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THE EFFECT OF COASTAL TRANSECT EXTRACTION METHODS AND RESOLUTIONS ON CALCULATED COASTLINE POSITION AND COASTAL SAND VOLUMES

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Preface

This report was written as a part of my Bachelor Thesis assignment conducted at Rijkswaterstaat. I chose this assignment as I was interested in coastal management and wanted to learn more about how this was done in the Netherlands.

Its production was made possible through my collaboration, for a period of ten weeks, with the department of Hoogwaterveiligheid at Rijkswaterstaat WVL, and most notably, my supervisor Niels van Kuik. This research was also made possible through the University of Twente, and my internal supervisor Geert Campmans. This report was written in collaboration with both supervisors who provided feedback throughout the writing process. Lastly, a special thanks goes out to both my fellow students and my parents who both read and provided feedback on the draft reports.

I hope you enjoy reading this report. Please contact me if you have any questions or if you need any clarifications.

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Summary

Knowing the position of the coastline is vital to the Netherlands as it enables Dutch coastal managers to keep track of the erosion of the coast. Rijkswaterstaat would like to explore whether the current software used for Morphological Analysis (MorphAn) is able to schematize the measured data into JarKus transects similarly to the Matlab-based program Maria. This will be done by visual inspection of a number of reference transects and an analysis of the calculated coastline position and coastal volumes. Secondly, Rijkswaterstaat would like to know how a change in the horizontal grid size of the topographic measurements affects the calculated coastline position and coastal volumes.

After comparing the transects both qualitatively and quantitatively, a change to MorphAn would show an average receding coastline by 1.05m. This is mainly caused by a cross-shore shift in the wet measurement due to the differences in transect extraction method between the Maria and MorphAn applications. This receding coastline can be attributed geographically to the Wadden islands and the Zeeland coast. The other coastal areas, such as the Holland coast, show a seaward shift of the calculated coastline. The changes to the calculated coastal sand volumes reflect this receding coastline with an average calculated loss of 3.15 million cubic metres (Mm^3) in the calculated total volume of sand. The calculated losses in volume can be found in deep and beach volume, which shows that those losses are heavily influenced by the wet measurement.

The second aspect of this research is focused on the effects of changing the horizontal topographic resolution of the transects within MorphAn. The results show a shift in calculated coastline position seaward by 0.87m when using a 2m dry resolution compared to a 5m dry resolution. This is caused by the intense variation of the measurements at a 2m dry resolution. The gains are geographically located in the Wadden islands and the Zeeland coast, whereas the areas around the Holland coast see a recession in the coastline. The change in resolution affects the calculated total sand volume, increasing it on the Dutch coast by 3.75 Mm^3.

These results show that a change in transect extraction method paired with a change in topographic resolution from 5m to 2m would show little effect on the current coastline measurements. A combined shift in calculated coastline position would then be 0.176m landward and a combined change in calculated total volume of 0.6Mm^3 of sand. These effects can be considered insignificant as the topographic grid size of 2m by 2m is much larger than the change in calculated coastline position. Furthermore the 0.6Mm^3 of sand lost is much smaller than the 12Mm^3 of sand supplied per year to the Dutch coast (Brand, Ramaekers, & Lodder, 2022).

The final recommendation of this paper would be that, based on these results the use of the MorphAn application along with a change of topographic resolution from 5m to 2m does not significantly affect the calculated coastline position and calculated coastal sand volumes. This needs to be further investigated with detailed research on each coastal area in order to verify that the results obtained on the reference transects indeed form a reliable generalisation of the Dutch coastline.

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1. Introduction

Knowing the position of the coastline is vital to the Netherlands as it enables Dutch coastal managers to keep track of the erosion of the coast. A receding coastline can be a sign of a problem as that means the sea gets closer to the people and their property. In 1990, Dutch policy adopted a plan to “hold the line” in reference to the 1990 coastline (Staten-Generaal, 1990) called the ‘base coastline’.

This plan involved monitoring the coastline to ensure that, at the locations where the base coastline was defined, no territory was being lost to the sea as was the case previously. This monitoring enables Dutch coastal managers to plan coastal nourishments in specific areas of the coast appropriately to prevent the coastline from receding (Brand, Ramaekers, & Lodder, 2022).

The coastline position is derived from transects perpendicular to the coast. These transects are separated by around 250m and logged in a dataset named JarKus. These JarKus transects are measured yearly since 1965. Today, the transects are derived by a Matlab-based program called ‘Maria’, allowing measured bathymetric and topographic data to be schematized in cross-shore transects.

Rijkswaterstaat would like to explore whether the current software used for Morphological Analysis (MorphAn) is able to extract the measured data into JarKus transects similarly to the Matlab-based program Maria. This will be done by visual inspection of the derived transects and an analysis of the calculated coastline position and coastal volumes. Secondly, Rijkswaterstaat would like to know how a change in the horizontal grid size of the topographic measurements effect the calculated coastline position and coastal volume.

1.1. Context

1.1.1. Terminology

The keywords and abbreviations used in this document are listed and defined in Table 1.

Table 1 Keyword definitions and abbreviations

Keyword	Definition
Current Coastline position (MKL)	Position where the current coastline lies based on the calculation detailed in ir. Verhagen, 1990.
Base coastline (BKL)	Dutch coastline position inscribed in law. First calculated in 1990 (ir. Verhagen, 1990) and later revised in 2001, 2012 and 2017 (expertisenetwerk waterveiligheid, 2016), (Ministerie van Infrastuctuur en Waterstaat, 2018).
Coastal sand volume	Volume of sand found in the dunes, beach and depths along the coast (Mulder, Hommes, & Hortsman, 2011)
Raster	Grid composed of "mutually exclusive cells that together make up the complete study space", these cells are here squares with a length of the **resolution**. (Faculty of Geo-Information Science and Earth Observation (ITC), 2013)

Resolution	Here referring to spatial **resolution**, represents the cell width of the **raster**. This means a data point is collected every so many meters. The lower the value of the resolution, the higher the resolution is as the raster then contains more cells of smaller size. (Faculty of Geo-Information Science and Earth Observation (ITC), 2013)
Transect	Line of data points going through a **raster**. (Faculty of Geo-Information Science and Earth Observation (ITC), 2013). The **resolution** of a **transect** represents the distance between two data points within a transect.
Topography	Measurement of the height of the terrain above the **water level**. (Gens, 2010)
Bathymetry	Measurement of the height of the terrain below the **water level**. (Gens, 2010)
JarKus	Yearly **topography** and **bathymetry** measurements taken in **transects** along the Dutch coast. Each logged **transect** has a topographic **resolution** of 5m. (Ministry of Transport, Public Works and Water Management, 1996)
NAP	Normaal Amsterdams Peil, Datum of the average sea level in the Netherlands measured by Rijkswaterstaat (Rijkswaterstaat, n.d.).
Alongshore	Parallel to the coastline
Cross-shore	Perpendicular to the coastline
RSP	Rijksstrandpalenlijn, locations along the coast marked by a beach pole separated by around 200-250m at which **cross-shore** coastal **transects** are made. (Directoraat-Generaal Rijkswaterstaat, 1995).
Coastal area (Kustvak)	**Alongshore** connected section of the Dutch coast used to separate the datasets (Directoraat-Generaal Rijkswaterstaat, 1995).
Transect number (raainummer)	**Alongshore** distance between a datum in the coastal area and the **RSP**. This serves as a unique numerical identifier for each **transect**. (Directoraat-Generaal Rijkswaterstaat, 1995).
J5 transects	Abbreviation mentioning the 2021 **JarKus** transects generated in the Maria software by schematizing raw wet measurements to the transects and extracting dry measurements from a grid. This method uses a **horizontal topographic resolution** of 5m and a **horizontal bathymetric resolution** of 10m.
M5 transects	Abbreviation mentioning the transects generated in MorphAn from grid data with a horizontal **topographic resolution** of 5m and a horizontal **bathymetric resolution** of 10m.
M2 transects	Abbreviation mentioning the transects generated in MorphAn from grid data with a horizontal **topographic resolution** of 2m and a horizontal **bathymetric resolution** of 10m.

1.1.2. Study area

The study will be conducted on transects along the Dutch coast. Most of the research will look at 26 reference transects set up by Deltares and Arcadis (Arcadis, 2021) as a good reference for Dutch coastal areas. These transects can be found in Table 2 which describes the coastal area ("Kustvak") containing the transect and its identifier ("raai"). The combination of both coastal area and transect number is unique. Figure 1 shows the locations of these reference transects.

Table 2 Representative reference coastal transects along the Dutch coast (Arcadis, 2021)

Waddenkust

Kustvak		Raai	
2	Schiermonnikoog	3.40	
2	Schiermonnikoog	7.00	*
3	Ameland	6.00	
3	Ameland	10.00	*
4	Terschelling	9.00	
4	Terschelling	17.00	*
5	Vlieland	43.77	*
5	Vlieland	52.89	
6	Texel	11.90	
6	Texel	18.53	*

Hollandse Kust

Kustvak		Raai	
7	Noord-Holland	3.08	*
7	Noord-Holland	9.28	*
7	Noord-Holland	14.83	*
7	Noord-Holland	19.55	*
7	Noord-Holland	37.75	*
8	Rijnland	66.25	*
8	Rijnland	81.75	*
9	Delfland	99.75	*
9	Delfland	111.96	*
9	Delfland	118.25	*

Deltakust

Kustvak		Raai
11	Voorne	10.02
12	Goeree	10.00
13	Schouwen	5.29
15	Noord-Beveland	3.00
16	Walcheren	15.30
17	Zeeuws Vlaanderen	10.46

** = raailocatie in bestaande set met profielen*

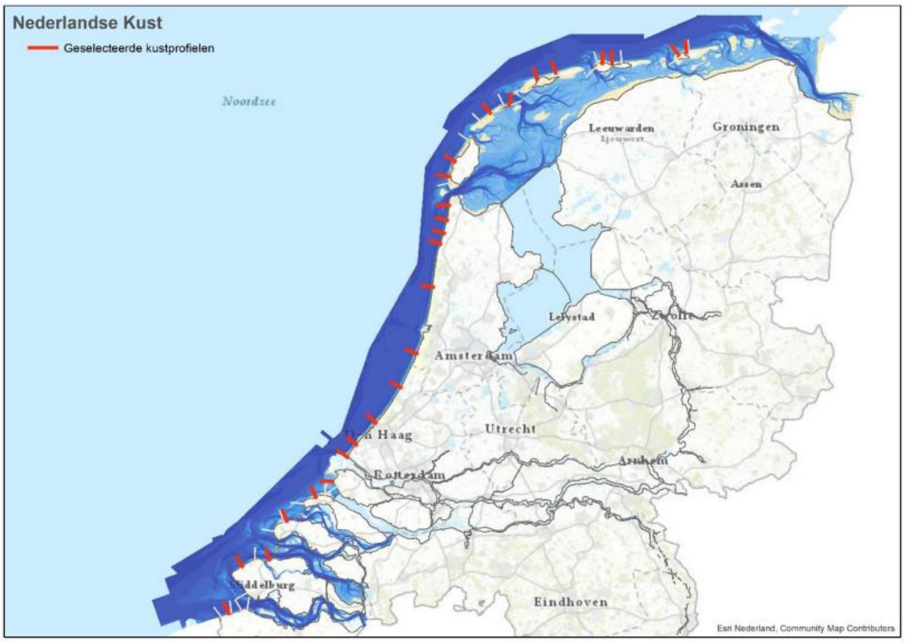

Figure 1 Overview of the Dutch reference coastal transects seen in red (Arcadis, 2021)

1.2. Theoretical framework

1.2.1. Deriving the Dutch coastline

The morphology of the Dutch coastline is measured in cross-shore transects. The transects are currently extracted from raw measurements using the Maria application. Each transect is both measured and derived yearly to log it into the JarKus dataset. This dataset is used to analyse the coastline position and to compare it to the base coastline (Ministry of Transport, Public Works and Water Management, 1996). This is done to indicate whether the coastline stays in place with regards to the base coastline (Staten-Generaal, 1990). Nourishing of the coastline is prioritised strategically in those areas where the current coastline is further landward than the base coastline (Brand, Ramaekers, & Lodder, 2022). The extraction of transects directly from data is also possible in MorphAn, which is looking to replace Maria in creating the future JarKus dataset.

1.2.2. Calculating the coastline position

The current Dutch coastline or “Momentane Kustlijn” (MKL) is an alongshore line derived by using the method inscribed in law in 1990.

The coastline position is derived from each transect using the steps shown in this section (ir. Verhagen, 1990). This method comes with an explanatory diagram shown in Figure 2. In this figure, H represents the height between the low water level and the dune foot, A represents the sand volume seaward of the dune foot and above the level calculated by

$Low\ water\ level - H$" (ir. Verhagen, 1990), x_{DV} is described as the distance between the dune foot and the RSP line, and lastly, x_{MKL} is the distance between the RSP and the current coastline position or MKL. In Verhagen 1990, the following five steps were defined:

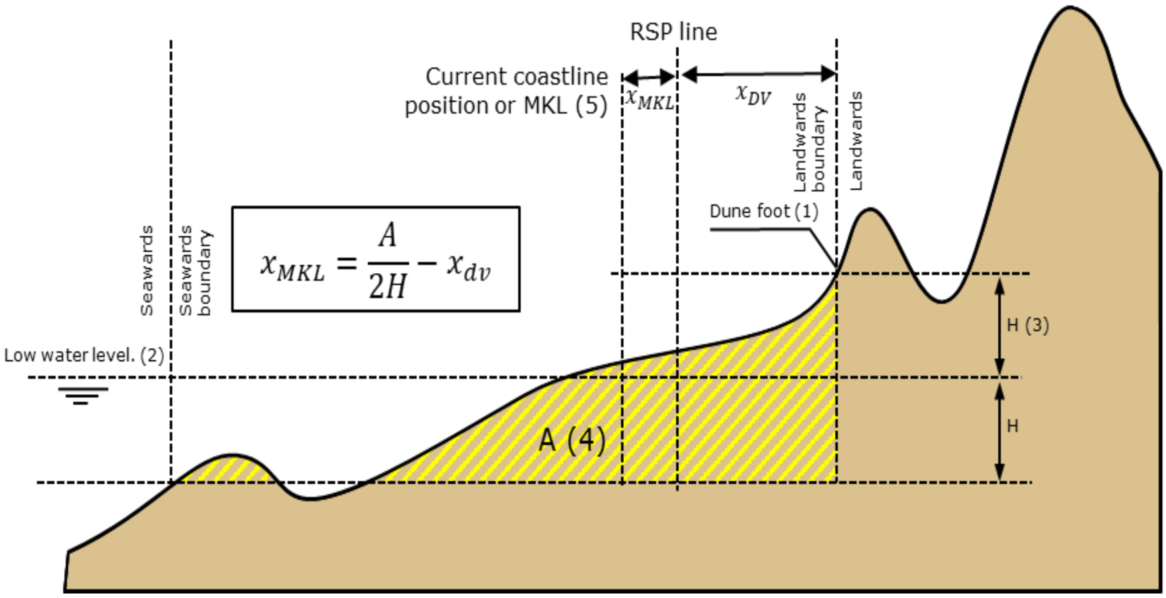

Figure 2 Transect side view of the parameters needed to calculate the Dutch coastline position adapted from ir. Verhagen, 1990.

1. "Determine the location of the dune foot. This is in principle determined by looking for the intersection between the slope of the dune front and of the dry beach."
2. "Determine the height of the average low water level"
3. "Calculate height of the dune foot (H) above average low water level"
4. "Calculate the sand volume (A) seaward of the dune foot and above the level calculated by $Low\ water\ level\ - H$."
5. "Define the position of the instantaneous coastline (MKL) along the national beach pole line as: $(A/2H) - x_{dv}$ " (ir. Verhagen, 1990).

At specific locations along the Dutch coast, adaptations are made on the standard procedure presented here. For example, the height of the dune foot is lowered, or a set seaward boundary is used to exclude sand volume further seaward. A basic explanation is given in Hillen et al., 1991. For simplicity, these are not discussed in this report.

1.2.3. Measuring coastal sand volume along the Dutch coastline

An indication of the sand volume within different heights along a transect can be calculated as follows:

- The deep volume from -50m NAP to -2m NAP
- The beach volume from -2m NAP to +4m NAP
- The dune volume from +4m NAP to +50m NAP

The volume of sand is a result of direct integration of the topography and bathymetry measured along the coastline. This integration results in a cross-shore sand volume in m^3 per meter alongshore. The final volume is therefore in m^3/m. A diagram of the volume calculation can be found in Figure 3 where A represents the volume of sand calculated.

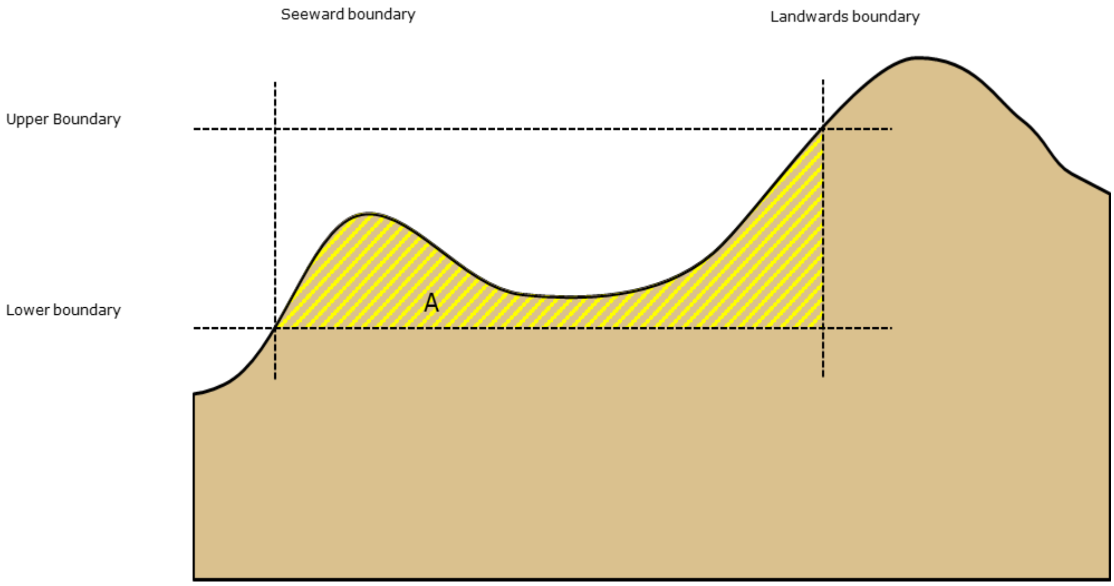

Figure 3 Sand volume measurement sections

1.3. Research dimension

1.3.1. Problem statement

The problem faced is as follows: Rijkswaterstaat would like to change the transect extraction method from using the method employed by Maria to the method employed by MorphAn. The change in extraction method is caused by the necessity to provide a method that is user-friendly to coastal managers. Rijkswaterstaat would like to explore the change in transects derived through MorphAn with respect to the current transects derived using Maria. Effects on the calculated coastline position and coastal sand volumes will be analysed. This research provides a first exploration on these effects.

Furthermore, within MorphAn, Rijkswaterstaat would like to know how changing the topographic resolution from 5 to 2 meters affect the calculated coastline position and coastal volume.

1.3.2. Research objective

From the problem statement the research objective can be defined in two statements:

1) Determining whether the effects of a switch to deriving JarKus transects using the MorphAn application are significant by analysing calculated coastal volumes and coastline positions along the Dutch coastline.
2) Determining whether a change in topographic horizontal resolutions from 5 to 2 meters are significant by analysing calculated coastal volumes and coastline positions along the Dutch coastline.

1.3.3. Research questions

The goal of Rijkswaterstaat is to know whether the change in resolution and transect extraction method has any effects on calculated coastline positions and total sand volume along the Dutch coastline. To achieve this goal, research questions have been formulated and will be discussed in this section.

1. ***What are the effects of deriving transects using the MorphAn application on the same resolution as the current JarKus transects derived using Maria regarding calculated Dutch coastline position and coastal sand volumes?***

Coastline position and coastal sand volumes are linked to the methods used to calculate them. This change in model software also comes with a change in method, instead of using transects directly, transects are now derived from raster data obtained through topography and bathymetry. The effects of these changes will be measured on the 26 Dutch reference transects (Arcadis, 2021) using the calculated coastline position and coastal sand volume as a criterion. This research question leads to sub questions listed below.

- 1a. What are the main differences in calculated coastline position and coastal sand volumes when extracting transects from the MorphAn application compared to the Maria application on reference transects?
- 1b. What could be the cause of the differences in calculated coastline position and coastal sand volumes when deriving transects from the MorphAn application compared to the Maria application on reference transects?
- 1c. How significant are the differences in calculated coastline position and coastal sand volumes when deriving transects from the MorphAn application compared to the Maria application on reference transects?
- 1d. In which reference transects are large differences observed in calculated coastline position and coastal sand volumes when deriving transects from the MorphAn application compared to the Maria application?

2. ***What are the effects of a change in topographic horizontal resolutions using the MorphAn application to the calculated Dutch coastline position and coastal sand volumes?***

After investigating the change in transect extraction method, the change of horizontal topographic resolution from 5m to 2m will be investigated. The effects of these changes will be measured on the 26 Dutch reference transects (Arcadis, 2021) using the calculated coastline position and coastal sand volume as a criterion. This research question leads to sub questions listed below.

- 2a. What are the main differences in calculated coastline position and coastal sand volumes when changing the horizontal topographic resolution from 5m to 2m?
- 2b. What could be the cause of the differences in calculated coastline position and coastal sand volumes when changing the horizontal topographic resolution from 5m to 2m?
- 2c. How significant are the differences in calculated coastline position and coastal sand volumes when changing the horizontal topographic resolution from 5m to 2m?
- 2d. In which reference transects are large differences observed in calculated coastline position and coastal sand volumes when changing the horizontal topographic resolution from 5m to 2m?

1.3.4. Scope

The research will focus on calculated coastline position and coastal sand volume in the Netherlands. These two elements serve as performance indicators for both research questions. The differences in performance will be assessed qualitatively and quantitatively. The main goal of this research is identifying the causes of the differences. A qualitative explanation for the causes is given for each observed difference. In this way, Rijkswaterstaat is supported to consider whether MorphAn could replace Maria. Rijkswaterstaat is also supported if a change in the horizontal resolution of the JarKus transect has significant effects.

2. Methodology

2.1. Coastal transect creation

2.1.1. Measuring topographic and bathymetric data

The Dutch coast is separated into several areas. Coastal areas or “kustvakken” are areas defined for a certain part of the coast. The names and locations of Dutch coastal areas, along with the transects they include within them can be seen in Table 3 and Figure 4 (Directoraat-Generaal Rijkswaterstaat, 1995).

Table 3 Coastal areas and transect numbers (Directoraat-Generaal Rijkswaterstaat, 1995)

1. Rottumeroog/plaat	raai	00.25	t/m	15.25 (m.i.v. 1995 niet meer op te nemen)
2. Schiermonnikoog	raai	01.00	t/m	16.10
3. Ameland	raai	46.00	t/m	25.16
4. Terschelling	raai	30.04	t/m	59.02
5. Vlieland	raai	33.00	t/m	54.60
6. Texel	raai	04.16	t/m	34.52
7. Noord-Holland	raai	00.20	t/m	55.00
8. Rijnland	raai	56.25	t/m	97.25
9. Delfland	raai	97.40	t/m	118.50
10. Maasvlakte	raai	00.00	t/m	16.10
11. Voorne	raai	06.20	t/m	17.00
12. Goeree	raai	02.80	t/m	25.25
13. Schouwen	raai	00.84	t/m	18.00
14. Oosterschelde	raai	00.20	t/m	07.00
15. Noord-Beveland	raai	01.20	t/m	05.20
16. Walcheren	raai	05.40	t/m	37.50
17. Zeeuws-Vlaanderen	raai	00.11	t/m	14.87
18. t/m 25. Reserve voor mogelijke nog nader aan te wijzen gebieden.				

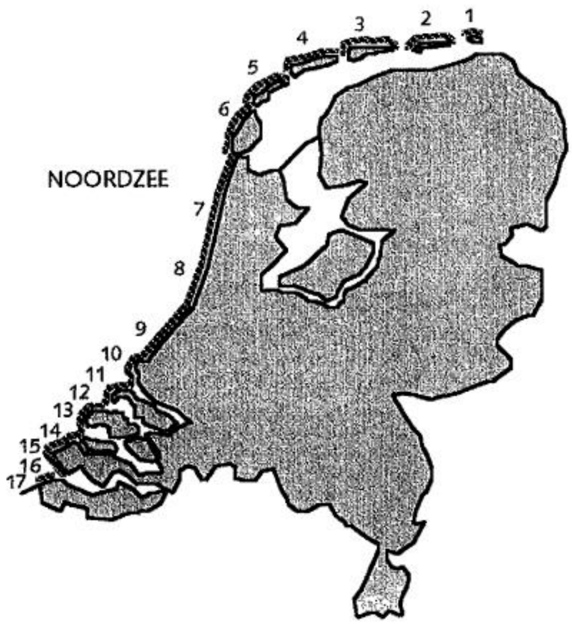

Figure 4 Coastal area locations in the Netherlands (Directoraat-Generaal Rijkswaterstaat, 1995)

The coastline position in the Netherlands is calculated in cross-shore transects for beach pole lines (RSP) present along the Dutch coast as shown in Figure 5. These transects are defined normal to the shoreline and are separated alongshore by around 250m. Each transect has a unique combination of coastal number (‘kustvak nummer’, in Dutch) and transect ID (‘raai nummer’, in Dutch) associated to it as shown in Table 3.

Two measurements are made for each transect: topography measures the height of the surface above the water level and is also referred to as ‘dry’ measurement. Bathymetry measures the height of the surface below the water level and is also referred to as ‘wet’ measurement.

Figure 5 Example of transects in Delfland (Rijkswaterstaat, n.d.)

The measurement of the topography was performed through an aerial laser scan. A plane flew over the coastal area during low tide and sent out a laser to the ground. That laser then bounced back and the time it took gave an indication of the height of the surface. Together with the altitude of the plane, the surface elevation was measured. This enabled a calculation of the altitude of the shoreline through a digital elevation model or DEM (Ministry of Transport, Public Works and Water Management, 1996).

The altitude below the shoreline or bathymetry was measured using a ship that went on high tide along the transect and used an automatic sounding system. This system sent out a sound signal through the water that bounced back from the seabed. The time it took for the sound wave to cover the distance from the ship to the seabed and back along with the altitude of the ship was measured. This data enabled the measurement of the seabed depth (Ministry of Transport, Public Works and Water Management, 1996).

Topography and bathymetry data was provided to Rijkswaterstaat in the form of gridded data. The process used to create the grid is a process named “gridding”. This process involved using a weighted average of the data points found within a cell to obtain a value for the cell centre. The weights used for each data point were proportional to the distance to the cell centre. Topographic measurements were stored within grids with a cell size of either 5m or 2m. These grids share the same topographic measurements and differ only in grid size. Bathymetry measurements were stored within grids with a cell size of 10m.

2.1.2. Transect extraction framework

From the raw topography and bathymetry data, different types of reference transects were extracted. The types of transects used in this research were:

- Transects extracted using the MorphAn application with a horizontal topographic resolution of 5m (M5)

- Transects extracted using the MorphAn application with a horizontal topographic resolution of 2m (M2)
- Transects extracted using the Maria application provided by Rijkswaterstaat with a horizontal topographic resolution of 5m (J5)

The extraction of the M2 and M5 transects was essential to the research as they were required to perform the comparisons showcased in Figure 6. The M5 and M2 transects were derived following the scheme depicted in Figure 7.

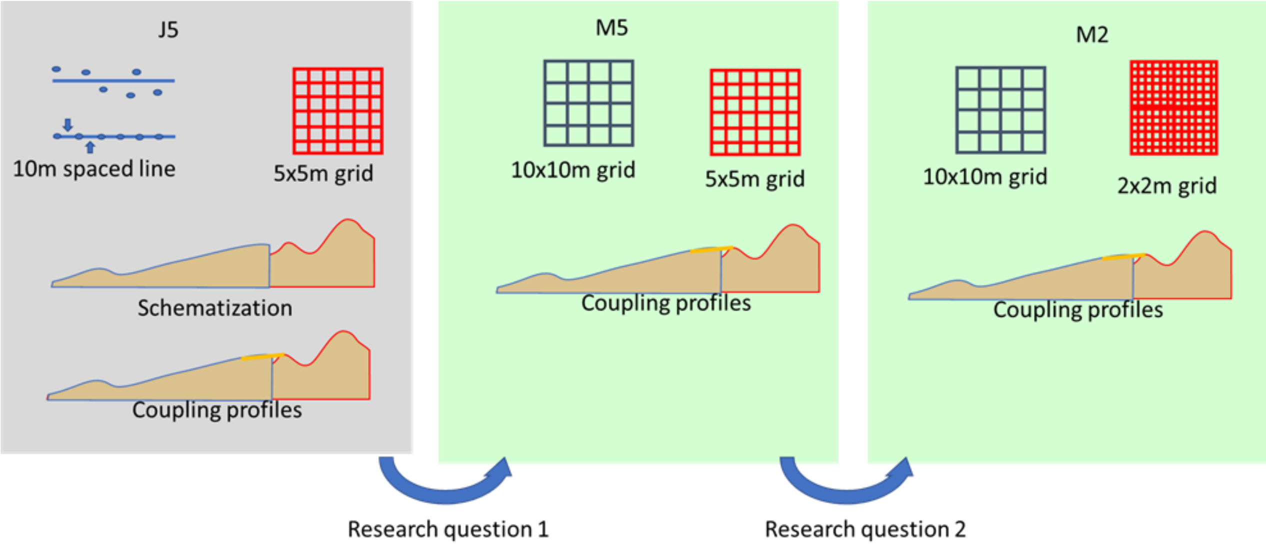

Figure 6 Different transects compared

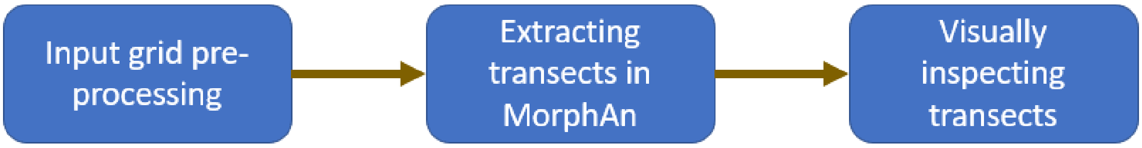

Figure 7 Transect extraction from MorphAn workflow

2.1.3. Transect pre-processing

When extracting transects from the MorphAn application (M5 or M2), the input grids needed to be pre-processed. This was done to ensure a smooth transect once it would be extracted. The 5m topographic raster was clipped using the ArcGIS application to obtain a raster for each coastal area. The clipping per coastal area enables MorphAn to run quicker and helps future work.

Certain coastal areas showed difficulty, when imported in MorphAn, due to their size and needed to be clipped even further. This was the case for coastal areas 4, 7 and 8 which are Terschelling, Noord-Holland and Rijnland, respectively.

After clipping the gridded data, certain gaps in data were noticed that could lead to large impacts on the transects and the performance indicators which was not in the scope of this research. Therefore, all missing data cells in the 5m dry grid data were filled in ArcGIS using the mean values of the neighbouring cells in the grid following the formula in Appendix A (section 7.1) and the scheme in Figure 8.

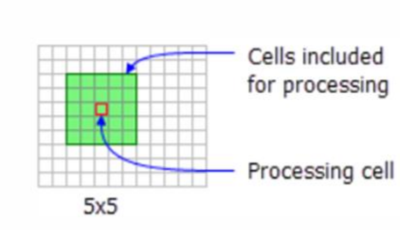

Figure 8 Diagram showing the filling of missing data points in ArcGIS

This method uses a weighted average of the 24 neighbouring cells to calculate the values of missing data points. An example showing the missing data before and after the fill is shown in Figure 9.

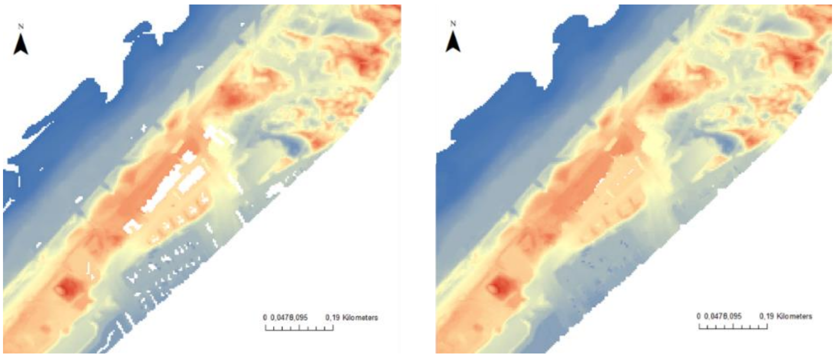

Figure 9 Patching the missing data in coastal area Delfland

The dataset containing the 2m dry resolution and the 10m wet resolution to be used in M2 transects was provided in the form of grid data by Rijkswaterstaat. After visual verification, no large gaps in data could be noticed on these datasets. This meant no pre-processing of the raster in ArcGIS was required.

2.1.4. Extracting transects using different software tools

Extracting J5 transects is currently performed in a software named Maria. The dry part of the transects were extracted from the 2x2m topographic grid. The software firstly used cubic convolution as an interpolation method to extract 1m resolution transects from the grid. The details of the cubic convolution interpolation method are detailed in Appendix B in section 7.2.

After the transects were extracted, they were "thinned out" ('uitdunnen, in Dutch) using averaging. This ensured that the transects would be read as 5m spaced points along the dry measurement. The spacing along the line is referred to as the "resolution" of the transect. A last post-processing step involved filling gaps over 5 meters within the dry transect. In this step, the transects were filled using so-called "1D smoothing", which included interpolating gaps in the dry measurement.

The wet part of a J5 transect was directly derived from the raw bathymetry data. As a ship sailed along the transect when measuring, the raw data points were "placed" onto the line using the nearest distance. The wet transect was then generated by averaging the data points every 10m. This process is referred to as 'schematization' and led to a 10m spaced line that served as the wet part of the measurement for the JarKus transect. The process used by Maria is schematized in Figure 10.

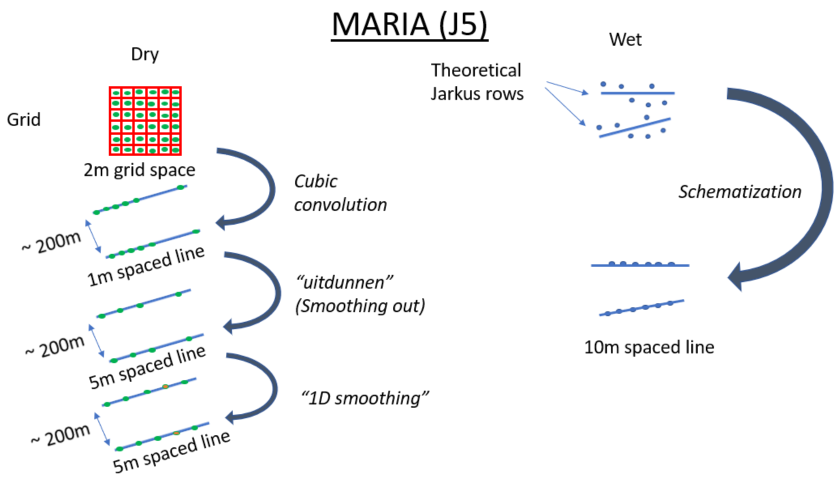

Figure 10 Transect extraction method using Maria

The other transect extraction method used was the one performed in MorphAn. For the dry measurement, the software was given a 5x5m grid as input. The dry transects were extracted using bilinear interpolation. This interpolation method is detailed in Appendix B in section 7.2.

The wet measurement used the interpolation method DIGIPOL to place the raw measurements into a regular spaced grid of 10 by 10m. As the boat sails along the transect lines, DIGIPOL interpolation was needed to find the values between transects and place them in a 10x10m grid. The DIGIPOL interpolation method is detailed in Appendix B in section 7.2. The regular spaced 10x10m grid was used to create a wet transect through bilinear interpolation. The process used by MorphAn to extract transects is schematized in Figure 11.

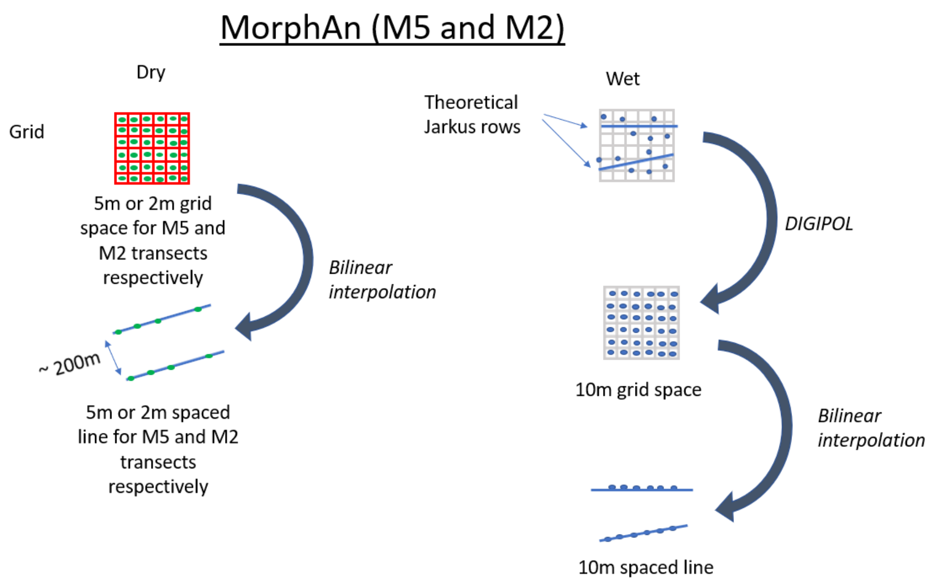

Figure 11 Transect extraction method using MorphAn

Specific options needed to be set in MorphAn to properly extract transects using the method detailed above. Firstly, all reference transects must be selected, secondly, the height factor of the 5m topographic grid must be set to 0.01. This is because the grid was given in meters and not in centimetres. The type of measurement must be set in the options to dry or wet depending on the used grid, and the resolutions on each grid must be set to 2 for the 2m dry grid, 5 for the 5m dry grid, and 10 for the 10m wet grid. Lastly, the interpolation type chosen was bilinear and the discretization resolution interpolated profile was set to 5 for M5 transects, and 2 for M2 transects

2.1.5. Coupling wet and dry transects

A cross-shore transect is composed of a wet and a dry measurement, generally measured at different dates. The consequence of this can be an overlap between wet and dry measurements which needs to be dealt with when creating the final transect. This was performed in both Maria and MorphAn through a weighted average that interpolates both measurements onto one line. The weights chosen depended on the cross-shore location of the measurement. Bathymetric measurements received larger weights when the point was seaward, and topographic measurements when the point was further landward. An example of a coastal transect can be found in Figure 12. If there was no overlap between wet and dry measurements, a straight line was drawn between the dry and wet measurements.

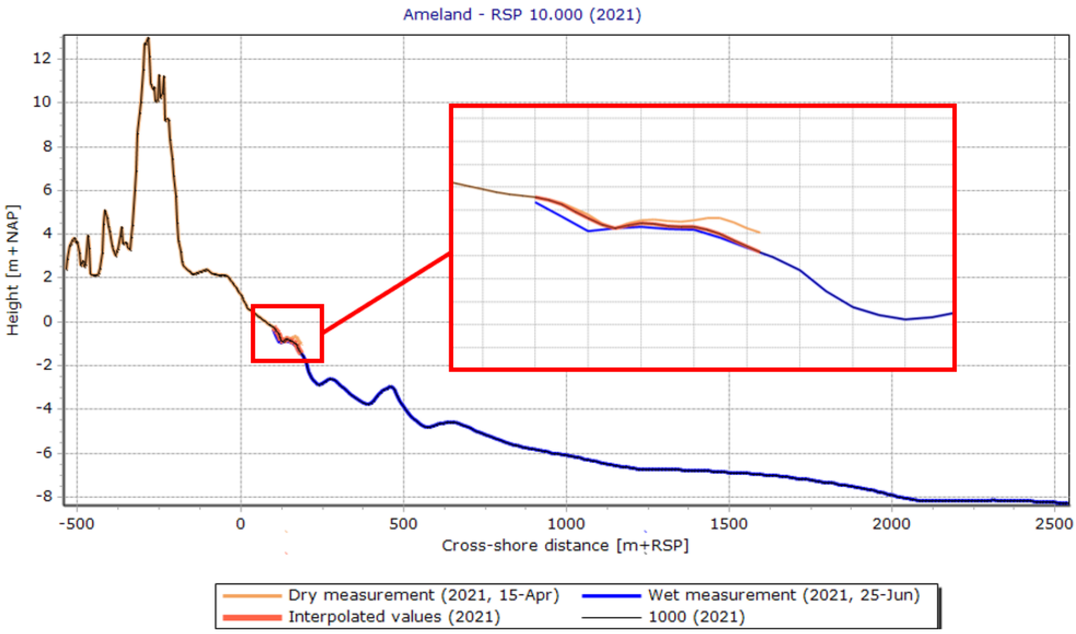

Figure 12 Side view of the cross-shore transect number 10.00 in the coastal area of Ameland

Once all the M5 and M2 transects were extracted, they were merged into one JarKus data file. This file is a text file that defines the topography and bathymetry of each transect and, when combined, contains all the data for the 26 reference transects.

Lastly, the transects were visually inspected to look for any large outliers in the data. Some examples of these large outliers are showcased in appendix C in section 7.3.

2.2. Result analysis methodology

2.2.1. Qualitative assessment methodology

The qualitative analysis focused on finding the probable causes of the individual differences in calculated coastline positions and coastal sand volumes. This was performed by looking at the transects and understanding the differences in results. These differences could be caused by the changes in either transect extraction methods, or horizontal dry resolutions.

Qualitative assessment focused on finding any data that behaved differently than expected. It was expected that the change in transect extraction method would lead to similar profiles. This is because the method used to extract the transects should not influence the result. A change to a finer horizontal resolution in the topographic measurements was expected to lead to higher and narrower peaks. Any shifts or differences in the profiles are analysed and discussed in section 3.1.2 and section 3.2.2.

2.2.2. Quantitative assessment methodology

The values of the performance parameters, namely the calculated coastline positions and coastal sand volumes, were extracted using the MorphAn application. This simply required running the models using certain boundary conditions valid for each transect. These boundary conditions detail the landward, seaward, upper, and lower boundaries used to calculate the coastline positions and coastal sand volumes. The boundary conditions for the calculations of the performance indicators used in this report were obtained from Rijkswaterstaat. These boundary conditions represent the conditions used for the analysis of the calculated coastline position and coastal volumes Rijkswaterstaat applied in 2021. The model follows the theoretical calculations shown in section 1.2.

The models in MorphAn were then run and the results were collected and analysed in a spreadsheet. Coastal volumes were collected in all depth intervals shown in section 1.2.3. The difference in total volume was also analysed.

An additional analysis was conducted to check the significance of the differences between transect extraction methods and between horizontal dry resolutions. This method involved a two-tailed paired t-test with an arbitrary alpha value of 0.05. This test offers the possibility to check whether the difference between two related contextual variables, here the difference in criterion (position and volume) along the same transect using different methods or resolutions, is significant with a chosen alpha value.

The test was conducted on each criterion which includes: MKL position, total volume, deep volume, beach volume, and dune volume. The tests were conducted on each research question leading to a total of 10 tests. It is assumed that the null hypothesis H_0 is here that there are no differences between the two methods or the two resolutions.

The procedure used to follow these tests is as follows:

- Calculate the difference in results in one criterion between two methods or two dry horizontal resolutions for all transects. The total number of transects here is n=26.
- Collect the mean ($\bar{x}$), the standard deviation ($s(x)$) and the standard deviation of the mean ($s(\bar{x}) = s(x)/\sqrt{n}$) of the differences.
- Calculate a t-score (t) for each test using the following formula:

$$t = \frac{\bar{x}}{s(\bar{x})}$$

- Find the critical boundaries of a significant value for the t-score. These lie out of the boundaries of $-t_{critical} \leq t \leq t_{critical}$. The critical value is found in Table 4 using the two-tailed significance value of 0.05 and 25 degrees of freedom ($n - 1 = 26 - 1 = 25$) .

Table 4 t-test critical values (T Table, n.d.)

cum. prob	$t_{.50}$	$t_{.75}$	$t_{.80}$	$t_{.85}$	$t_{.90}$	$t_{.95}$	$t_{.975}$	$t_{.99}$	$t_{.995}$	$t_{.999}$	$t_{.9995}$
one-tail	**0.50**	**0.25**	**0.20**	**0.15**	**0.10**	**0.05**	**0.025**	**0.01**	**0.005**	**0.001**	**0.0005**
two-tails	**1.00**	**0.50**	**0.40**	**0.30**	**0.20**	**0.10**	**0.05**	**0.02**	**0.01**	**0.002**	**0.001**
df											
1	0.000	1.000	1.376	1.963	3.078	6.314	12.71	31.82	63.66	318.31	636.62
2	0.000	0.816	1.061	1.386	1.886	2.920	4.303	6.965	9.925	22.327	31.599
3	0.000	0.765	0.978	1.250	1.638	2.353	3.182	4.541	5.841	10.215	12.924
4	0.000	0.741	0.941	1.190	1.533	2.132	2.776	3.747	4.604	7.173	8.610
5	0.000	0.727	0.920	1.156	1.476	2.015	2.571	3.365	4.032	5.893	6.869
6	0.000	0.718	0.906	1.134	1.440	1.943	2.447	3.143	3.707	5.208	5.959
7	0.000	0.711	0.896	1.119	1.415	1.895	2.365	2.998	3.499	4.785	5.408
8	0.000	0.706	0.889	1.108	1.397	1.860	2.306	2.896	3.355	4.501	5.041
9	0.000	0.703	0.883	1.100	1.383	1.833	2.262	2.821	3.250	4.297	4.781
10	0.000	0.700	0.879	1.093	1.372	1.812	2.228	2.764	3.169	4.144	4.587
11	0.000	0.697	0.876	1.088	1.363	1.796	2.201	2.718	3.106	4.025	4.437
12	0.000	0.695	0.873	1.083	1.356	1.782	2.179	2.681	3.055	3.930	4.318
13	0.000	0.694	0.870	1.079	1.350	1.771	2.160	2.650	3.012	3.852	4.221
14	0.000	0.692	0.868	1.076	1.345	1.761	2.145	2.624	2.977	3.787	4.140
15	0.000	0.691	0.866	1.074	1.341	1.753	2.131	2.602	2.947	3.733	4.073
16	0.000	0.690	0.865	1.071	1.337	1.746	2.120	2.583	2.921	3.686	4.015
17	0.000	0.689	0.863	1.069	1.333	1.740	2.110	2.567	2.898	3.646	3.965
18	0.000	0.688	0.862	1.067	1.330	1.734	2.101	2.552	2.878	3.610	3.922
19	0.000	0.688	0.861	1.066	1.328	1.729	2.093	2.539	2.861	3.579	3.883
20	0.000	0.687	0.860	1.064	1.325	1.725	2.086	2.528	2.845	3.552	3.850
21	0.000	0.686	0.859	1.063	1.323	1.721	2.080	2.518	2.831	3.527	3.819
22	0.000	0.686	0.858	1.061	1.321	1.717	2.074	2.508	2.819	3.505	3.792
23	0.000	0.685	0.858	1.060	1.319	1.714	2.069	2.500	2.807	3.485	3.768
24	0.000	0.685	0.857	1.059	1.318	1.711	2.064	2.492	2.797	3.467	3.745
25	0.000	0.684	0.856	1.058	1.316	1.708	2.060	2.485	2.787	3.450	3.725
26	0.000	0.684	0.856	1.058	1.315	1.706	2.056	2.479	2.779	3.435	3.707
27	0.000	0.684	0.855	1.057	1.314	1.703	2.052	2.473	2.771	3.421	3.690
28	0.000	0.683	0.855	1.056	1.313	1.701	2.048	2.467	2.763	3.408	3.674
29	0.000	0.683	0.854	1.055	1.311	1.699	2.045	2.462	2.756	3.396	3.659
30	0.000	0.683	0.854	1.055	1.310	1.697	2.042	2.457	2.750	3.385	3.646
40	0.000	0.681	0.851	1.050	1.303	1.684	2.021	2.423	2.704	3.307	3.551
60	0.000	0.679	0.848	1.045	1.296	1.671	2.000	2.390	2.660	3.232	3.460
80	0.000	0.678	0.846	1.043	1.292	1.664	1.990	2.374	2.639	3.195	3.416
100	0.000	0.677	0.845	1.042	1.290	1.660	1.984	2.364	2.626	3.174	3.390
1000	0.000	0.675	0.842	1.037	1.282	1.646	1.962	2.330	2.581	3.098	3.300
z	0.000	0.674	0.842	1.036	1.282	1.645	1.960	2.326	2.576	3.090	3.291
	0%	50%	60%	70%	80%	90%	95%	98%	99%	99.8%	99.9%
	Confidence Level										

As seen above, Table 4 shows that the critical t value to be 2.060. This means if the t score is outside of the interval $-t_{critical} \leq t \leq t_{critical}$, the null hypothesis H_0 can be rejected, showing a significant difference between the methods or the resolutions with a significance level of 0.05.

3. Results

3.1. Analysing the change in transect extraction method

3.1.1. Overall results of a change in transect extraction method

The changes in calculated MKL position and total sand volume on the reference transects are presented in Figure 13 and Figure 14. The average cross-shore calculated MKL shift on reference transects is 1.05m landward, when comparing M5 to J5 transects. The average change in total sand volume on the Dutch coast based on these reference transects is a loss of 9.01 m^3/m. Assuming the Dutch coast is 350km long (Rijkswaterstaat, 2019), this places the total loss of calculated volume to 3.15 million cubic metres (Mm^3). Results of deep, beach and dune volumes can be found in Appendix E in section 7.5.

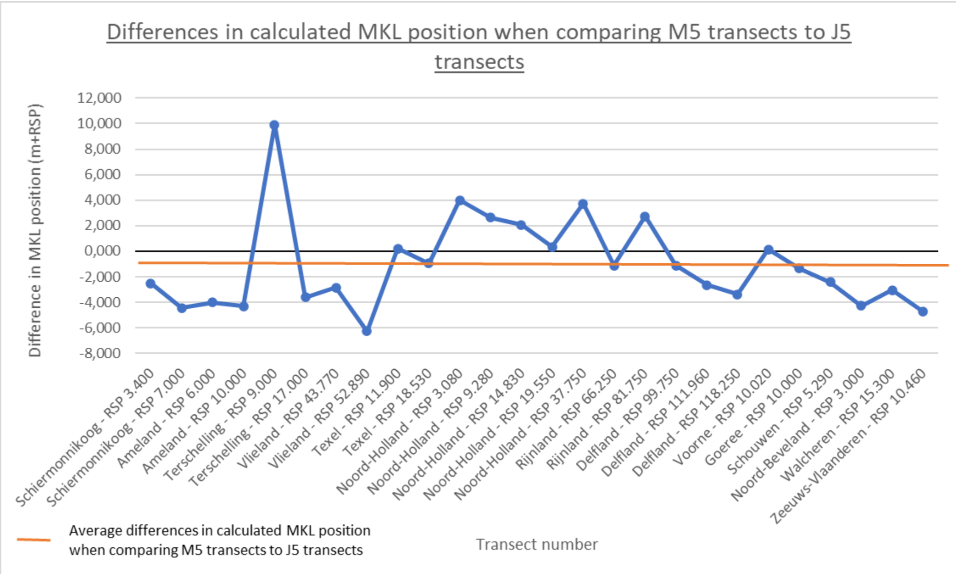

Figure 13 Differences in calculated MKL position when comparing M5 transects to J5 transects

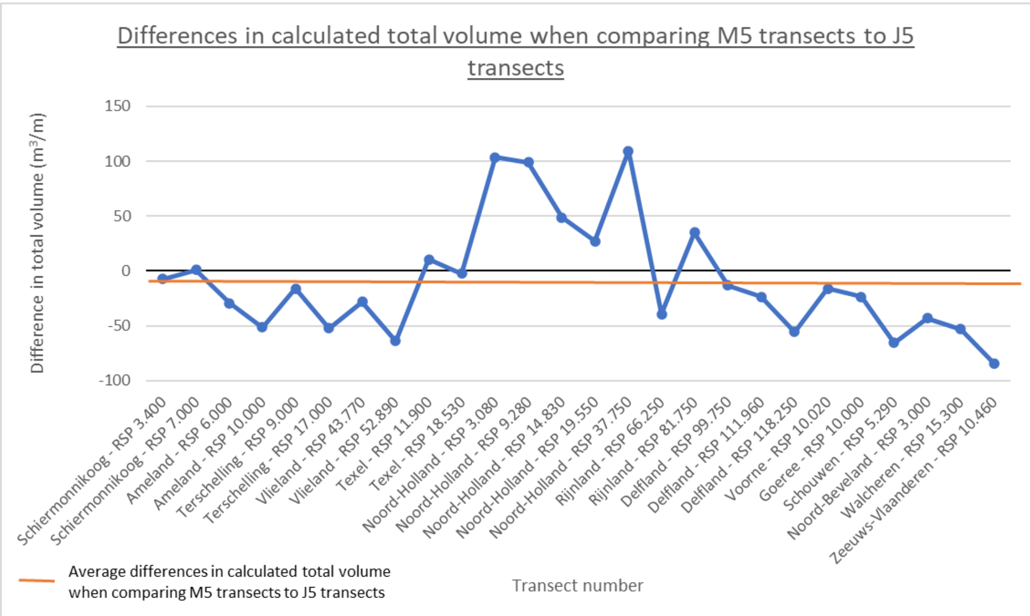

Figure 14 Differences in calculated total volume when comparing M5 transects to J5 transects

3.1.2. Results analysis and qualitative observations of a change in transect extraction method

The results in section 3.1.1 show an average landward shift in calculated MKL and an average loss in total calculated volume along the Dutch coast. After qualitatively analysing the profiles, several causes for these changes were found. Firstly, a general cross-shore shift in wet measurements can be observed when comparing M5 and J5 transects. These shifts are best illustrated on transect 3.40 in coastal area Schiermonnikoog in Figure 15, and on transect 11.90 in coastal area Texel in Figure 16. A quantitative table showing the shifts in wet measurements for all reference transects can be found in Appendix D in section 7.4.

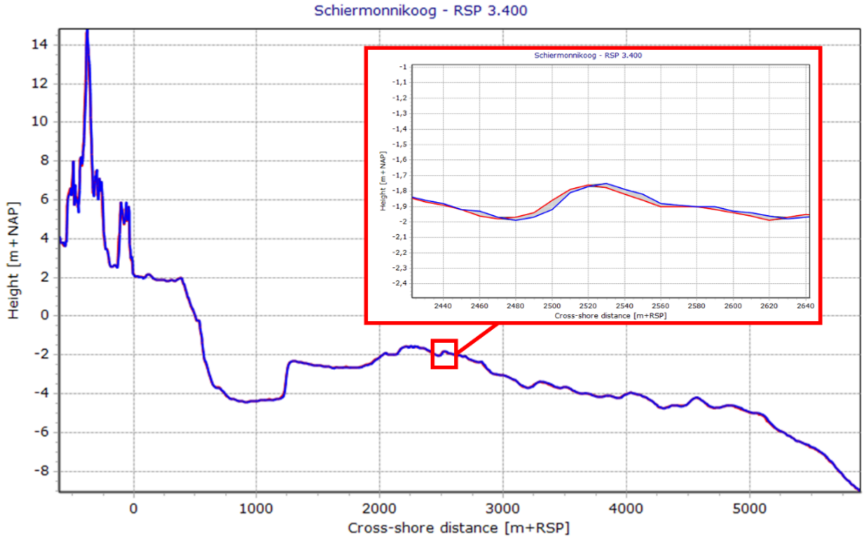

Figure 15 Wet profile shift on transect 3.40 in coastal area Schiermonnikoog between the M5 transect (red) and the J5 transect (blue)

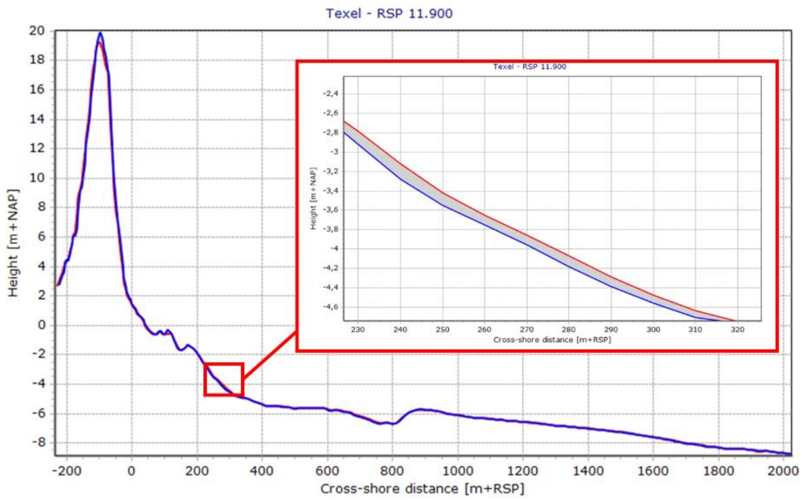

Figure 16 Wet profile shift on transect 11.90 in coastal area Texel between the M5 transect (red) and the J5 transect (blue)

Secondly, certain differences in coastal profiles were also observed on the dry measurements. These differences include shifts in the measurements, and differences in peak heights. These differences are best illustrated on transect 10.00 in coastal area Ameland in Figure 17.

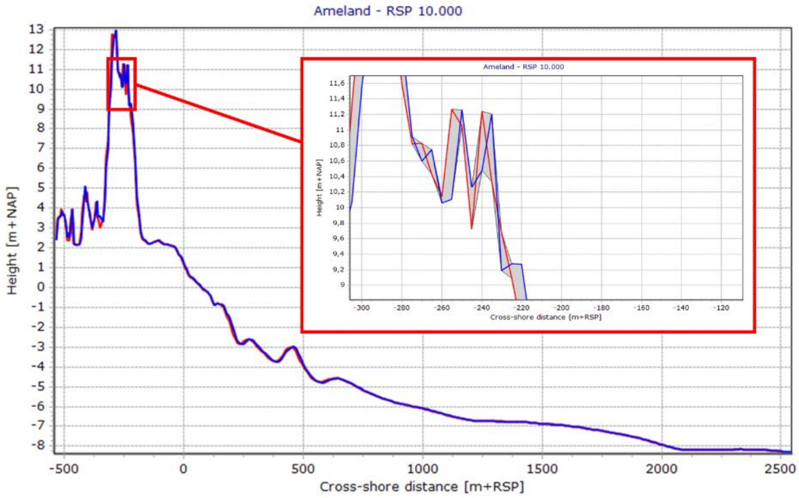

Figure 17 Dry measurement differences on transect 10.00 in coastal area Ameland between the M5 transect (red) and the J5 transect (blue)

Thirdly, the transects do always show similarities between each other with differences only being contained to peak height and shifts in measurements. This means no additional peaks were found when comparing M5 to J5 transects.

Lastly, a grouped analysis of the transects showed Rijnland and Noord-holland having a large shift of calculated MKL position seaward. Noord-Holland transects also showed a large gain in calculated total volume. In contrast, the areas around the Wadden islands (coastal areas 2 to 6 in Table 3) and Zeeland (coastal areas 11 to 17 in Table 3) showed a landward shift in calculated coastline position. These areas also showed an average loss of 32.84 m^3/m in total calculated coastal sand volume.

3.1.3. Largest differences in calculated MKL position and coastal sand volumes separated in layers of a change in transect extraction method

The largest differences in calculated MKL position and coastal sand volumes separated in layers (defined in section 1.2.3), along with the cause of these large changes are found in Table 5.

Table 5 Outlying largest changes in calculated MKL position and transect volumes when comparing J5 to M5 transects (Brown represents a landward calculated MKL shift of the M5 transect. Blue represents a seaward calculated MKL shift of the M5 transect. Red represents a volume loss on the M5 transect. Lastly, green represents a volume gain on the M5 transect)

Performance criterion observed	Type of change	Coastal area	Location	Criterion value	Criterion unit	Possible cause
MKL	Shift landwards	5	Vlieland - RSP 52.890	-6,271	m	Shift of the wet measurement landwards
MKL	Shift seawards	4	Terschelling - RSP 9.000	9,909	m	Shift of the dune foot from 120m+RSP to 268m+RSP
Deep volume	Loss	17	Zeeuws-Vlaanderen - RSP 10.460	-56,875	m3/m	Shift of wet measurement landwards
Deep volume	Gain	7	Noord-Holland - RSP 3.080	112,504	m3/m	Shift of wet measurement seawards
Beach volume	Loss	3	Ameland - RSP 10.000	-26,227	m3/m	Dry profiles differ in peak height and location
Beach volume	Gain	8	Rijnland - RSP 81.750	19,925	m3/m	Different dry measurement sizes leading to different coupling of the profiles. M5 dry measurement stops at 255m+RSP, whereas M2 dry measurement stops at 240m+RSP
Dune volume	Loss	6	Texel - RSP 11.900	-37,884	m3/m	Dry profiles differ in peak height and location
Dune volume	Gain	15	Noord-Beveland - RSP 3.000	26,946	m3/m	Dry profiles differ, large difference in peak height

3.1.4. Significance test of a change in transect extraction method

The results of the significance test between J5 and M5 transects for the different criteria are shown in Table 6. T scores in green do not reject a similarity whereas scores in red reject a similarity and therefore show significant change with a 95% probability. This test shows that only beach volume seems to change significantly between M5 and J5 transects. This is due to the change being consistent with the standard deviation (12.919 m^3/m) being close to the average change (-10.041 m^3/m).

Table 6 Significance test between J5 and M5 transects (Red represents a significant difference in the results. Green represents a non-significant difference)

	MKL		Total Volume		Deep Volume		Beach volume		Dune Volume	
	J5	M5	J5	M5	J5	M5	J5	M5	J5	M5
x̄	-1,048		-9,010		2,191		-10,041		-1,160	
s(x)	3,575		52,349		38,497		12,919		15,091	
s(x̄)	0,701		10,267		7,550		2,534		2,960	
t critical	2,060		2,060		2,060		2,060		2,060	
t	-1,496		-0,878		0,290		-3,963		-0,392	

3.2. Analysing the change in topographic horizontal resolution

3.2.1. Overall results of a change in topographic horizontal resolution

The changes in calculated MKL position and total sand volume on the reference transects are presented in Figure 18 and Figure 19. The average cross-shore calculated MKL shift on reference transects is 0.872m seaward when comparing M2 to M5 transects. The average change in total calculated sand volume on the Dutch coast based on these reference transects is a gain of 10.73 m^3/m. Assuming the Dutch coast is 350km long (Rijkswaterstaat, 2019), this places the total gain of volume to 3.75 Mm^3.

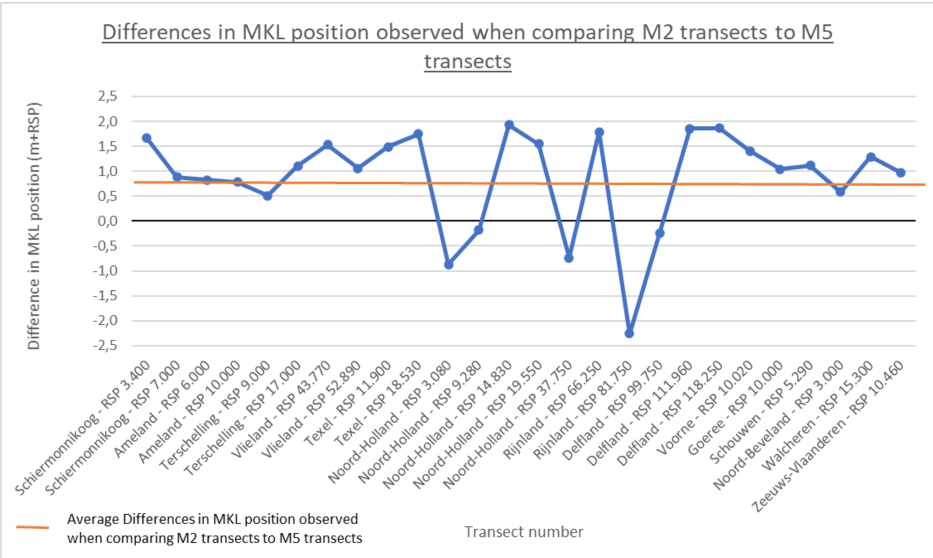

Figure 18 Differences in calculated MKL position when comparing M2 transects to M5 transects

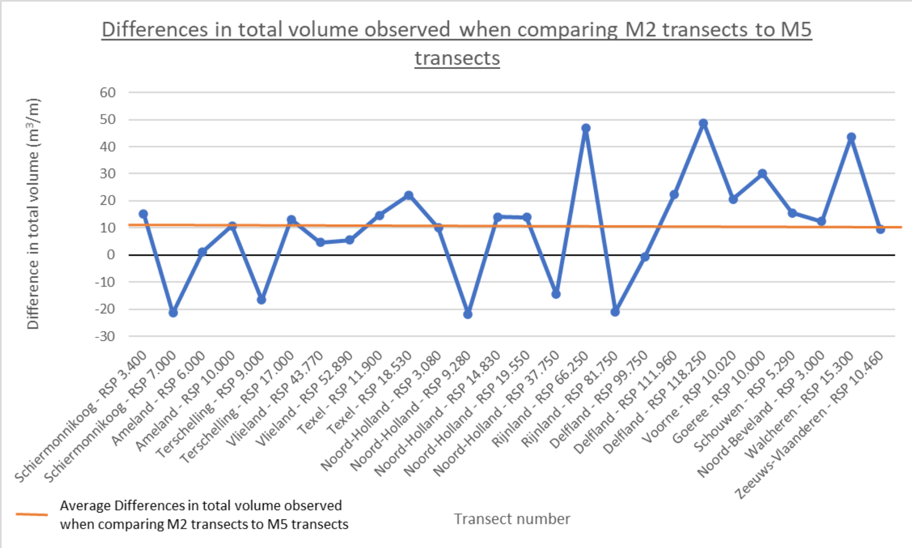

Figure 19 Differences in total volume when comparing M2 transects to M5 transects

3.2.2. Results analysis and qualitative observations of a change in topographic horizontal resolution

The most visible differences between M5 and M2 transects are differences found in the dry measurement. The wet measurement uses the same input grid and the same extraction method; therefore, no changes were observed along the wet part of the transect. The dry part of the transect shows differences in certain areas in peak height and location. This is shown best in transect 118.25 in coastal area Delfland shown in Figure 20.

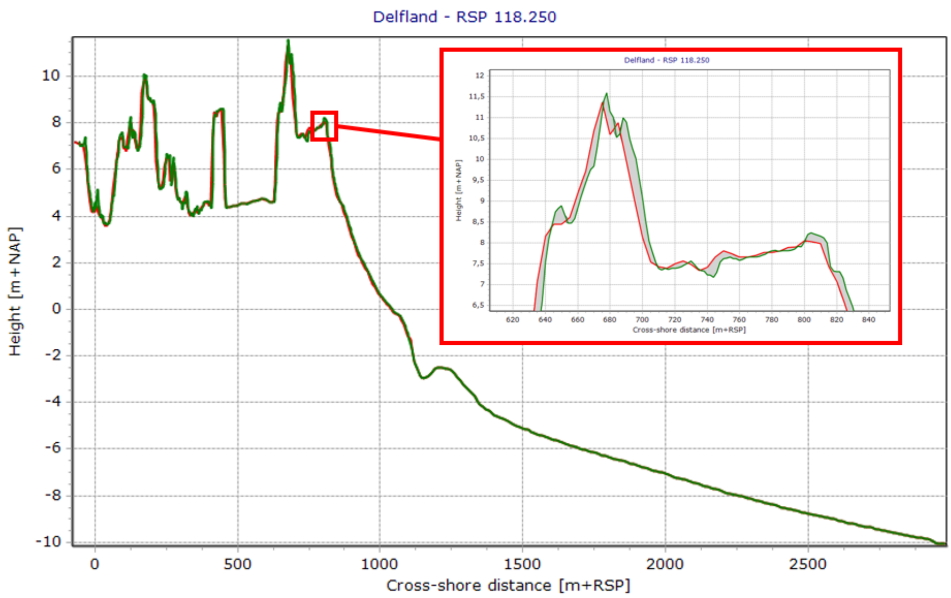

Figure 20 Dry measurement differences on transect 118.25 in coastal area Delfland between the M2 transect (green) and the M5 transect (red)

3.2.3. Largest differences in calculated MKL position and coastal sand volumes separated in layers of a change in topographic horizontal resolution

The largest differences in calculated MKL position and coastal sand volumes separated in layers (defined in section 1.2.3) along with the cause of these large changes are found in Table 7.

Table 7 Largest changes in calculated MKL position and transect volumes when comparing M2 to M5 transects

Performance criterion observed	Type of change	Coastal area	Location	Criterion value	Criterion unit	Possible cause
MKL	Shift landwards	8	Rijnland - RSP 81.750	-2,260	m	Different dry measurement sizes leading to different coupling of the profiles. M5 dry measurement stops at 255m+RSP, whereas M2 dry measurement stops at 240m+RSP
MKL	Shift seawards	7	Noord-Holland - RSP 14.830	1,929	m	Shift in dry peak locations
Deep volume	Loss	None	None	0,000	m3/m	Same wet grid and interpolation method used
Deep volume	Gain	None	None	0,000	m3/m	Same wet grid and interpolation method used
Beach volume	Loss	8	Rijnland - RSP 81.750	-18,653	m3/m	Different dry measurement sizes leading to different coupling of the profiles. M5 dry measurement stops at 255m+RSP, whereas M2 dry measurement stops at 240m+RSP
Beach volume	Gain	2	Schiermonnikoog - RSP 3.400	19,050	m3/m	M2 tansect is pointier leading to a gain in beach volume
Dune volume	Loss	4	Terschelling - RSP 9.000	-17,769	m3/m	M2 tansect is pointier leading to a loss in dune volume
Dune volume	Gain	9	Delfland - RSP 118.250	31,000	m3/m	M2 tansect is pointier leading to a gain in dune volume

3.2.4. Significance test of a change in topographic horizontal resolution

The results for the quantitative analysis between M5 and M2 transects are shown in Table 8. T scores in green do not reject a similarity whereas scores in red reject a similarity and therefore show significant change with a 95% probability. This test shows a significant difference between M5 and M2 transects for calculated MKL position, total volume, and beach volume. This significance stems from the consistent changes in those indicators.

Table 8 Significance test between M5 and M2 transects

	MKL		Total Volume		Deep Volume		Beach volume		Dune Volume	
	M5	M2	M5	M2	M5	M2	M5	M2	M5	M2
x̄	0,872		10,727		0,000		6,643		4,083	
s(x)	1,004		19,418		0,002		10,432		12,626	
s(x̄)	0,197		3,808		0,000		2,046		2,476	
t critical	2,060		2,060		2,060		2,060		2,060	
t	4,427		2,817		1,342		3,247		1,649	

4. Discussion

4.1. Results discussion

4.1.1. Research question 1

A small difference in calculated MKL position between J5 and M5 transects is found on the Holland coast with an average calculated difference of 0.73m seaward. The other coastal areas showed a shift landward of 2.16m. An explanation of these shifts can be the different methods used in the wet measurements. The change of schematization in J5 transects to DIGIPOL interpolation and then bilinear interpolation in M5 transects seems to show a shift in bathymetry of up to 10m. This is the equivalent of 1 grid step, which shows the result is not significant, however, it is important to note this shift could impact calculated MKL placement up to 6m landward on transect 52.89 in Vlieland. The average calculated MKL shift on the 26 reference transects is around 1m landward which represents around 1/5th of a topographic grid cell of 5m. This change is not consistent along the Dutch coastline, which makes this result statistically non-significant.

Other causes of the change in calculated MKL and coastal sand volume could be the different coupling methods used between Maria and MorphAn. The dry measurements in MorphAn seem to extend further seaward. This is the case on transect 81.75 in coastal area Rijnland shown in Table 5. It can be noted that J5 transects are manually corrected, which does not occur on M5 transects and can lead to some differences in coupling.

Large outliers can be found when changing the transect extraction method as certain transects can have their dune foot shifted. The dune foot is defined in section 1.2.2 and is the intersection of the most seaward point on the transect and an arbitrary horizontal line set at a certain height in the boundary conditions. This shift in dune foot is observed most notably in transect 9.00 in coastal area Terschelling, where the calculated MKL shifts 9.9m. These changes can seem large; however, they occur sometimes yearly as profiles change and are properly accounted for.

The wet profile shift between M5 and J5 transects leads to a loss in total calculated volume of around 3.15Mm^3 along the Dutch coast. The loss in total calculated volume mainly occurs in the deep and beach volume area. This confirms the idea that the main cause of this loss of calculated volume is the shift in the wet measurement.

Certain differences in calculated beach and dune volumes can be explained by a different dry measurement. These differences stem from the dry transect being extracted differently between J5 and M5 transects. J5 transects go through a complex procedure to be created, detailed in section 2.1.4. J5 transects use different input grids and use 16 neighbouring points to calculate the value placed on the transect every 5m. M5 transects only use 4 neighbours to do so. This causes differences in areas where large changes in topography are observed. Considering different neighbours can lead to different peak heights and locations depending on the values in the surrounding cells.

The changes in the dry profile affect the calculated dune and beach volumes. The beach volume change is deemed statistically significant with a confidence degree of 95%, as M5 transects mostly lose beach volume, when compared to J5 transects. This change seems to be consistent apart from some areas on the Holland coast, for which the shift in wet measurement compensates the changes to the dry measurement.

4.1.2. Research question 2

The results shown in section 3.2 show some differences between M5 and M2 transects. Firstly, it seems the calculated MKL remains quite constant when looking at the transects qualitatively. However, the test shown in section 3.2.4 shows this change is indeed statistically significant to a degree of 95%. This is due to the standard deviation being small with M2 transects showing an average calculated MKL change of 0.87m seaward compared to M5 transects. This change is consistent which is why it is significant.

The main source of these changes is the core difference between M5 and M2 transects. M2 transects are derived from a grid with a spacing of 2 meters. M2 transects also show a shift in dry measurements, mostly due to the bilinear interpolation taking 4 neighbours into account when the transect goes through a lower point in the dune. On a 5m resolution the 4 neighbours of the examined point are higher than the 4 neighbours on a 2m resolution. This is shown in Figure 21.

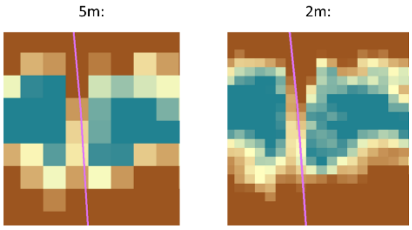

Figure 21 Differences between M5 and M2 grids in transect 7.00 in coastal area Schiermonnikoog

Calculated deep volume is not affected by a switch from M5 to M2 transects. This is due to both transects sharing the same wet grid and having the same interpolation method. In general data from the transects below -2m NAP are in the wet measurement area.

Calculated beach volume shows a significant difference between M5 and M2 transects. This is due to the coupling of the profiles, sometimes not occurring in the same locations, as in some cases one of the grids extends further seaward than the other. This is the case in transect 81.75 in coastal area Rijnland shown in Table 7. The dry measurement of this transect ends at 255m+RSP for the M5 transect and at 240m+RSP for the M2 transect. This causes a landward shift in calculated MKL of 2.26m and a loss of calculated beach volume of 18.65 m^3/m. This coupling difference seems to be observed only along certain transects, therefore attention must be paid to avoid such issues when switching from M5 to M2 transects.

4.2. Results implication

The results on both these research questions lead to some implications on Rijkswaterstaat deciding if the J5 transects are still the ones to be used in the future. The differences observed in section 3.1 show that a change to M5 transects does not show much significant difference as the differences in calculated MKL positions do not vary much when comparing those to certain trends per year. The shifts in calculated MKL together with the trend per year along reference transects is shown in Figure 22. The average calculated MKL trend of the 26 reference transects taken over the years is around a 1.4m seaward shift. Based on this value, the average 1m landward shift observed between M5 and J5 transects would take the Dutch coast on average, back by around one year. This is however a one-time change which will not perpetuate yearly.

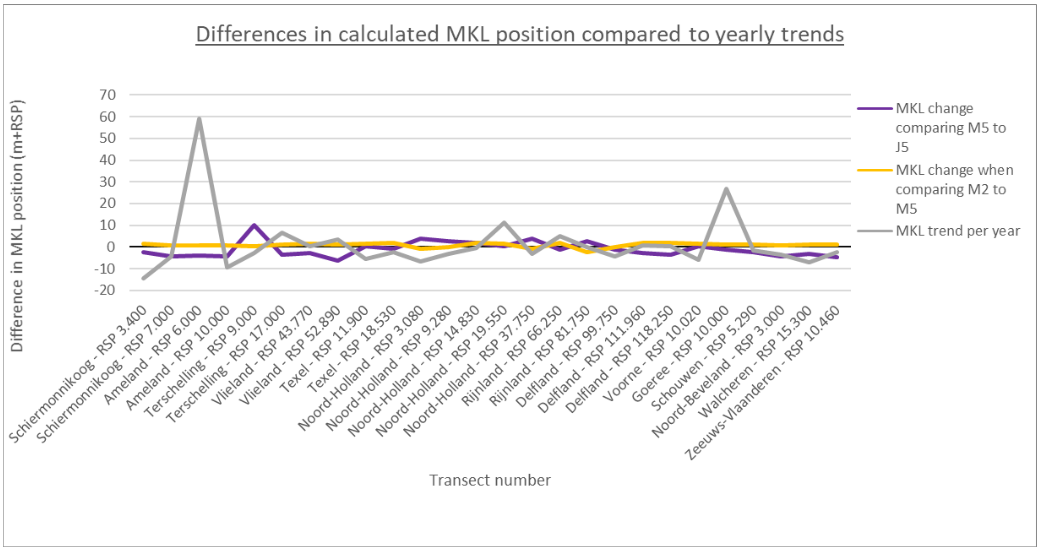

Figure 22 Comparing changes to calculated MKL position with yearly trends

Regarding coastal sand volumes, the total loss of calculated volume on the Dutch coast assuming a coastline length of 350km, is around 3.15 Mm^3 of sand. This represents 26.25% of the total 12Mm^3 annual supply of nourished sand to Dutch beaches and depths (Brand, Ramaekers, & Lodder, 2022). The largest changes in calculated beach volume are all below 30 m^3/m, which represents around 10% of an average beach supply of 300 m^3/m.

Regarding deep volume, the largest calculated gains occur in Noord-Holland gaining 23% of the average supplied deep volume of 479 m^3/m. The calculated losses here are much less and occur mostly outside of the Holland coast. In Zeeuws-Vlaanderen, the calculated loss of 84 m^3/m represents around 17.5% of one deep volume supply of 479 m^3/m.

Additionally, the switch from M5 to M2 transects could be beneficial as it would lead to more accurate depictions of the topography along the transect. M2 transects differ significantly moving the calculated MKL seaward by around 0.872m. If a change from J5 directly to M2 transects were to occur, the average calculated MKL would only move 0.176m landward as shown in Figure 23.

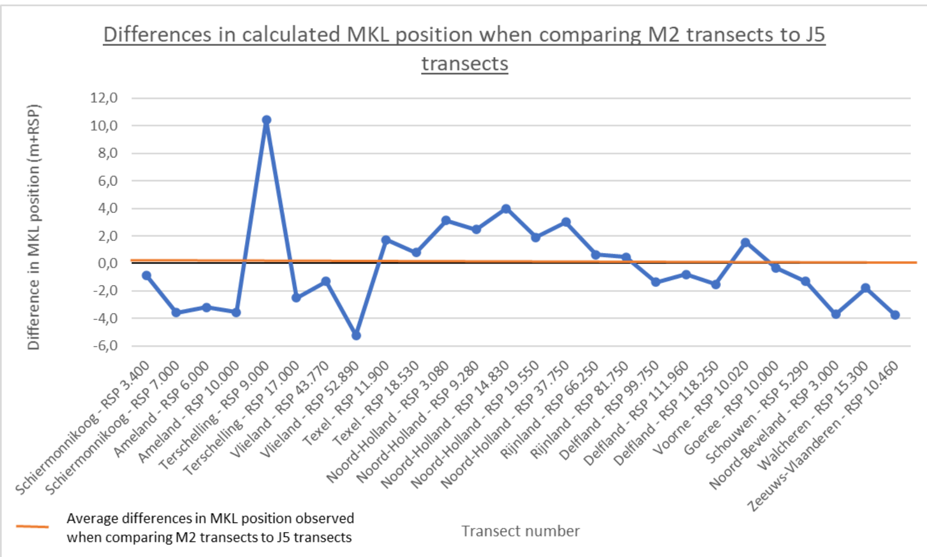

Figure 23 Differences in calculated MKL position when comparing M2 transects to J5 transects

The change is also accompanied by an average gain of 10.7 m^3/m in total calculated volume of which 6.6 m^3/m is beach volume. This largely compensates for the losses found in research question 1 as the Netherlands would then gain 0.6 Mm^3 of calculated coastal sand when switching directly from J5 to M2 transects as shown in Figure 24.

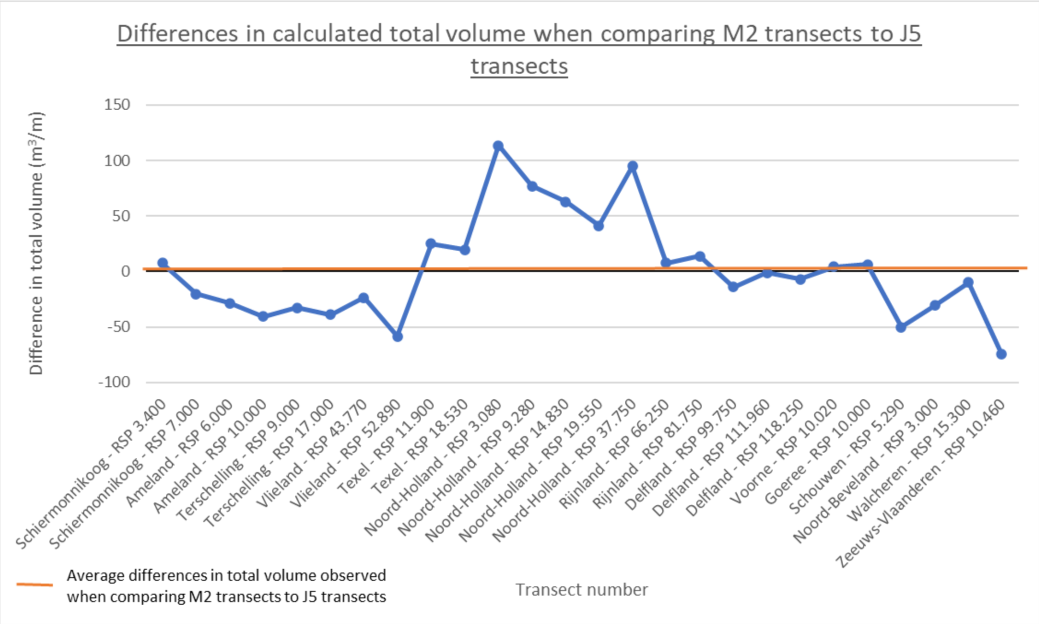

Figure 24 Differences in calculated total volume when comparing M2 transects to J5 transects

4.3. Recommendations and limitations

Based on the observations throughout this report, a change to deriving transects through MorphAn at 2 meters resolution instead of Maria at 5m resolution for the dry measurement is recommended. All the changes described in this report would occur once, which would be important to note for all stakeholders receiving the coastal data. These include the differences in calculated MKL position with an average 0.176m landward difference and calculated coastal volume with an average gain of 0.6Mm^3 of calculated total sand volume.

Lastly, it is important to understand the limitations of this research. This research was conducted on 26 reference transects (Arcadis, 2021) representing the Netherlands. Individual coastal areas need to be examined one by one to see whether a change of extraction method and a change in topographic resolution would have an impact on calculated coastline positions and coastal sand volume. These results only show general ideas, and individual calculated coastline position changes need to be checked to see if they are indeed insignificant to the current policy. Further research on Maria is also needed to fully understand the causes of the differences observed when answering research question 1.

5. Conclusions

A change of transect extraction method and different resolutions bring several one-time changes to calculated coastline position and coastal sand volumes. The main differences found when extracting a transect using the MorphAn software instead of Maria are differences in dry topographic measurements and a shift found in bathymetric measurements.

These are caused by the different interpolation methods used and the different amount of smoothing applied to both areas. These changes are, however, only statistically significant in the beach volume area between -2m and +4m NAP. All other differences found on a reference profile can be seen as statistically insignificant as they are not consistent changes over the whole of the Netherlands. It is found that the calculated MKL would shift landward by 1m on average, which is much smaller than the grid size of 5m. This shows that differences are present in some areas, however they are small enough to not be noticed.

Several patterns within the Netherlands were found. Most profiles in Noord-Holland see a gain in volume and a shift of calculated MKL seaward, whereas the areas such as Schouwen and Ameland see a loss of volume and a landward calculated MKL shift. It seems with these results that this could be generalised to the Holland coast gaining calculated volume and the Wadden islands in the North of the Netherlands and the Southern coastal areas in Zeeland losing calculated volume. This volume does remain small, as in total the Netherlands would lose a calculated 3.15 Mm^3 of sand, which represents 26.25% of the annual 12Mm^3 of yearly nourished sand.

Additionally, 5m and 2m topographic resolutions also lead to different calculated coastline positions and coastal sand volumes. These can be attributed to differences in the dry profiles, most notably in peak height and peak locations.

As can be expected, when moving to a 2m topographic resolution from a 5m resolution many peaks in the dry measurement become more significant in value as less averaging occurs within these measurements. The measurements also seem to show more variation on transects extracted at a 2m resolution. Additional differences are found in specific cases with M5 peaks sometimes being higher than M2 peaks or occurring earlier due to the nature of bilinear interpolation used in MorphAn.

The consequences of these changes are an average shift of the calculated coastline position seaward of 0.872m and a gain of 3.75 Mm^3 in total calculated coastal sand volume. This gain in calculated volume and shift in calculated coastline position shows that the losses occurring when changing the transect extraction method are compensated when changing the resolution. The locations of the transects having their calculated MKL shift seaward are all around the Netherlands. A pattern is hard to distinguish here as all profiles except a few outliers show a consistent shift in calculated coastline position and a gain in calculated coastal sand volume.

A change in transect extraction to MorphAn and to a topographic resolution of 2m is therefore beneficial as it does not show concerning differences. The differences may be statistically significant; however, they compensate each other on average and remain small when looking at the current grid size, the total volume present, or the current beach and deep volume supplies. More research may be needed comparing each individual transect if a switch to MorphAn at a 2m topographic resolution is to be made.

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7. Appendix

7.1. Appendix A: Pre-processing formula used in ArcMap

```
CON(isnull([raster]), FOCALMEAN([raster], rectangle,5,5), [raster])
```

7.2. Appendix B: Different interpolation methods

The cubic convolution used in Maria to extract the dry transects is a method of interpolation that relies on the neighbours of a target cell to determine its value. In this case, cubic convolution uses sixteen neighbours as shown in Figure 25. In this figure, the centre of the input raster is illustrated by the grey points. The orange points are here the sixteen nearest neighbours averaged and weighted to obtain the value of the red point placed in the corresponding yellow cell in the green output raster. In this instance the output is not a raster, but a transect; however, a transect can simply be viewed as a straight line of 1x1m cells.

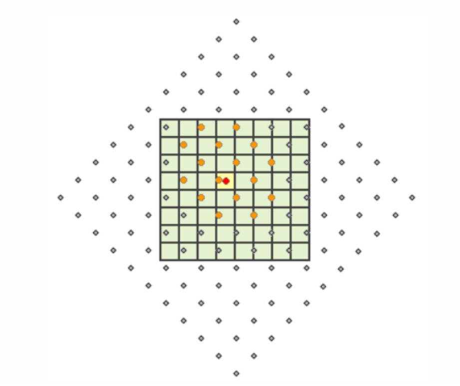

Figure 25 Cubic convolution diagram (ESRI, 2021)

The DIGIPOL is an iterative algorithm that interpolates using two or three neighbours found in specific detailed directions relative to the missing data point. When creating the grid, the DIGIPOL algorithm selects the two or three data points around the centre of the grid point and determines the value of that centre point using the algorithm.

Similar to cubic convolution, bilinear interpolation used in MorphAn uses a weighted average of the four nearest data point to determine the value of the missing data point as seen in Figure 26 (ESRI, 2021). In this figure, the cell centres of the input raster is illustrated by the grey points. The orange points are here the four nearest neighbours averaged and weighted to obtain the value of the red point placed in the corresponding yellow cell in the green output raster.

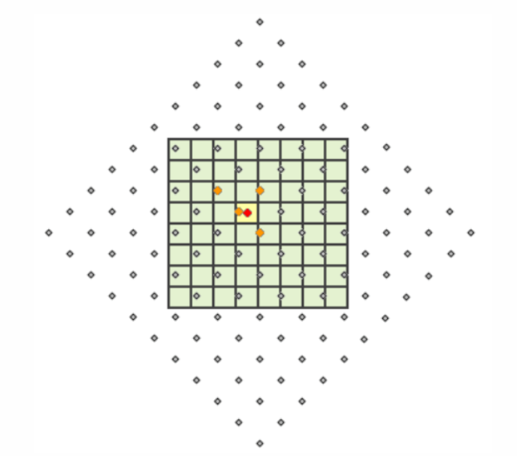

Figure 26 Bilinear interpolation diagram (ESRI, 2021)

7.3. Appendix C: Large outlier corrected in the reference transects: Schiermonnikoog 3.40

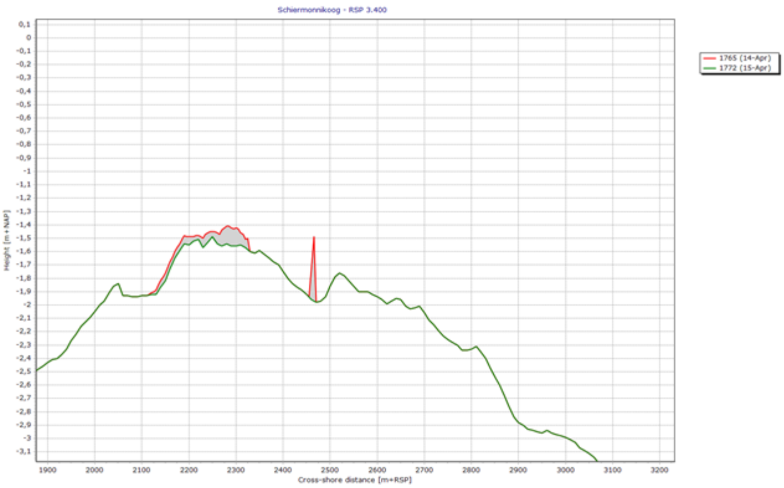

Figure 27 Transect 3.40 in Schiermonnikoog shows outlying peaks

The reason for this peak is the outlying dry measurement present on the 5m resolution grid in Schiermonnikoog along transect 3.40 which then is recorded in the dry M5 transect. MorphAn therefore interpolates between the wet measurement and the outlying dry measurement which leads to the outlying peak as shown in Figure 27.

The transect was therefore adapted to avoid this outlier by setting the seaward boundary of the dry measurement before the outliers to eliminate them when creating the transect in MorphAn.

No other large outliers were visually found which was enough to move further into the qualitative and quantitative comparison of both J5 and M5 transects and M5 and M2 transects.

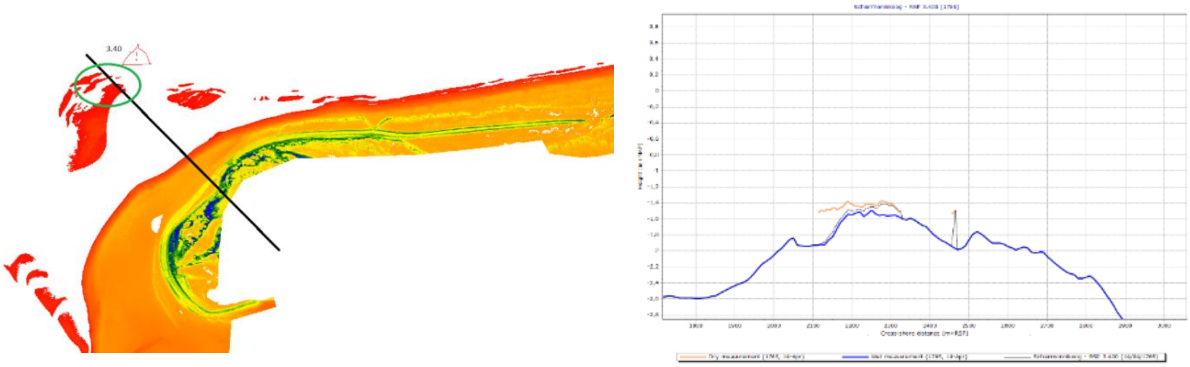

Figure 28 Cause of the outlying peak in transect 3.40 in Schiermonnikoog

7.4. Appendix D: Quantitative assessment of the shift in wet measurements

Table 9 Quantitative assessment of the shift in wet measurements

Profile	Landwards shift	Average difference (m+RSP)
02_Schier 3.40	M5 and M2	10
02_Schier 7.00	M5 and M2	5
03_Ameland 6.00	M5 and M2	5
03_Ameland 10.00	M5 and M2	5
04_Terschelling 9.00	M5 and M2	5
04_Terschelling 17.00	M5 and M2	5
05_Vlieland 43.77	M5 and M2	2,5
05_Vlieland 52.89	M5 and M2	10
06_Texel 11.90	J5	10
06_Texel 18.53	None	None
07_N-Holland 3.08	J5	10
07_N-Holland 9.28	J5	10
07_N-Holland 14.83	J5	10
07_N-Holland 19.55	J5	10
07_N-Holland 37.75	J5	10
08_Rijnland 66.25	None	None
08_Rijnland 81.75	None	None
09_Delfland 99.75	None	None
09_Delfland 111.96	None	None
09_Delfland 118.25	M5 and M2	5
11_Voorne 10.02	J5	10
12_Goeree 10.00	None	None
13_Schouwen 5.29	M5 and M2	5
15_N-Beveland 3.00	M5 and M2	10
16_Walcheren 15.30	M5 and M2	10
17_Z-Vlaanderen 10.46	M5 and M2	5

7.5. Appendix E: Additional quantitative analysis results on reference transects

7.5.1. Results of deep, beach and dune volume for a change in transect extraction method

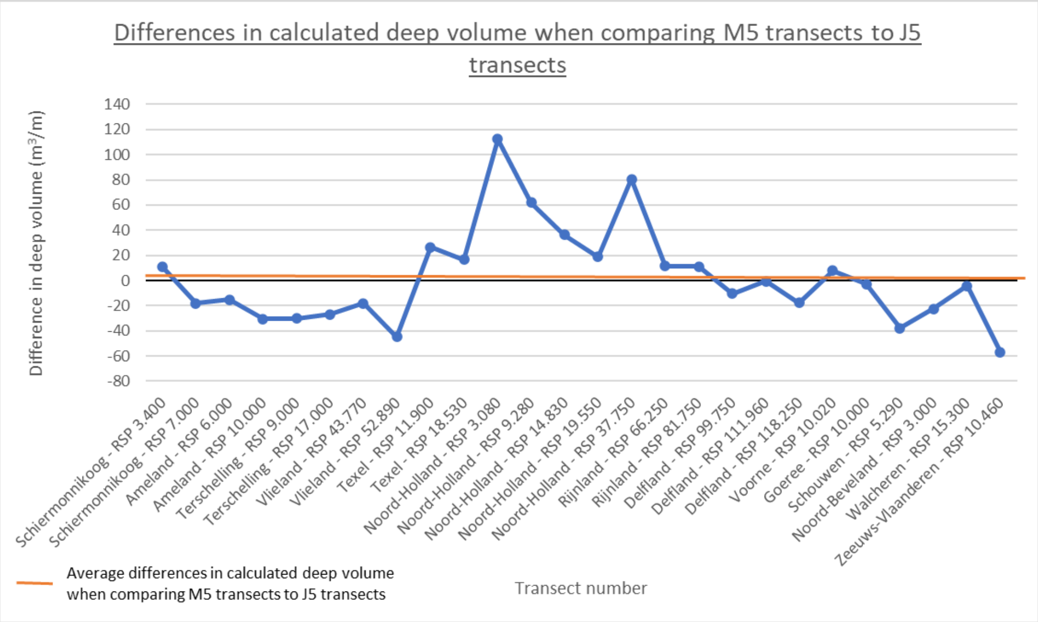

Figure 29 Differences in calculated deep volume when comparing M5 transects to J5 transects

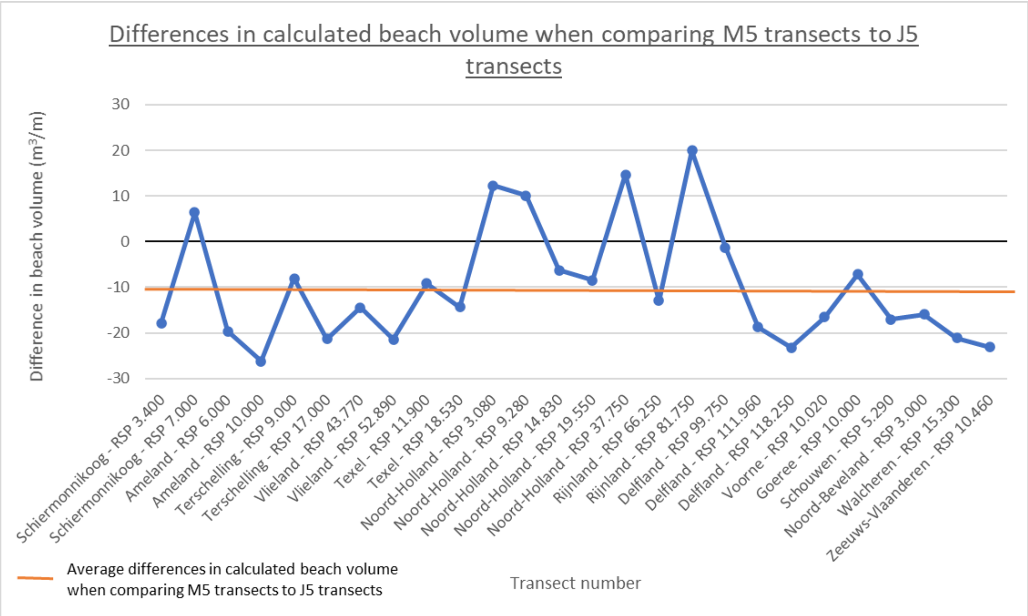

Figure 30 Differences in calculated beach volume when comparing M5 transects to J5 transects

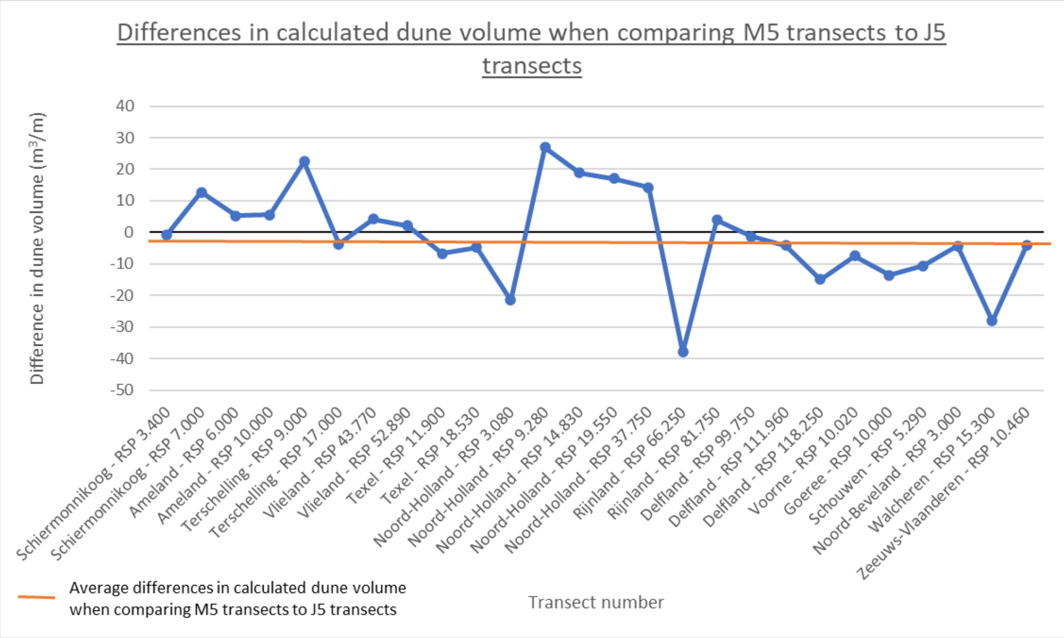

Figure 31 Differences in calculated dune volume when comparing M5 transects to J5 transects

7.5.2. Results of beach and dune volume for a change in horizontal topographic resolution

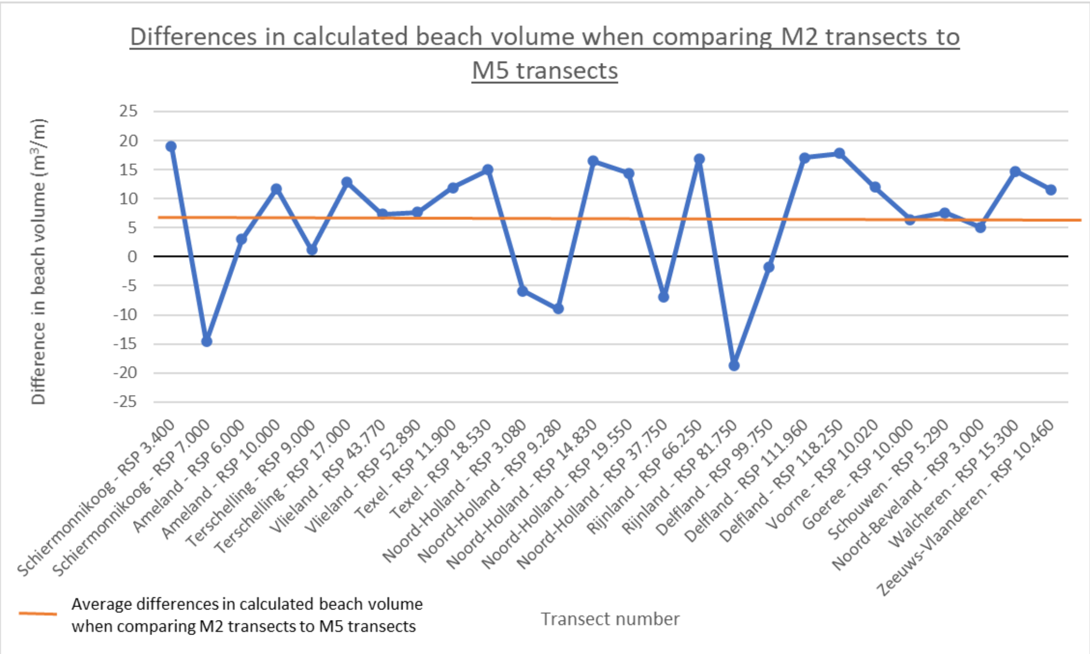

Figure 32 Differences in calculated beach volume when comparing M2 transects to M5 transects

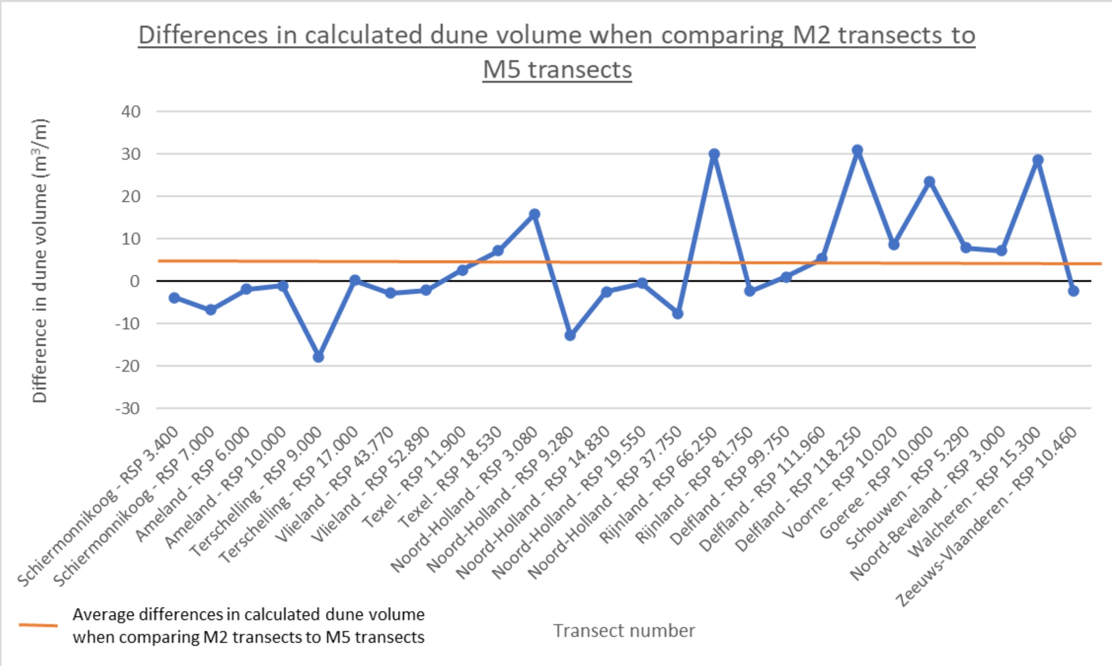

Figure 33 Differences in calculated dune volume when comparing M2 transects to M5 transects

7.6. Appendix F: Additional results found analysing the coastal areas of Terschelling, Noord-Holland and Schouwen.

7.6.1. Transects showing large changes in calculated MKL position and total coastal sand volume for a change in transect extraction method

Table 10 Calculated MKL changes larger than 5m when comparing M5 to J5 transects in coastal areas Terschelling, Noord-Holland and Schouwen

Performance criterion observe	M5 change compared to J5	Coastal area	Location	Criterion value	Criterion unit	Possible cause
MKL	Shift landward larger than 5m	5	Vlieland - RSP 52.890	-6,271	m	Shift of the wet measurement landward
MKL	Shift landward larger than 5m	13	Schouwen - RSP 3.770	-5,048	m	Landward shift of both wet and dry measurement
MKL	Shift landward larger than 5m	13	Schouwen - RSP 4.170	-5,211	m	Landward shift of both wet and dry measurement
MKL	Shift landward larger than 5m	4	Terschelling - RSP 12.000	-11,366	m	Shift of the dune foot from J5: 16m+RSP to M5: -84m+RSP
MKL	Shift landward larger than 5m	4	Terschelling - RSP 11.400	-8,314	m	Shift of the dune foot from J5: -9m+RSP to M5: -74m+RSP
MKL	Shift landward larger than 5m	4	Terschelling - RSP 4.400	-5,343	m	Coupling: dry M5 ends at 1060m+RSP, J5 ends at 995m+RSP. Also wet landward shift ~6m
MKL	Shift seawards larger than 5m	4	Terschelling - RSP 9.000	9,909	m	Shift of the dune foot from J5:120m+RSP to M5:268m+RSP
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 35.750	7,797	m	Coupling: dry M5 ends at 165m+RSP, J5 ends at 95m+RSP. Also wet seaward shift ~9m
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 34.750	7,668	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 27.160	7,625	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 44.500	7,314	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 49.500	6,938	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 51.500	6,794	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 39.000	6,556	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 41.000	6,393	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 12.880	6,160	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 45.250	6,027	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 46.000	5,816	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 27.820	5,798	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 43.000	5,728	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 50.750	5,667	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 37.000	5,501	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 46.500	5,432	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 12.730	5,393	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 5.480	5,337	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 3.900	5,277	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 32.500	5,220	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 30.250	5,175	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 27.000	5,095	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	7	Noord-Holland - RSP 5.280	5,000	m	Coupling: dry M5 ends later J5 ends earlier. Also wet seaward shift.
MKL	Shift seawards larger than 5m	13	Schouwen - RSP 17.190	5,449	m	Seaward shift of both wet and dry measurement

Table 11 Calculated total volume changes larger than 100m³/m when comparing M5 to J5 transects in coastal areas Terschelling, Noord-Holland and Schouwen

Performance criterion observed	M5 change compared to J5	Coastal area	Location	Criterion value	Criterion unit	Possible cause
Total Volume	Loss larger than 100m3/m	13	Schouwen - RSP 4.170	-109,375	m3/m	Shift in both wet and dry measurements landward
Total Volume	Loss larger than 100m3/m	4	Terschelling - RSP 8.600	-131,000	m3/m	Wet profile shift landward
Total Volume	Loss larger than 100m3/m	4	Terschelling - RSP 13.000	-119,375	m3/m	Wet profile shift landward
Total Volume	Loss larger than 100m3/m	4	Terschelling - RSP 6.800	-116,375	m3/m	Wet profile shift landward
Total Volume	Loss larger than 100m3/m	4	Terschelling - RSP 19.200	-101,075	m3/m	Wet profile shift landward
Total Volume	Loss larger than 100m3/m	4	Terschelling - RSP 20.200	-100,675	m3/m	Wet profile shift landward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 46.250	206,850	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 2.490	182,225	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 45.250	171,075	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 46.000	170,900	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 41.500	167,000	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 7.080	164,600	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 3.900	159,500	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 48.250	149,525	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 34.000	142,100	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 40.000	134,325	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 39.750	130,125	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 1.900	127,950	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 42.500	127,925	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 39.000	126,325	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 40.500	125,875	m3/m	Wet profile shift seaward

Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 49.500	124,075	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 35.750	123,925	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 46.500	123,025	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 3.690	120,175	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 30.500	119,700	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 41.000	119,100	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 4.490	117,450	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 35.500	117,275	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 49.250	117,150	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 28.470	116,000	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 43.000	115,275	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 29.230	115,175	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 7.680	114	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 1.500	113,65	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 29.870	113,15	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 6.480	112,15	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 4.290	111,6	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 28.640	110,3	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 37.750	109,45	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 33.500	108,825	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 27.320	105,65	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 28.820	103,625	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 3.080	103,375	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 2.890	100,95	m3/m	Wet profile shift seaward

Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 29.000	100,925	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	7	Noord-Holland - RSP 40.250	100,2	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	13	Schouwen - RSP 16.280	229,55	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	13	Schouwen - RSP 16.480	201,225	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	13	Schouwen - RSP 16.680	190,95	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	13	Schouwen - RSP 15.480	137,05	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	13	Schouwen - RSP 16.880	133,925	m3/m	Wet profile shift seaward
Total Volume	Gain larger than 100m3/m	13	Schouwen - RSP 15.880	122,025	m3/m	Wet profile shift seaward

7.6.2. Transects showing large changes in calculated MKL position and total coastal sand volume for a change in horizontal topographic resolution

Table 12 Calculated MKL changes larger than 5m when comparing M2 to M5 transects in coastal areas Terschelling, Noord-Holland and Schouwen

Performance criterion observed	M2 change compared to M5	Coastal area	Location	Criterion value	Criterion unit	Possible cause
MKL	Shift seawards larger than 5m	4	Terschelling - RSP 14.800	13,896	m	Shift of the dune foot from M5:197m+RSP to M2:149m+RSP
MKL	Shift seawards larger than 5m	4	Terschelling - RSP 12.600	10,741	m	Shift of the dune foot from M5: -118m+RSP to M2: 0m+RSP
MKL	Shift seawards larger than 5m	4	Terschelling - RSP 9.200	9,270	m	Shift of the dune foot from M5:101m+RSP to M2:199m+RSP
MKL	Shift seawards larger than 5m	4	Terschelling - RSP 16.200	8,288	m	Shift of the dune foot from M5: -355m+RSP to M2: -270m+RSP
MKL	Shift seawards larger than 5m	4	Terschelling - RSP 12.000	7,928	m	Shift of the dune foot from M5: -84m+RSP to M2:14m+RSP
MKL	Shift seawards larger than 5m	4	Terschelling - RSP 15.800	6,661	m	Shift of the dune foot from M5: -347m+RSP to M2: -266m+RSP

Table 13 Calculated total volume changes larger than 5m when comparing M2 to M5 transects in coastal areas Terschelling, Noord-Holland and Schouwen

Performance criterion observed	M5 change compared to J5	Coastal area	Location	Criterion value	Criterion unit	Possible cause
Total Volume	Loss larger than 100m3/m	7	Noord-Holland - RSP 52.250	-114,620	m3/m	M5 peaks are higher up
Total Volume	Loss larger than 100m3/m	7	Noord-Holland - RSP 49.250	-125,380	m3/m	M5 transect is around 0.8m higher from -210m+RSP to -100m+RSP
Total Volume	Loss larger than 100m3/m	7	Noord-Holland - RSP 48.250	-143,925	m3/m	M5 transect is around 1m higher from -260m+RSP to -120m+RSP
Total Volume	Loss larger than 100m3/m	7	Noord-Holland - RSP 41.500	-177,090	m3/m	M5 peak at -200m+RSP is at 17.5m+NAP, M2 is lower at 15.70m+NAP. Other minor peak height differences