situations at the Hornafjörður inlet would be to demanding regarding computational resources, so it was decided to use the JONSWAP spectrum. The JONSWAP spectrum, a well-established wave spectrum used in various coastal simulations, has been applied in the simulations of this present paper. The dominating wave direction at the Hornafjörður inlet are waves approaching from southwestern direction, but observation shows that waves with southeastern origin seem to result in higher mobilization of sediments. To ensure a comparable results, three angles of approach have been selected, which are 212°, 141° and 180°, with true north at 0°. These

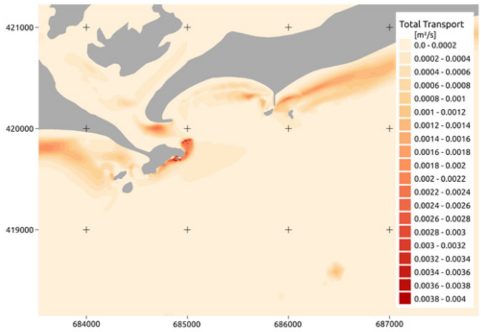

Figure 8. *Total sediment transport rates at low spring tide and waves from southwestern origin.*

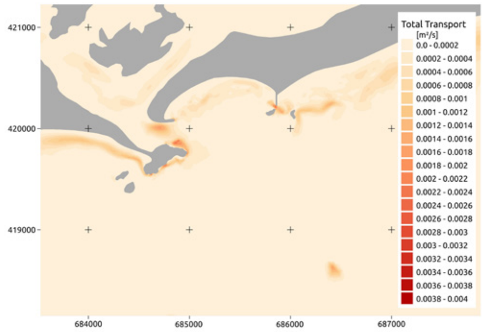

Figure 9. *Total sediment transport rates at low spring tide and waves with southeastern origin.*

three angles result from statistical analysis of wave directions from the years 2002 to 2018.

3.2. Simulation Results

The analysis of the model results show not just a clear difference in the specific wave climate, but also a clear difference in bed shear stresses and sediment transport rates. As expected, the inlet itself is dominated by wave and tidal currents to almost the same amount. Generally spoken transport rates are much higher at spring tide events, which results in the unwanted accumulation of sediments in front of the inlet. Especially when comparing the results at neap tide for waves approaching from southwest to the results with waves approaching from southeast, large differences are noticeable in the total transport rates (see Figure 8 and Figure 9). Because the transport rates with waves from southeastern origin are lower at low tide, more sediment masses can pile up, which can result in navigational limitations.

As the simulation results give a better understanding of the present sediment transport, different measures could be introduced to improve the navigation through the inlet. Aim of such measures should be the limitation of sediment transport to the inlet to minimize accumulation (Omarsson, 2015). One of the most discussed and considered structures is the construction of connecting jetty between the headland Hvanney and one of the southern rocks of Einholtskletter (see Figure 10). Implementing this jetty into the model gives significant results regarding the limitation of sediment transport to the inlet area. Even though the accumulation of sediment west of the jetty increases up to 150 % the sediment transported to the ebb shoal shows a decrease of up to five times at the area of the ebb shoal. For a high energy event as the one simulated (spring tide, waves with 212° of approach) the total amount of sediment transported could be limited up to 10.800 m^3. However, it is important to notice that this sediment mass will be trapped west of the jetty and might have to be dredged in the longer run.

4. Discussion and conclusion

To allow a feasible modeling process simplifications and assumptions are needed, which will result in different restrictions and uncertainties. To give an example, the limitation of a mathematical model should be mentioned, not just by its input

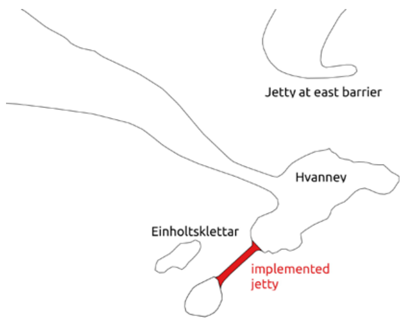

Figure 10. *Implementation of a jetty to limit sediment transport to the inlet.*

data but also by the distorted application of a real phenomenon.

Due to the complexity of the issue at the Hornafjörður inlet, simplifications have been unavoidable. The main simplifications made concern the bathymetry and the coastline and result in a stationary appearance of them. Since the modeled time is reasonable short, this kind of simplifications are acceptable and assumed to have minor influences on the results.

Tidal variations and wave actions have been limited to a specific event and well known research spectrum. This simplification may not represent local characteristics but is justifiable, since various researches have proofed its applicability (GODA, 2008). General transport patterns gain reasonable results yet transport quantities should be considered with care and need further investigation if specific measures limiting the sediment transports will be realized in future projects.

Despite assumptions made and simplifications, the simulations are able to show the interactions between wave and tidal currents regarding the mobilizations of sediments. The simulations show that sediment transport to the inlet can be limited when implementing specific measures. A detailed analysis of available measurement data will always be a helpful tool to empirical understand the acting processes and local phenomena. Especially for the inlet at Höfn the great amount of collected data is not always analytically processed. A more detailed data analysis and evaluation will help to understand morphological patterns even better. One should consider to apply automated processes as well as machine learning for this kind of data processing.

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