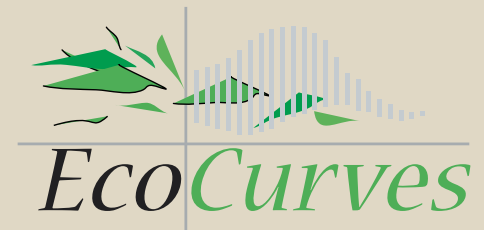
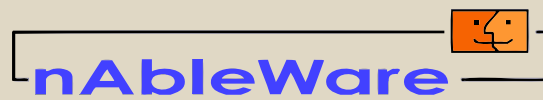
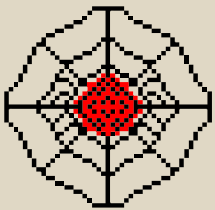


InterTides 2

maps of the intertidal by interpolation of tidal gauge data

C. Rappoldt, O.R. Roosenschoon, D.W.G. van Kraalingen



InterTides 2

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InterTides 2

maps of the intertidal by interpolation of tidal gauge data

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This report is a concise manual of the program InterTides. InterTides calculates water levels by interpolation between levels measured levels by tidal gauge stations. The interpolation corrects for phase differences between the stations. Calculated water levels are used by InterTides to construct a waterlevel map, a water level movie, an exposure time map or an exposure status movie. Further, the distributions of flooding and exposure time for user defined points can be calculated, maps of mean high tide, mean low tide and the fraction of tidal periods a point is flooded or exposed. Finally GPS tracks can be visualised in a movie in combination with mudflat exposure. Maps are written as ASCII grid files and can be combined in Geographic Information Systems with other data. Movies are calculated as MOV or MP4 files and text is exported as CSV files.

Keywords: Wadden Sea, Eastern Scheldt, water level, exposure time, GPS track, high tide, low tide

InterTides 2.00 (version April 19, 2023)

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Frontpage: “Rising tide near Oerderduin at the island Ameland” (by first author)

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Introduction to InterTides

InterTides most basic function is interpolation between water levels measured at tidal gauge stations. Nine different functions depend on this this functionality and one of them can be selected in the user interface. Depending on this choice, a parameters must be set. These required or optional parameters deal with the selection of a time or a period, the choice of a height map, interpolation settings, and a few output options.

1.1 Regions

InterTides has been configured for five regions

Eastern Scheldt (Oosterschelde) The estuary in Zeeland with water levels from 1990 onwards. The Eastern Scheldt storm surge barrier is the western boundary. Details for this region can be found in [Chapter 6.1](#).

Western Scheldt (Westerschelde) The estuary in Zeeland with water levels from 1995 onwards. The line Vlissingen–Cadzand is western boundary. Details for this region can be found in [Chapter 6.2](#). **This region is not available in InterTides online.**

Voordelta en Vlake van de Raan (Zeeland coastal waters) Coastal area between the port of Rotterdam and the Belgian border. Water levels are implemented from 2001 onwards. Details for this region can be found in [Chapter 6.3](#). **This region is not available in InterTides online.**

Wadden Sea (Waddenzee) The Dutch part of the Wadden Sea with water levels from 1981 onwards. Details for this region, like the tidal gauge stations used, can be found in [Chapter 6.4](#).

Wadden Sea Area (Waddengebied) The Wadden Sea extended with the tidal inlets between the wadden islands and a coastal zone. Water levels are implemented from 2000 onwards. Details for this region can be found in [Chapter 6.5](#).

For some regions a subarea may be selected. For the Wadden Sea or the Wadden Sea Area for instance, a calculated map may be limited to one of the tidal basins. And for the Zeeland Coastal Waters the calculations may be limited to either the "Voordelta" or the "Vlake van de Raan".

[Chapter 2](#) lists all functions of InterTides by means of an example. [Chapter 3](#) is about the input of water levels measured by tidal gauge stations. The meaning of

InterTides' parameters is explained in [Chapter 4](#). [Chapter 5](#) contains an extensive explanation of the interpolation method. [Chapter 6](#) gives shows the configuration details for the various regions and [Chapter 7](#) documents the harmonic analysis used by InterTides to fill in missing water levels.

1.2 Output formats

Besides simple text files in CSV format (Comma Separated Values), InterTides produces plots, maps and movies.

1.2.1 Plots

Plots are always written as vector graphics in PDF format. Sometimes there is just a single graph, like the distribution of high tide levels for a single point. The InterTides function "Point values" ([section 2.8](#)) also plots all water levels thus producing a PDF file which may contain thousands of plots, each of them containing the water levels for a single day. The PDF files can either be directly used or edited with a program like Adobe Illustrator.

1.2.2 Maps

Several functions of InterTides involve the calculation of a map. A calculated map is available as an ASCII grid file which can be imported in a GIS program. The cells outside the selected area will contain NODATA values. For direct inspection a TIFF image is produced showing the values on a colour scale. The colour scale is shown in a separate legend file in PDF format.

1.2.3 Movies

Movies are written to file as animated GIF, but may be converted by the user interface into a more common format.

The functions of InterTides

2.1 Waterlevel map

For the selected area a map is calculated with the water levels at a user-defined time. Hence, the required parameters are the name which is given to the calculated map, the date and time and the cell size. Without specific area selection the map is generated for the entire region. [Figure 2.1](#) shows an example.

The water level map is generated in the form of an ASCII grid file which can be imported in a GIS program. The TIFF image uses a colour scale corresponding

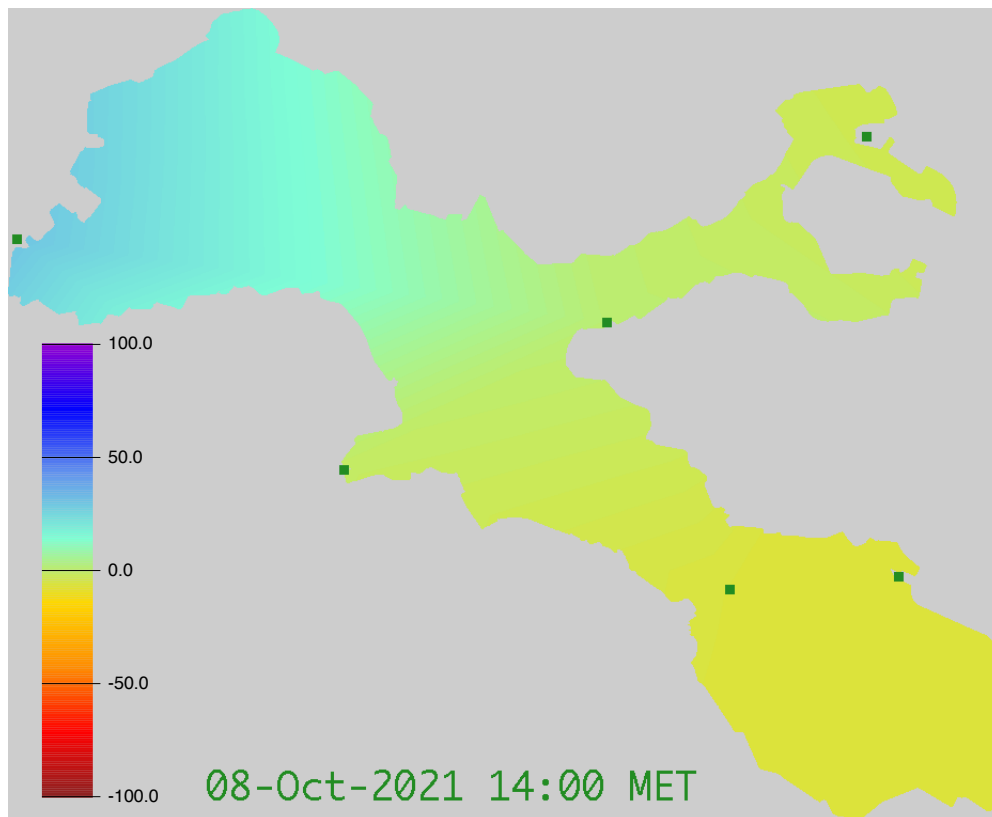
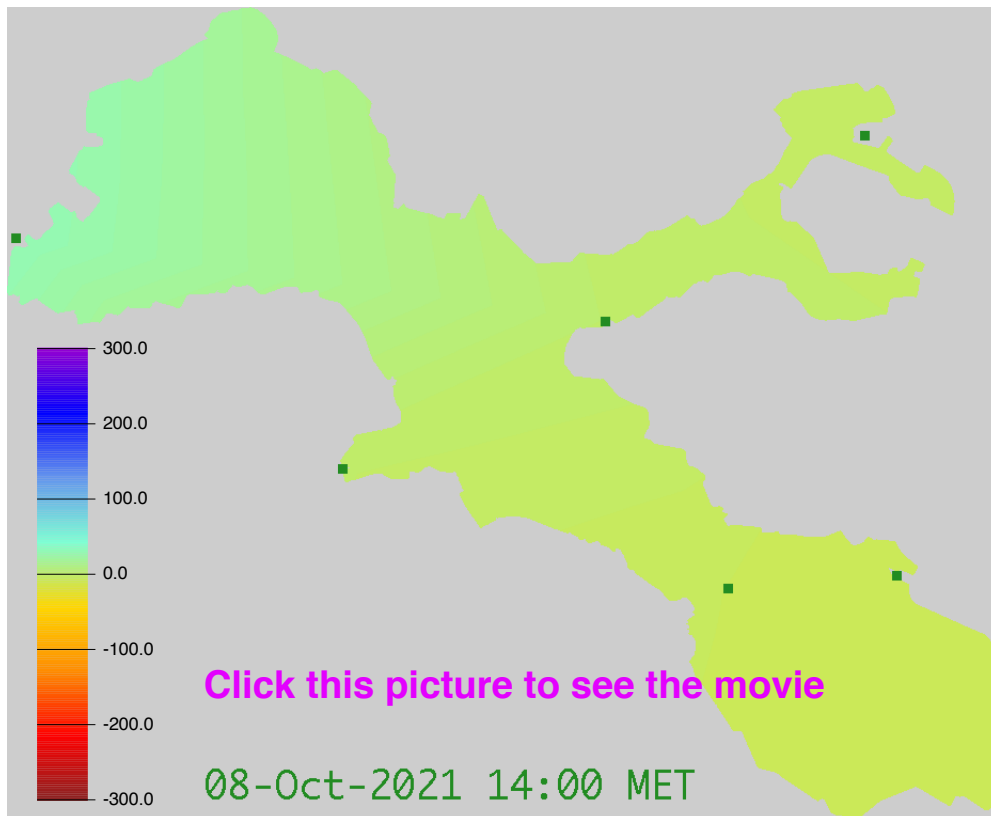


Figure 2.1. Eastern Scheldt interpolated water levels calculated for October 8, 2021 at 14:00. The scale is in cm. The green points mark the positions of the tidal stations.



Movie 2.1. Eastern Scheldt levels between Oct 8, 2021 14:00 and Oct 9, 2021 14:00. The water levels at the start time are the same as those in [Figure 2.1](#), but at a different scale.

by default to the range $[-200, +200]$ cm. This level range is an optional parameter which can be changed in the user interface. Colour scale and associated level range are written to an additional output file in PDF format (the legend file).

2.2 Waterlevel movie

A movie of the changing water levels can be made by specifying a begin time and an end time. InterTides then generates a series of pictures like the one in [Figure 2.1](#) which are combined into a movie file. By choosing a smaller or larger time step (in minutes) the changes in water level are presented slowly or more quickly. A waterlevel movie can be generated for the entire region or for a selected (cropped) subarea. [Movie 2.1](#) shows an example.

[Movie 2.1](#) shows that the high tide water levels increase towards the south eastern end of the Eastern Scheldt. InterTides mimics this well-known effect by means of a tidal amplitude map¹. Interpolation uses the station levels *relative* to their amplitude and each calculated point level, which is then relative as well, is multiplied with its *local amplitude*. Since the amplitude at the far end of the tidal basin is large, the calculated water levels exceed those of the tidal gauge stations further west.

¹The used amplitude map is a map of the principal lunar component M2 of the tide.

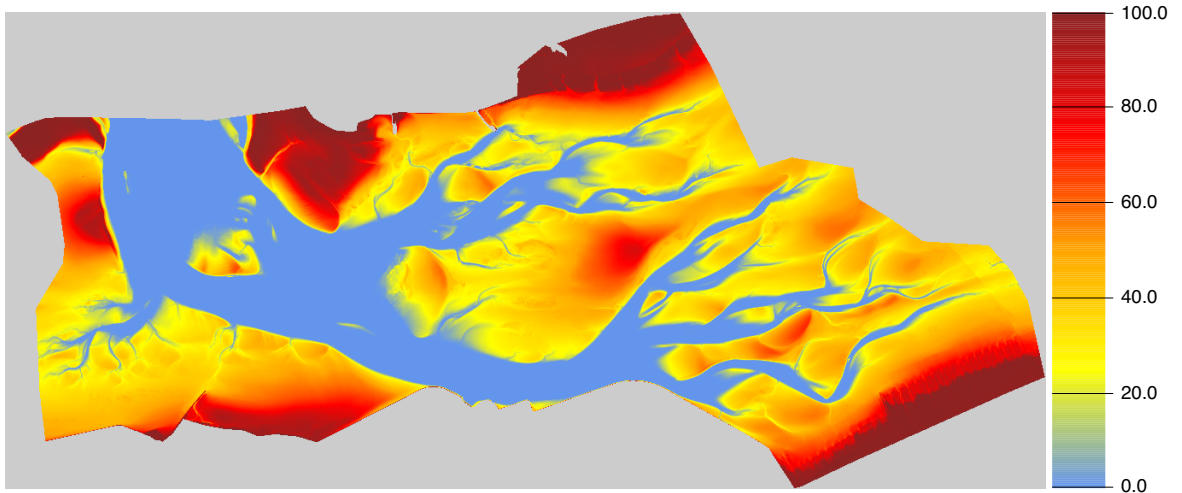


Figure 2.2. Exposure time map calculated for the Wadden Sea subarea "Zoutkamperlaag", which is the tidal basin around the equally named tidal gully at the west side of the island Schiermonnikoog. The map has been calculated with height map "Wadsea_2013_2019" using the 368,073 waterlevels recorded by each of the nearby tidal stations in the period [01-Jan-2013, 31-Dec-2019]. Begin and end time of this period have been adjusted to the nearest high tide.

2.3 Exposure time map

The calculation of an exposure time map ("droogvalduurkaart") is probably the most popular function of InterTides. The exposure time of a certain point is defined as the fraction of time that it is exposed, i.e. not covered by water. Hence, an exposure time map requires a height map and is calculated for a certain period.

For each cell of the desired map a water level is calculated for each of the 10-minute intervals in the selected time period. At each interval, the cell is exposed if the estimated water level is below its height on the height map. The fraction of 10-minute intervals at which the cell is exposed is its (fractional) exposure time.

Figure 2.2 shows an example map for the tidal basin Zoutkamperlaag (a subarea of the Wadden Sea region). The map is based on the "Wadsea_2013_2019" height map of Rijkswaterstaat and is calculated for the period between 01-Jan-2013 and 31-Dec-2019.

Like a water level map, an exposure time map is generated in the form of an ASCII grid file which can be imported in a GIS program. And again, for direct inspection a TIFF image is written with a colour scale ranging from 0.0 (never exposed) to 1.0 (always exposed). Optionally the value for "always exposed" can be set to 100, which converts the scale to a percentage of time.

In practice, the computing time required for calculating an exposure time map varies between a few minutes and a few hours, depending on the choices made. This is due to the large number of water levels that may have to be calculated. The Wadden Sea region map at full resolution (20 m) contains about 6 million data cells and a time period of 10 years consists of about half a million of 10-minute intervals. This amounts to the evaluation of roughly 3,000,000,000,000 water levels.

Therefore, before final submission of a computing task InterTides makes an estimate of the required time. A reduction can be achieved by (at first) selecting a subarea, choosing a larger cell size (a lower resolution) or a shorter period.

2.3.1 Corrections

In order to calculate an "honest" fraction of time, the begin and end times of the period can be automatically adjusted to the nearest high tide time. This adjustment is optional and can be switched on in the input screen. In the example of [Figure 2.2](#) the begin and end times were adjusted to the high tide times 00:20 (at 01-Jan-2013) and 1:40 (at 1-Jan-2020) for station Schiermonnikoog².

The phase differences between the various tidal stations potentially lead to considerable errors in interpolated water levels. This problem is solved by synchronising the tidal waves recorded at the tidal stations (for details see [section 5.6](#)).

2.3.2 The cells of the ASCII grid map

The cell size of the calculated exposure time map is a user defined parameter. The precise position of the cells is always derived from the region (or subarea) map. At first the (cropped) region or subarea map is converted to the desired resolution. Then, for each of the resulting cells, the selected height map is read and an exposure time is calculated.

There is one exception to this rule. If the user selects the native cell size of the height map as the desired resolution of the exposure time map, the area map is converted to the height map grid. Hence, the resulting exposure time map will then use the same cell size and the same cell positions as the height map. The names of the produced files contain the additional text "hgrid". This procedure prevents the smoothing of height map values if the grid is just shifted.

2.3.3 Seasonal exposure times

An interesting option is the choice of a season, which is the time between two dates (a day and a month). If a season is defined the exposure time map is still calculated for all selected years, but now only for the defined season within those years.

As an example, [Figure 2.3](#) shows the exposure time map for the Wadden Sea calculated for dates in November only, using the same height map, years and options as the example in [Figure 2.2](#). A second map has been calculated for dates in May ([Figure 2.4](#)). The differences are revealed by calculating (with a separate program or in a GIS) the difference map "November minus May" which is shown in [Figure 2.5](#). The figure caption contains some comments.

²Note that an adjusted end time may lie outside the entire time range available for the region. Therefore the astronomical tide is calculated for one day before and one day after the water levels installed.

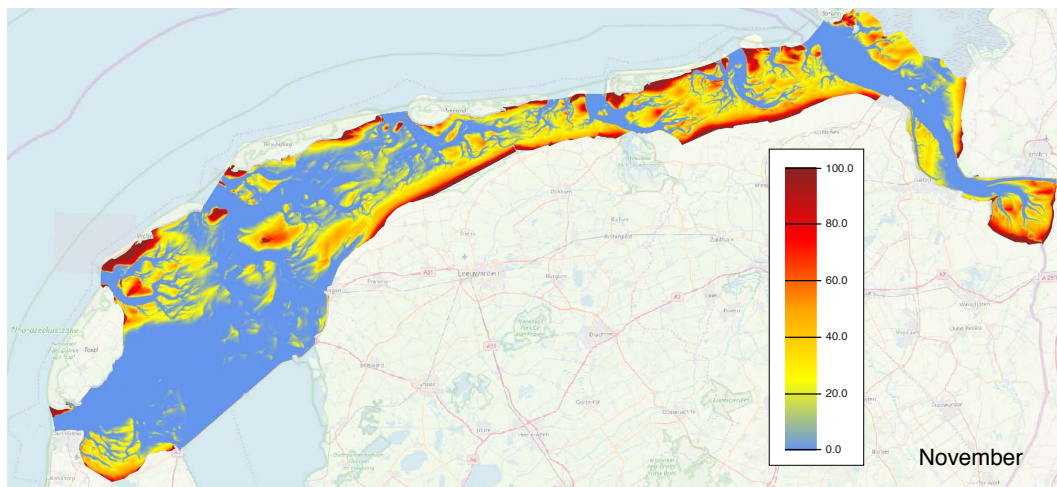


Figure 2.3. Exposure time for the InterTides region map calculated with the height map "Wadsea_2013_2019" for the month November in the years 2013–2019. Exposure time is expressed as a percentage of time. The 7 november time windows were all adjusted to the nearest high tide and the tides were synchronised on the M2 astronomical component (the same choices as in [Figure 2.2](#)). The NODATA area of the region map has been filled with the OpenStreetMap.

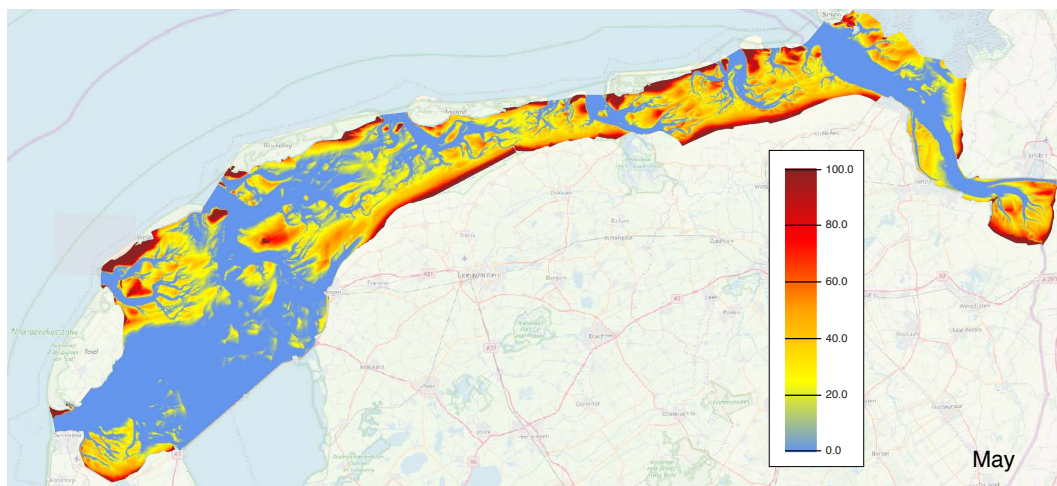


Figure 2.4. Exposure time for the InterTides region map calculated with the height map "Wadsea_2013_2019" for the month May in the years 2013–2019. Exposure time is expressed as a percentage of time. The 7 may time windows were all adjusted to the nearest high tide and the tides were synchronised on the M2 astronomical component (the same choices as in [Figure 2.2](#)). The NODATA area of the region map has been filled with the OpenStreetMap.

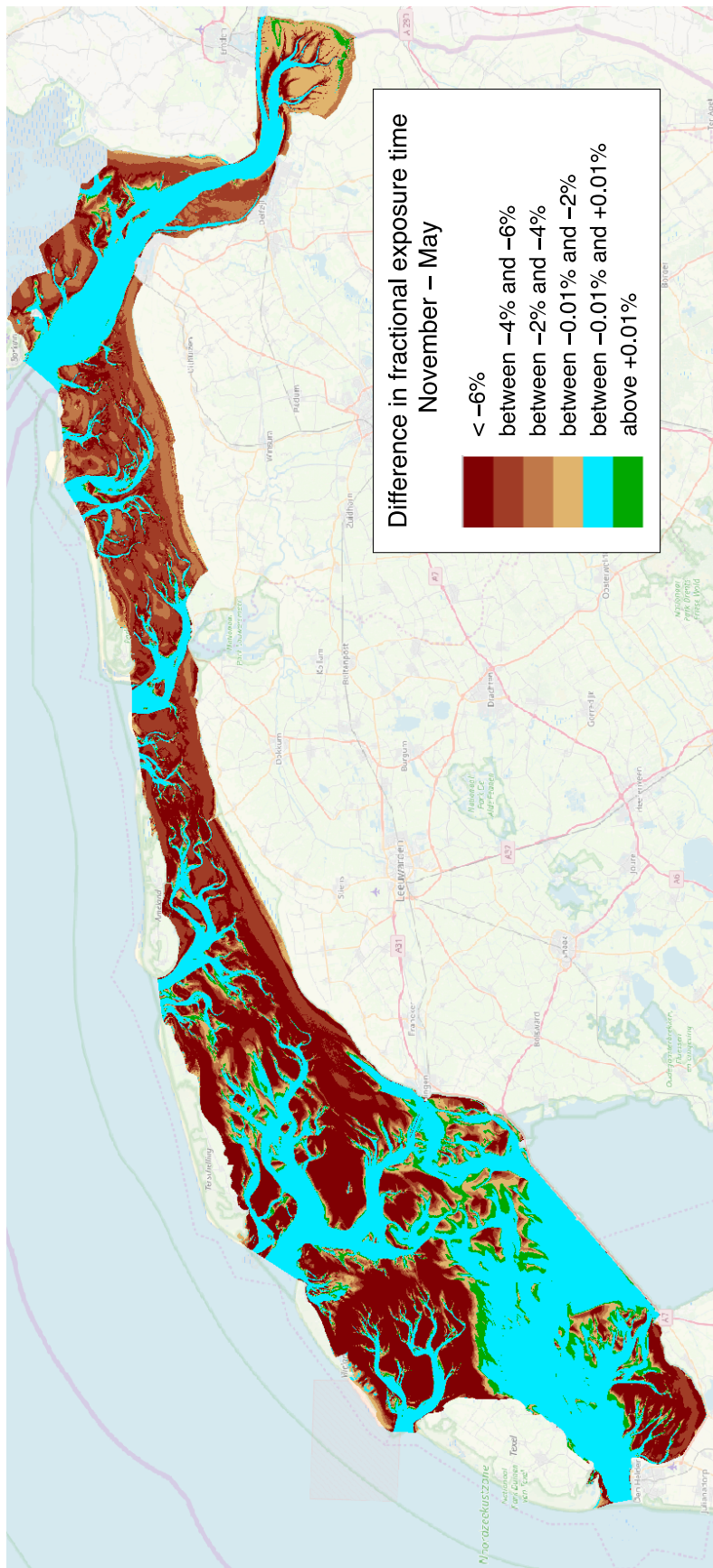


Figure 2.5. The difference between the fractional exposure times in November and May as a percentage of time (see Figures 2.3 and 2.4 for the two exposure time maps). Astronomical and weather effects cause the differences which are smaller in the east. The tidal amplitude is larger there which makes the exposure time less sensitive to changes. In the western part we see that the lowest parts of the mudflats are exposed slightly more often in november. The higher parts, however, are flooded more often, up to about 8% of time, which is almost 2 hours per day.



Movie 2.2. Exposure status of a rectangular area of 26×14 km in the Wadden Sea between the Frysian coast and the islands Ameland and Schiermonnikoog. The movie runs from 19:00 at May 30, 2015, to 8:00 at the next day. For exposed areas the underlying height map is shown at the colour scale included in the first frame of the movie.

2.4 Exposure status movie

The exposure status of a point is "flooded" or "exposed". The movie produced by function "Exposure status movie" is a visualisation of the periodic flooding of the area. A point is exposed if its height exceeds the calculated water level and for the exposed parts of the map the underlying height map is shown. The flooded parts are blue.

As an example, [Movie 2.2](#) shows the exposure status of a rectangular part of the Wadden Sea. The movie has been calculated using the Rijkswaterstaat height map from 2013–2019.

2.5 Mean high tide and low tide maps

This function of InterTides calculates maps of the mean high tide level ("GHW") and the mean low tide level ("GLW"). For each cell of the map all water levels in a given period are calculated and used to find the local high tides and low tides. [Figure 2.6](#) shows the high tide maps of three InterTides regions combined in a single image. The effect of the storm surge barrier between the the Eastern Scheldt and the open sea is clearly visible.

Nota that these maps do not require a height map. Levels are calculated by interpolation and not by physical modelling. A mudflat height exceeding the mean low tide level means that it will usually be exposed during low tide. Hence, by comparing the calculated maps with a height map the contours for mean high tide and mean low tide may be found. The contours lie where the height map value equals to the hight tide or low tide level.

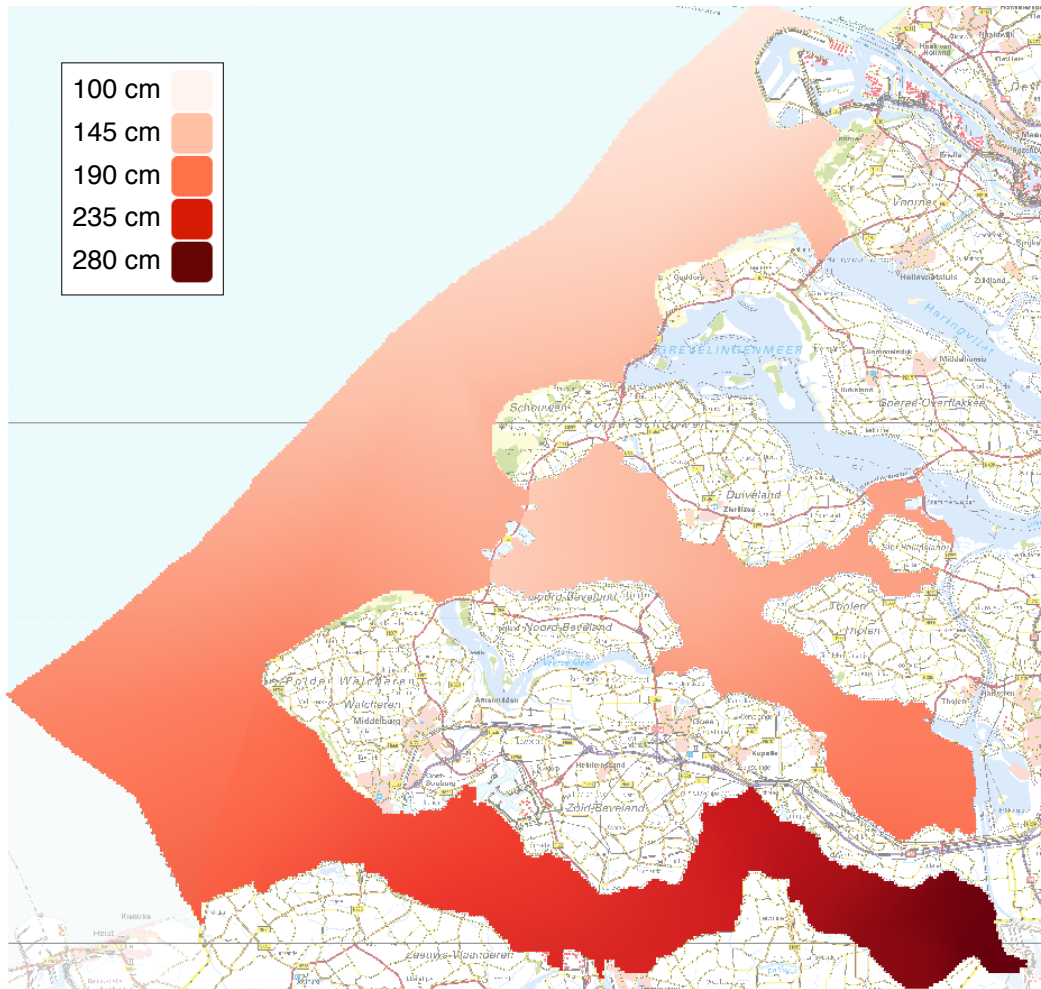


Figure 2.6. The mean high tide level in 2010–2020 for three InterTides regions: "VordeltaVlakteRaan", "Oosterschelde" (Eastern Scheldt) and "Westerschelde" (Western Scheldt). For Eastern and Western Scheldt Normalisation was used (see [section 5.8](#)).

In addition to the mean high and low tide levels maps are calculated of the median high and median low tide level. Usually the median levels do not differ significantly from the mean levels. Median levels, however, are relatively insensitive to storm tides and their ecological meaning is straightforward: half of the high tides do not reach the median high contour and the other half of the tides passes over it.

2.6 Frequency maps

The idea of this InterTides function is that high tide levels and low tide levels are combined with a height map in order to calculate all sorts of "frequencies" or "probabilities": the fraction of high tide or low tide levels at a certain point that do or do not exceed its height. InterTides then calculates maps of such fractions.

In the following list of calculated maps *Name* (in *italics*) is the map name provided by the user, *Region* is the name of the selected region and *XX* is the desired resolution in meter (e.g. 40m).

Name_mean_high_XXm.asc The mean high tide level at resolution *XX*m, the same map as in [section 2.5](#).

Name_mean_low_XXm.asc The mean low tide level at resolution XXm, the same map as in [section 2.5](#).

Name_median_high_XXm.asc The median high tide level at resolution XXm, the same map as in [section 2.5](#).

Name_median_low_XXm.asc The median low tide level at resolution XXm, the same map as in [section 2.5](#).

dif_Region_height-Name_mean_high_XXm.asc Difference between the selected height map "HeightMap" and the mean high tide level. The zero contour of this map is the mean high tide contour of the area.

dif_Region_height-Name_mean_low_XXm.asc Difference between the selected height map "HeightMap" and the mean low tide level. The zero contour of this map is the mean low tide contour of the area.

dif_Region_height-Name_median_high_XXm.asc Difference between the selected height map "HeightMap" and the median high tide level. The zero contour of this map is the median high tide contour of the area.

dif_Region_height-Name_median_low_XXm.asc Difference between the selected height map "HeightMap" and the median low tide level. The zero contour of this map is the median low tide contour of the area.

Name_exp_hi_XXm.asc The fraction of high tides at which a map cell remains exposed at resolution XXm.

Name_exp_lo_XXm.asc The fraction of low tides at which a map cell becomes exposed at resolution XXm.

Name_fld_hi_XXm.asc The fraction of high tides at which a map cell becomes flooded at resolution XXm.

Name_fld_lo_XXm.asc The fraction of low tides at which a map cell remains flooded at resolution XXm.

Name_depth_XXm.asc The average depth for those high tides at which the point is flooded at resolution XXm.

For each map also a tif image is provided with the colour scale used in a legend file. A few examples are discussed below.

For the mudflats south of the Wadden island Terschelling, [Figure 2.7](#) shows the map "dif_waddengebiedc.height-terschelling_median_low_40m" which is the difference between a cropped height map of region "Waddengebied" (the Rijkswaterstaat 2013–2019 height map) and a map of the median low tide level. The colour scale used visualises the median low tide contour. The green areas become exposed during at least half of the tidal periods. The magenta colours refer to areas which become exposed less often.

More detail with respect to these latter areas is provided by [Figure 2.8](#). This figure is based on output map "terschelling_exp_lo_40m.asc" and the image uses a logarithmic colour scale to study in more detail the areas which are rarely exposed. The black areas are the same as all the green stuff in [Figure 2.7](#) and the other colours go down to really small probabilities.

A final example has some significance for wader birds. These birds forage at the mudflats and rest at high tide. At neap tides they sometimes can use the highest parts of mudflats as a high tide roost. These places are not known as well as the usual roosts since bird counts in the Wadden Sea are usually carried out during spring tide. Neap tide roosts may be explored by using a map like the one in

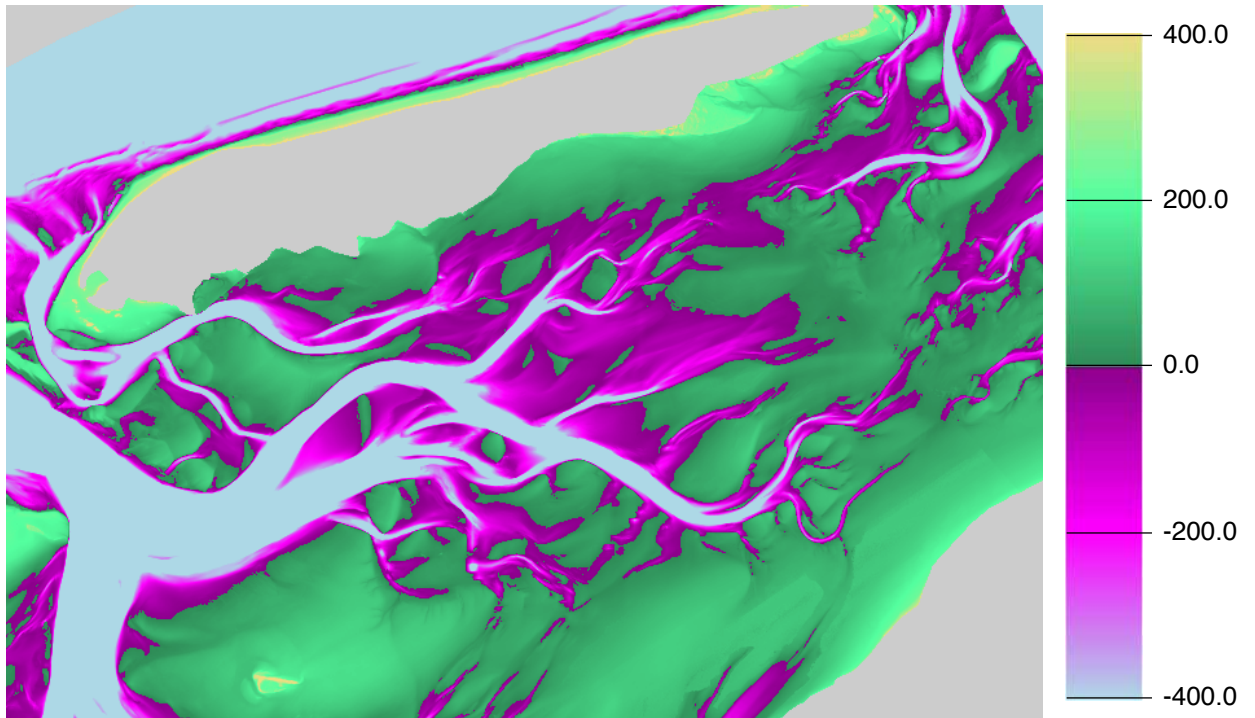


Figure 2.7. Difference between the Rijkswaterstaat 2013–2019 height map and the median low tide level for the 4939 low tides during 2013–2019. The median low tide level contour lies at the transition from green to magenta where the difference is zero.

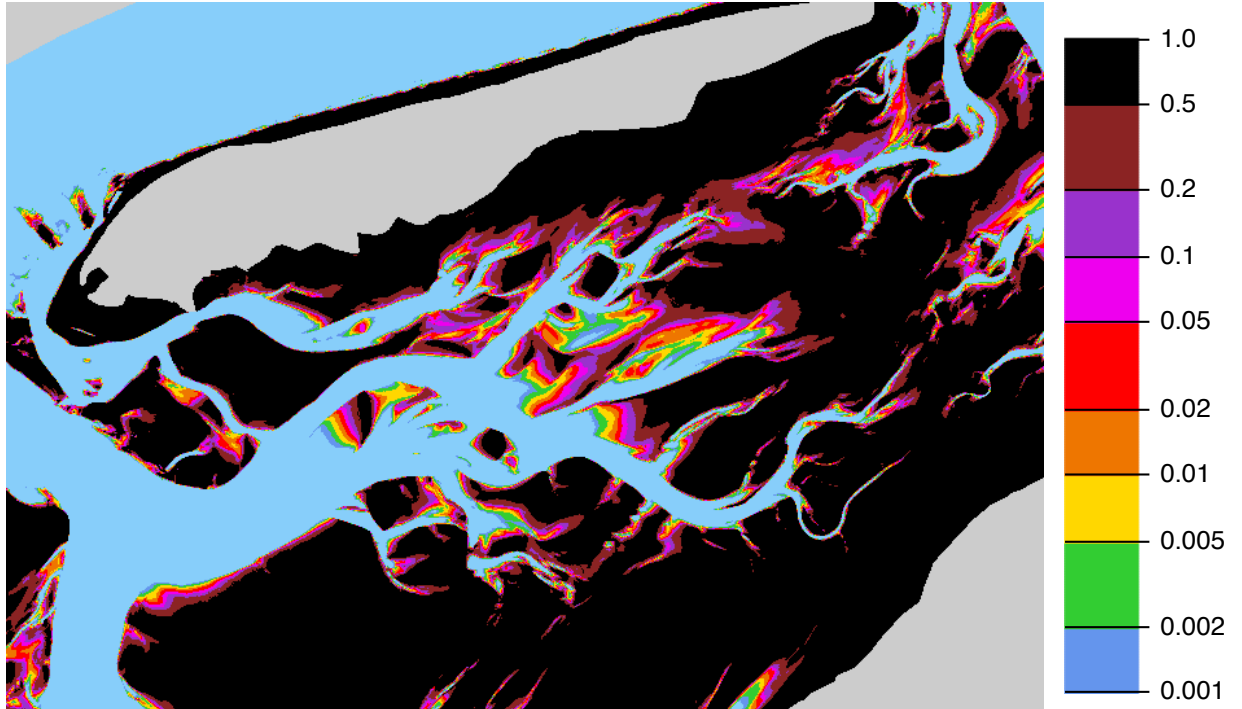


Figure 2.8. The fraction of low tides at which the area is exposed calculated with the Rijkswaterstaat 2013–2019 height map and the median low tide level for the 4939 low tides during 2013–2019. The black area lies above the median low tide level contour. The brown and purple areas will usually be exposed during spring tide. The other colours show rarely exposed areas.

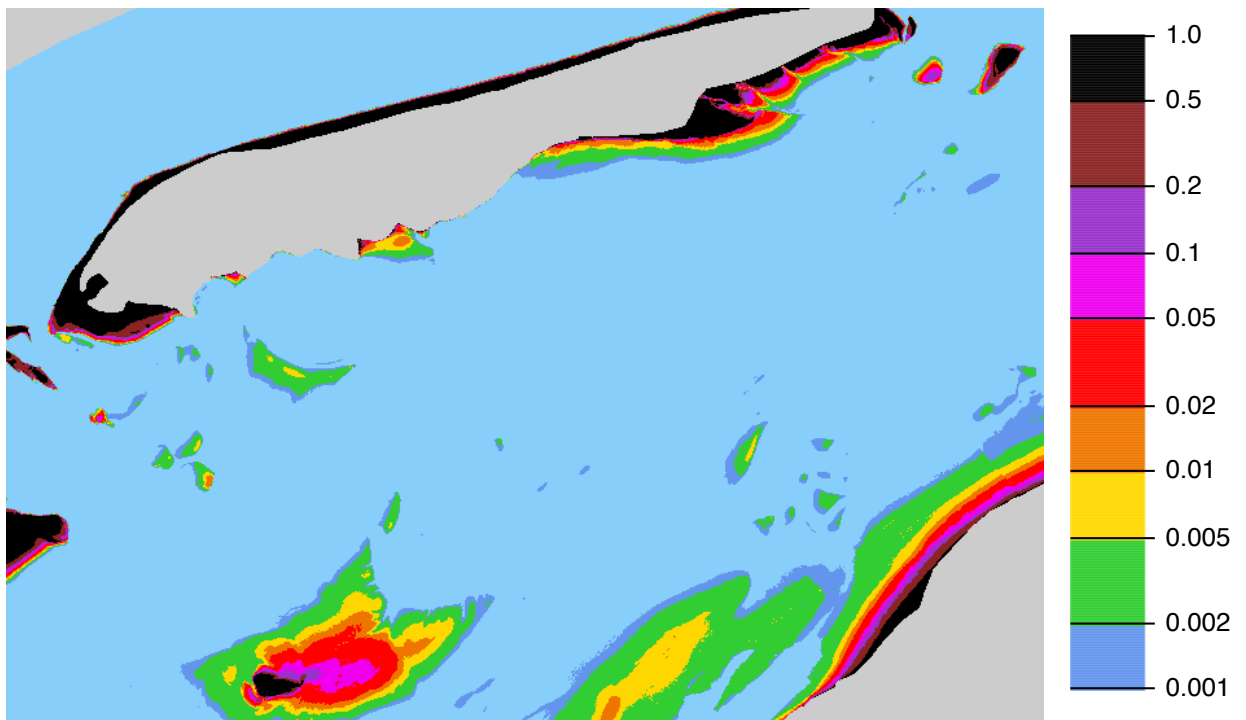


Figure 2.9. The fraction of high tides at which the area is exposed calculated with the Rijkswaterstaat 2013–2019 height map and the median high tide level for the 4938 high tides during 2013–2019. The black area lies above the median high tide level contour. The brown and purple areas will usually remain exposed during neap tide.

Figure 2.9, again for the mudflats south of Terschelling and produced by the same InterTides run as the maps in Figure 2.7 and Figure 2.8.

Areas remaining exposed during neap tide only are dark brown or purple in Figure 2.9. The figure shows such areas but just as an extension of the well known roosts. Specific neap tide roots probably do not occur in this part of the Wadden Sea with the possible exception of a small spot between the "Blauwe Balg" and the "Boschplaat" in the north-east corner of Figure 2.9.

2.7 Area statistics

This function returns results for a user-defined grid of points. A grid is defined by a lower-left point and a grid spacing. For all grid points inside the selected area, water levels are calculated and used to estimate a total water volume in the area and a total exposed surface area. These are presented as CSV files and as plots.

The amount of water at each grid point is the amount in excess of NAP (positive) or needed to reach NAP (negative). This means

for points above NAP, the water level used is the height of the water column above the surface.

for points below NAP, the water level used is either the (positive) level above NAP or the negative level below NAP but not further down than the point height.

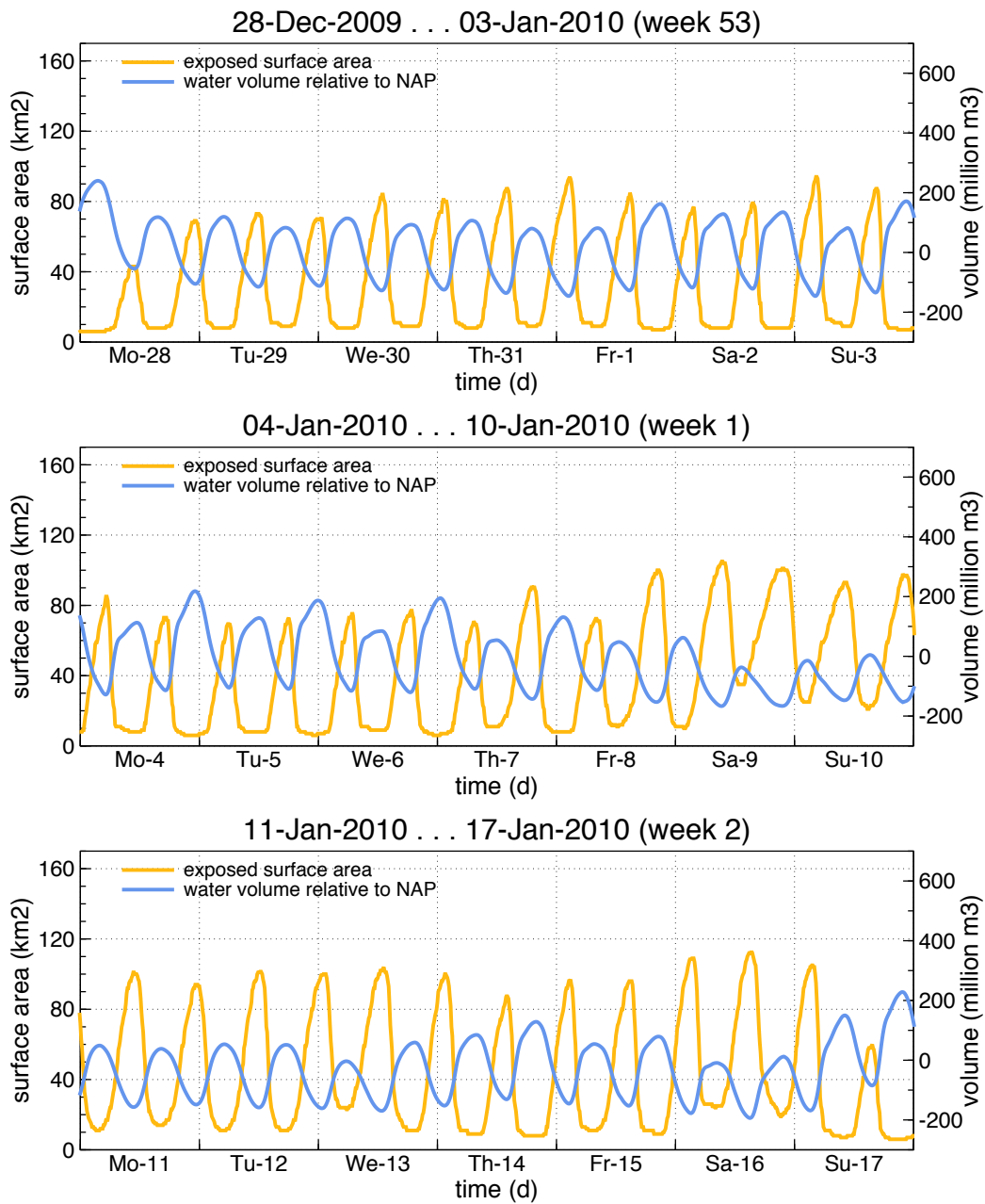


Figure 2.10. Three weeks of exposed surface area and water volume for subarea Balgzand, calculated using the "Area Statistics" function of InterTides. The amount of water is the amount in excess of the NAP level (positive) or required to reach NAP (negative).

The (positive or negative) amount of water in each cell is this level multiplied by the cell surface area which is simply the cell distance squared. The total amount for the area is the sum of the amounts calculated for the grid points.

For a maximum of 25400 grid points the calculated water levels and water column heights can optionally be downloaded in "level files". These CSV files can be imported in any spreadsheet program. This allows the subsequent use of biological models for the water column, e.g. light and primary production models.

Some care is required using this option since a dense grid in combination with a period of years easily leads to gigabytes of CSV files.

Figure 2.10 shows an example calculated for subarea Balgzand and based again on there Deltares Cycle 5 height map "wadsea_cycle5". The file contains a separate plot for each week in the specified period. On top of each plot is the ISO 8601 week number.

2.8 Point values

This function requires a number of user-defined points. For each point various quantities are calculated: the distribution of low and high tide water levels and the distribution of times flooded and times exposed (in hours per tidal cycle). These distributions are given as frequency histograms and as CSV files.

The points are specified by the user in a simple CSV file ("Comma Separated Values") which is uploaded automatically. The file must have extension CSV and

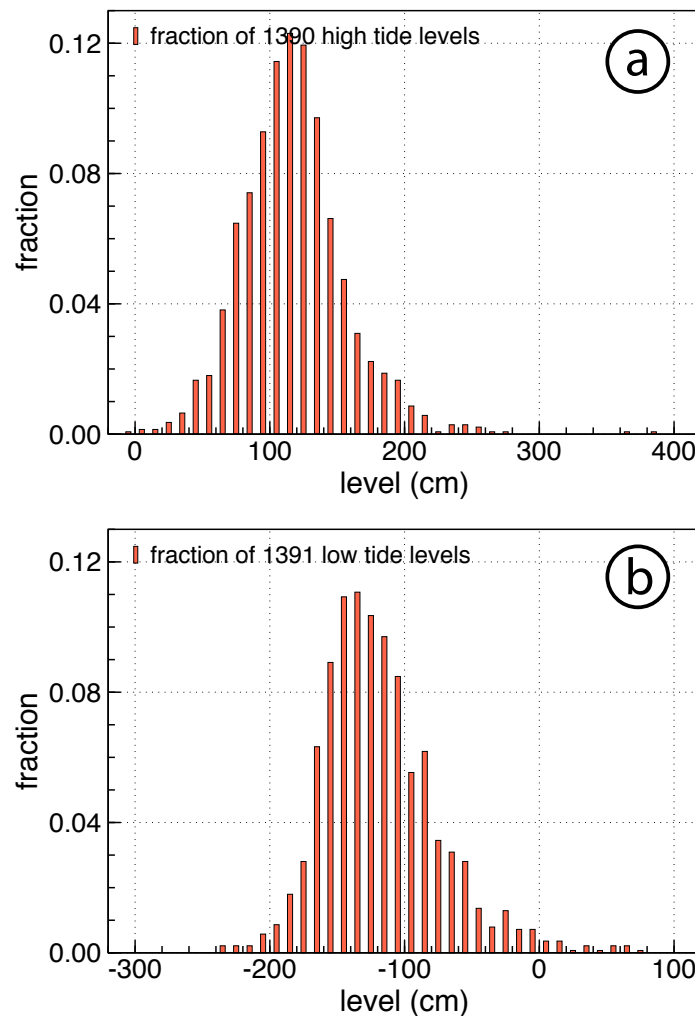


Figure 2.11. The distribution of (a) high tide and (b) low tide levels in november calculated for a point at (228935,607479). The calculations were made for the period [1990, 2013].

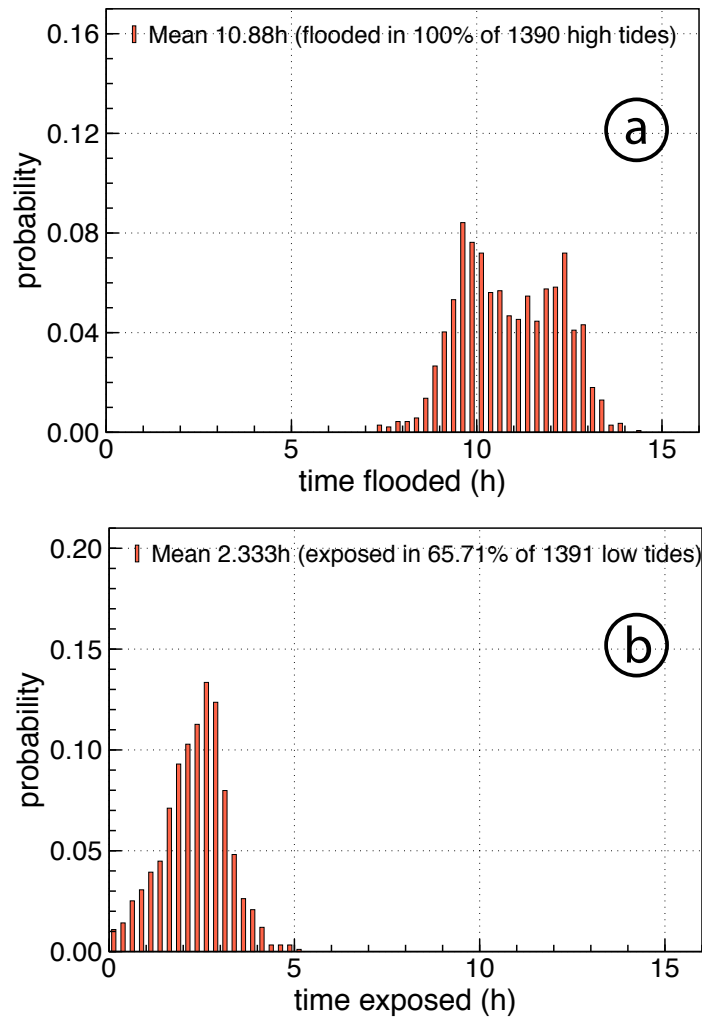


Figure 2.12. The distribution of (a) the time flooded during high tide and (b) the time exposed calculated for the november tides for a point at (228935,607479) during the period [1990,2013]. The height of the point is -108.4 cm read from the selected map "wadsea_cycle5" (Elias and Wang, 2013).

has three columns named "Name", "RDX" and "RDY". Point names will appear in the InterTides output and the RDX and RDY columns contain the coordinates. A short example file is

Name,	RDX,	RDY
Linthorst,	228935,	605079
Noorderleech ,	177932,	594724
Paesemerlannen,	202879,	602261
Test,	228935,	607479

The heights of the points are read from the height map specified in the user interface, just like for the other InterTides functions.

Alternatively, **the uploaded file may have a fourth column named "Height"**, which contains the point heights in cm relative to NAP. In this case the height map is neglected.

The calculations are carried out for a selected period, usually spanning at least one year, and optionally for a season within each year. CSV files with times and levels of all high tides and low tides are also constructed, and all calculated water levels can be inspected by optionally writing CSV level files.

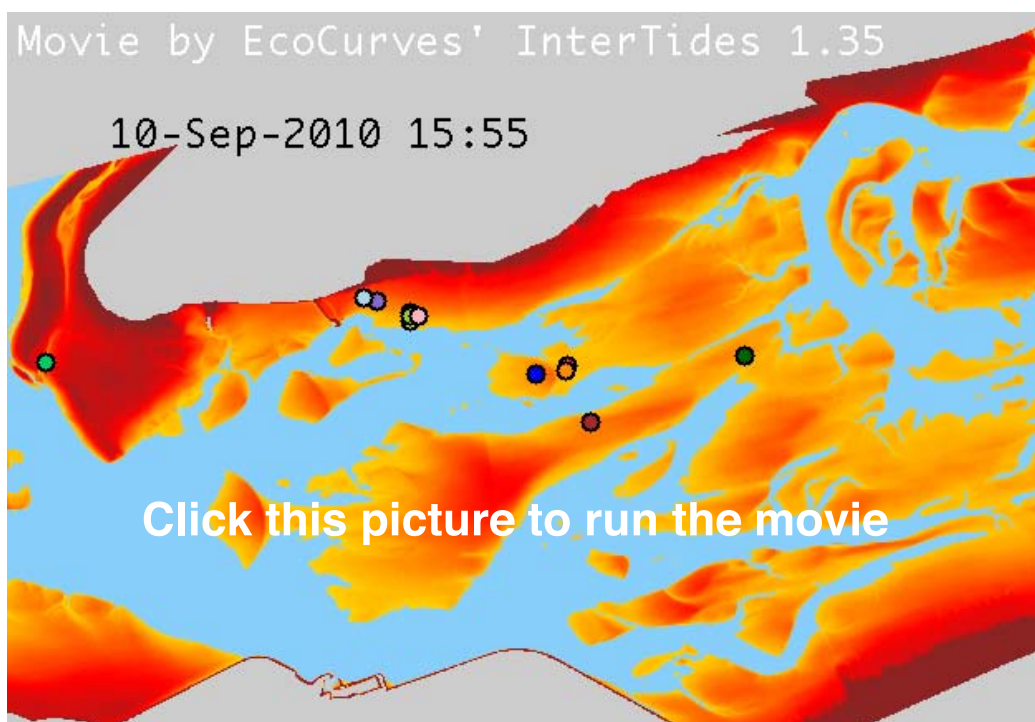
As an example we show the results for the point named "Test" in the period [1990, 2013]. An InterTides run was specified with a season between November 1 and November 30. Hence, the results refer to November tides only.

Figure 2.11 shows the distribution of high and low tide levels. Figure 2.12 shows the distribution of flooding and exposure times. Note that a point is not necessarily flooded and exposed during all tidal periods. The legend in Figure 2.12b contains the fraction of low tide periods during which the point is exposed (66%).

There is a pronounced difference between the november plots and results for a month like July (not shown here). This is due to differences in astronomical tide and weather.

2.9 Bird tracking

GPS trackers mounted on waders deliver valuable data on the movement of the birds and their foraging strategy (Bouten et al., 2013; Bakker et al., 2021). It is illustrative to visualise bird movement in combination with the tide, basically by combining bird positions with a movie of the mudflat exposure (see section 2.4). This is what InterTides function "Bird tracking" does.



Movie 2.3. Animation of 12 tracked Oystercatchers foraging at September 10, 2010 (van der Kolk et al., 2022). The movie play time is about 70 s. The mudflat exposure status was determined using the cycle 5 height map of the Wadden Sea (Elias and Wang, 2013).

Clearly, the GPS tracks do not necessarily originate from birds. Also the movements of other animals or ships may be visualised by means of this InterTides function. [Movie 2.3](#) shows an example calculated for 12 oystercatchers in the Wadden Sea near Schiermonnikoog (GPS data from [van der Kolk et al., 2022](#)).

Note that the files from the Oystercatcher datasets [Oosterbeek et al. \(2022b,a\)](#); [Spanoghe et al. \(2022\)](#); [Dijkstra et al. \(2022\)](#); [Dokter et al. \(2022\)](#); [van der Kolk et al. \(2022\)](#) are compatible with InterTides. Download links to the datasets are provided in each reference.

The GPS tracks are made available to InterTides by means of an (uploaded) comma delimited input file ("CSV file"). The file must contain columns for time, position and bird ID. Common column names like "Date", "Time", "Longitude", "RDX", "Bird ID" or "Bird Tag" are recognised and accepted. The precise time format can be communicated to InterTides by means of a format string like "DD-MM-YYYY", which may be added to the column header if the default does not work. Times must be expressed as UTC (Greenwich time). The program recognises WGS84 coordinates and converts them to "Amersfoort coordinates" (EPSG 28992) using the method of [Schreutelkamp and Strang van Hees \(2001\)](#). Further details can be found in [section 4.6](#) at [page 35](#).

Measured levels

3.1 Downloads

Measured water levels were downloaded from the Rijkswaterstaat site <https://waterinfo.rws.nl>. This Rijkswaterstaat service is clearly essential for the InterTides tool. The time series currently used by InterTides region Wadden Sea is from 1981 onwards. The other regions begin at a later year (see [Chapter 6](#) for details). For almost all days there is a continuous series of water levels at 10-minute intervals for each of the stations.

[Figure 3.1](#) at [page 30](#) shows an example of the data for two days. The plots demonstrate that the tidal wave moves from west to east and that its amplitude is larger in the east of the Wadden Sea.

3.2 Missing values

There are missing values, however. InterTides fills in the gaps by means of harmonic analysis, which is discussed in more detail in [Chapter 7](#). A few other problems are solved by removing small parts of a time series and thus handling the items as missing values. This applies to

- A few instances at which the time series contains the same water level for several hours.
- "Spikes" in the time series at which suddenly a much larger or smaller level is given for one or a few 10-minute intervals.

This cleaning work involves thousands of graphs which are inspected by eye. Of course, some "dirty data" may have been missed. In case you are suspicious you may check the data by asking InterTides for a time series for a certain point (see [section 2.8](#)).

[Figure 3.2](#) at [page 31](#) shows two weeks of Den helder data in which several "spikes" and a more serious malfunction are clearly visible. The erroneous data are corrected by treating them as missing values. In [Figure 3.3](#) the gaps have been filled with help of the astronomical tide (the blue curve) calculated by harmonic analysis (see [Chapter 7](#)).

With help of the astronomical tide also larger gaps in the time series can be filled with estimated water levels. For a gap larger than 26 hours a nearby tidal station is used to calculate the effect of wind and atmospheric pressure on the tide.

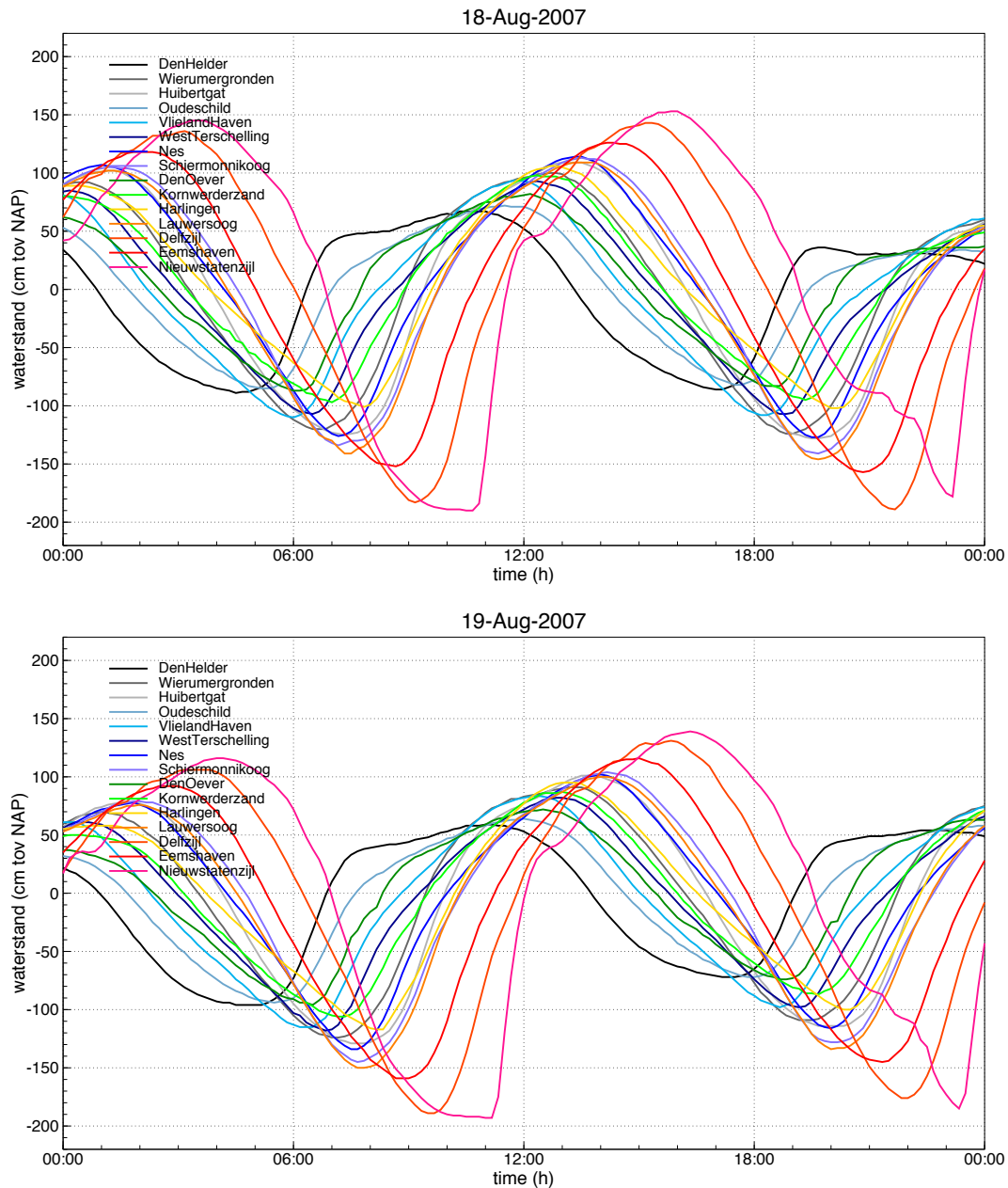


Figure 3.1. Most days of the time series downloaded from the Rijkswaterstaat site <https://waterinfo.rws.nl> look like these examples. The curves are smooth for all tidal stations except Nieuwstatenzijl. The water levels at that station are often strongly affected by the polder drainage water which flows into the Dollard at low tide.

3.3 Correction for Nieuwstatenzijl sluice discharge

Low tide levels measured at Wadden Sea tidal station Nieuwstatenzijl are often heavily affected by sluice discharge close to the station. This has been corrected by replacing the affected levels by the sum of the Nieuwstatenzijl astronomical tide and the wind effect at the nearby Delfzijl station. Details of the correction procedure and plots of corrected levels can be found in Appendix A.

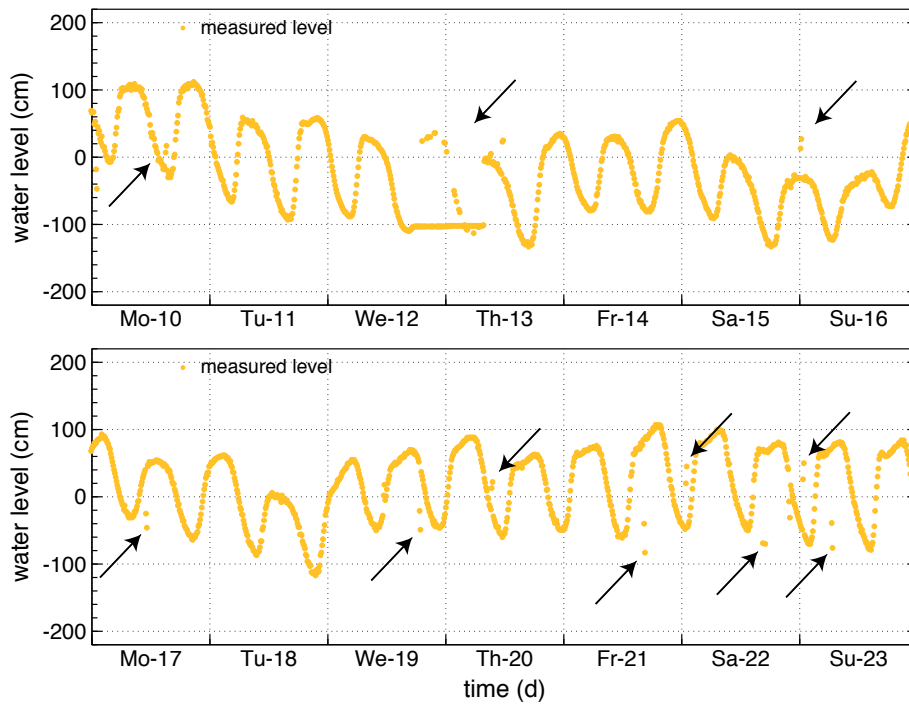


Figure 3.2. Erroneous data items in the time series for station Den Helder during two weeks in December 2018. Apparently, something went wrong in the night from December 12 to 13. Other arrows point to cases with just a few aberrant values. Note that weeks like these are rare, but the errors indeed tend to occur in clusters.

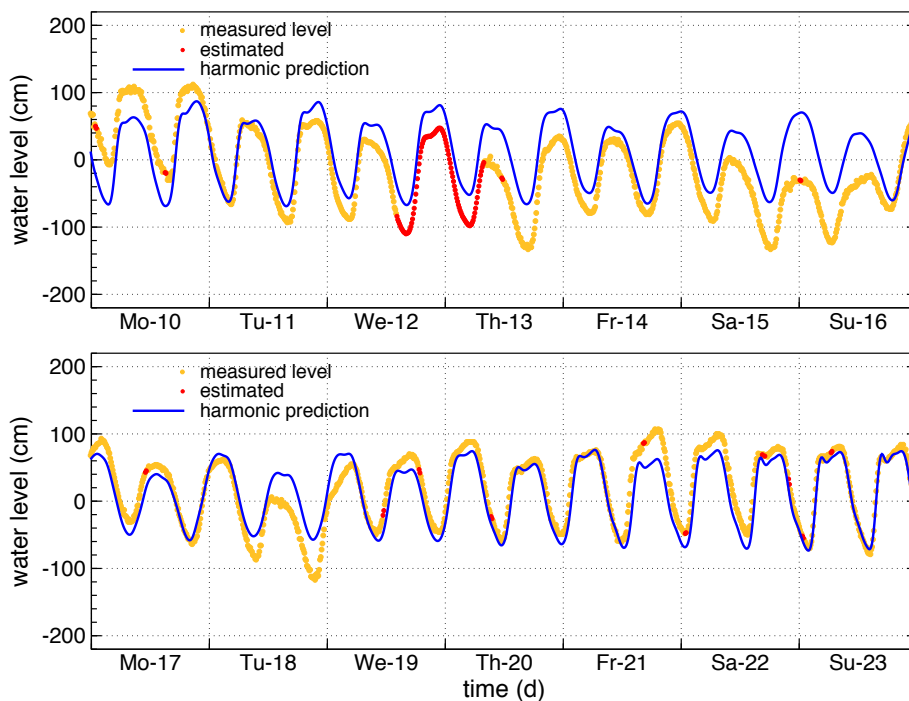


Figure 3.3. The Den Helder time series of [Figure 3.2](#) corrected by removing the wrong items and thus handling them as missing values. The gaps are filled with help of the astronomical tide calculated by harmonic analysis (see [Chapter 7](#)). The filled in values are shown as red dots.

Parameters of InterTides

This chapter describes the required and optional parameters for an InterTides run.

4.1 Area selection

The selection of an area involves

- The choice of an InterTides region from a predefined list.
- The optional choice of a subarea from a predefined list.
- The optional selection of a rectangular area by setting the cropping parameters **Crop Lower Left** which is the lower left corner of the cropping rectangle and **Crop XY rectangle**, which specifies the width and height of the cropping rectangle.

The two optional steps can be combined. Hence, a cropping rectangle may select part of a subarea.

If no subarea is selected and cropping is switched off, the calculations are done for the region map (see [Chapter 6](#)). The region map and all subarea maps installed have a resolution of 20 m. If a different resolution is requested for an output map, the selected area is resized.

4.2 Height map

A height map has to be selected for the functions "Exposure time map", "Exposure status movie", "Area statistics" and "Point Values". The height map is chosen from a predefined list of installed height maps (see [section 6.5.6](#) at [page 67](#) for regions Wadden Sea and Wadden Sea Area).

For the user-specified area values are read from the selected height map. This implies that the cells of an output map are the cells of the area map and not the ones of the height map (from which just values are read).

There is one exception to this rule, discussed already in [section 2.3.2](#). If the user selects the native cell size of the height map as the desired resolution of the exposure time map, the area map is converted to the height map grid and the names of the produced files contain the additional text "hgrid".

4.3 Resizing and cropping

During resizing and cropping the cells of a new map (the "target") are filled with data derived from the input map. It has often to be decided if a target cell contains a valid value or if it is a NODATA cell.

In making that decision InterTides either reads the input data for the midpoint of the target cell (**Resize Method** is "Nearest Neighbour") or calculates a fraction covered by input data (**Resize Method** is "Local Average"). If this fraction exceeds the value of **Covered Fraction** the cell contains valid data, the local average value. If not it will be a NODATA cell.

The two optional parameters **Resize Method** and **Covered Fraction** are used for subarea maps but also for reading values from the selected height map.

4.4 Time, period and season

The first function, water level map, requires just a single **Date** and **Time**. The other functions need a period which is defined using a **Start date** and **Start time** for period begin, and an **End date** and **End time** for period end.

In case of a movie this period will usually span just a few hours or days. There is a maximum number of movie frames which will be reached if you want a movie for a year, for instance. For exposure time maps, area and point functions, the period will usually span several years or even a few decades.

An interesting option of InterTides is that calculations can be limited to a certain **Season**. If this facility is switched on (by setting the switch **Season** on), you have to define a season as two dates, **Season start date** and **Season end date**. Both of them consist of just a day and a month, say 12,05 for May, 12. The season defined in this way is applied to all years in the period. You may calculate for instance an exposure time map for April and May for all years between 1990 and 2010.

A season with its end date *before* its start date defines a winter season. For instance, the season between 01,12 (december 1) and 31,01 (january 31) consists of december and january. Calculations will be limited to these two winter months within the period defined.

4.5 Tide and Interpolation options

If the optional parameter **AdjToNearHT** is switched on, the begin and end time of all calculations is adjusted to the nearest high tide of the region (Harlingen tidal station). This applies both to the a period (spanning years) and to the begin and end of each season within the period. This option guarantees that an integer number of tidal cycles is used in the calculations, which prevents biased results. Therefore the default value of this switch is ON.

The synchronisation option **SyncStations** causes InterTides to synchronize the tidal waves at the various stations. This prevents errors resulting from phase differences between stations used for interpolation. This has been explained extensively in [section 5.5](#). Since tidal waves are seldom symmetrical sine waves, different delays can be used, based on differences between high tide times, low tide times,

average differences or the M2 phase. Results calculated for the various delay times will probably differ very little from each other. Without synchronisation, however, considerable errors may be made.

The optional **Sea Level Rise** is just added to all water levels. Hence, it does not change the shape of the tidal curves.

4.6 Uploaded GPS tracks

GPS tracks are made available to InterTides by means of an (uploaded) comma delimited input file. The file must contain columns for time, position and bird ID. Times must be expressed as UTC (Greenwich time). Column names are not case sensitive.

Date and time can be provided as a single column with a header containing "TimeStamp", both "Date" and "Time" or both "Datum" and "Tijd". The default time format in this case is "YYYY-MM-DD HH:MM:SS".

As an alternative separate columns for Date and Time may be provided. In that case the default date format is "YYYY-MM-DD" and the default Time format is "HH:MM:SS".

If the default format is not applicable, a format string can be added to the column header. If the date is provided as "DD-MM-YYYY", for instance, the column name may be "Date [DD-MM-YYYY]" with the correct format in square brackets.

For the GPS position two columns are looked for, a longitude column and a latitude column. The longitude column name contains the string "Longitude" or contains both "Position" and "Lon", "Location" and "Lon", "Pos" and "Lon", "Loc" and "Lon", "Pos" and "RDX", "Pos" and "XRD", just "RDX" or just "XRD". Similarly a column name containing "Latitude", "Pos" and "Lat", "Pos" and "RDY", etc. is accepted as the latitude column. The program recognises WGS84 coordinates from their numerical values and converts them to "Amersfoort coordinates" (EPSG 28992) using the method of [Schreutelkamp and Strang van Hees \(2001\)](#)

Bird ID's (or object identification codes) are looked for in a column with name "Bird", "Ship" or simply "Object". Also "BirdID", the combination of "Bird" and "Number", "Tag", or "ID" are accepted. The column must contain integer numbers. The objects need not be in order. In the final movie each object gets its own color and a legend file is generated.

4.7 Output options

The **WaterRange** of **HeighRange** only defines the begin and end points of the colour scale used in images of calculated water level maps or height maps. The ranges do not influence the actual content of the maps.

The option **HmapImage** can be used to switch the generation of a height map image on or off. If many calculations are made for the same height map, you may want to switch this image off.

The option **LevelFiles** causes the generation of large CSV files containing all water levels for the grid points in InterTides function "Area Statistics" or the user-defined points in function "Point Values".

Interpolation Method

The interpolation is carried out in a purely geometrical manner, as a weighted mean of measured water levels. Hence, the hydrodynamics is not taken into account. The underlying assumption is that the distances between the tidal gauge stations are sufficiently small.

Most interpolated water levels are found inside a triangle with tidal stations at its corners. An InterTides region like Eastern Scheldt or Wadden Sea cannot be completely covered by suitable triangles of stations, however. Therefore interpolation may also use lines interconnecting two or more stations and in a few cases quadrangles are used.

In principle, the interpolation is linear which means that the interpolated water levels are found from the plane through the levels at the three corners. A correction is made, however, for the phase differences between the points.

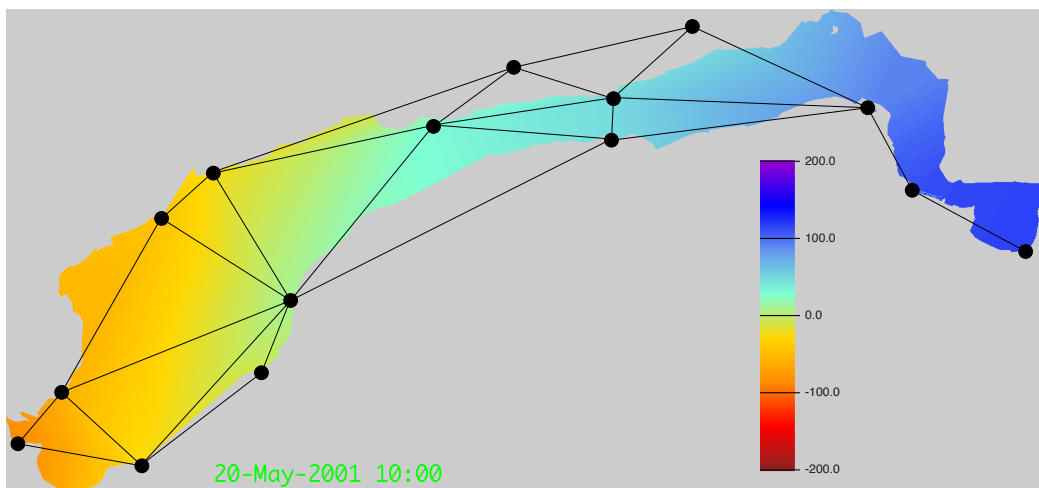


Figure 5.1. Tidal gauge stations of Rijkswaterstaat and interpolation triangles used for InterTides region Wadden Sea on top of interpolated water levels. For points outside the triangles, "edge interpolation" (section 5.4) is used. See also section 6.4 for more details.

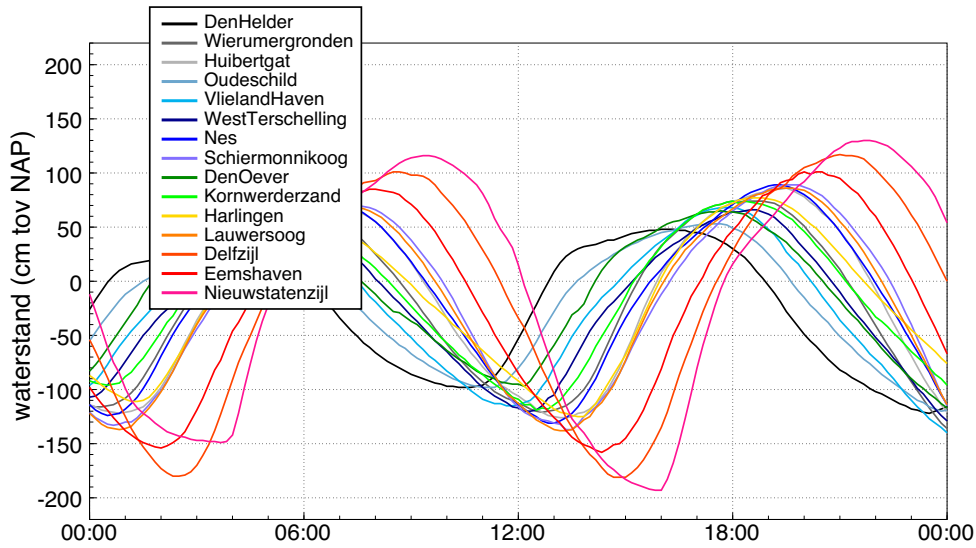


Figure 5.2. Waterlevels of April, 24 2006 measured at 15 tidal gauge stations of Rijkswaterstaat (data downloaded from <https://waterinfo.rws.nl>).

5.1 Data from the tidal gauge stations

The black dots in Figure 5.1 are the tidal gauge stations used for the region Wadden Sea (without coastal zone). From Den Helder along the North Sea coast these stations are Den Helder, Oudeschild, Vlieland haven, West-Terschelling, Nes, Wierumergronden, Schiermonnikoog and Huibertgat. And from Den Helder along the mainland coast: Den Helder, Den Oever buiten, Kornwerderzand, Harlingen, Lauwersoog, Eemshaven, Delfszijl and Nieuwstatenzijl. At these stations Rijkswaterstaat measures the water level every 10 minutes. Results are freely available from <https://waterinfo.rws.nl>.

Figure 5.2 shows an example of the measured water levels. The tidal wave moves from west to east and its amplitude increases.

5.2 Interpolation inside a triangle

Most of the InterTides regions (e.g. Chapter 1) are covered by triangles formed by three tidal gauge stations. Inside these triangles water levels are found as a weighted mean of three measured levels.

Figure 5.3a shows a point \vec{x} inside a triangle formed by three tidal stations. The tidal stations have positions given by two dimensional vectors \vec{S}_1 , \vec{S}_2 en \vec{S}_3 . By shifting the origine to \vec{S}_1 we get Figure 5.3b, in which the vectors $\vec{v}_2 = \vec{S}_2 - \vec{S}_1$ en $\vec{v}_3 = \vec{S}_3 - \vec{S}_1$ represent the triangle and point P is given by $\vec{p} = \vec{x} - \vec{S}_1$.

Now, the interpolation formula is found by describing \vec{p} as a linear combination of \vec{v}_2 en \vec{v}_3 . Hence,

$$\vec{p} = w_2 \vec{v}_2 + w_3 \vec{v}_3 . \quad (5.1)$$

For $\vec{x} = \vec{S}_1 + \vec{p}$ this means

$$\vec{x} = w_2 \vec{S}_2 + w_3 \vec{S}_3 + (1 - w_2 - w_3) \vec{S}_1 .$$

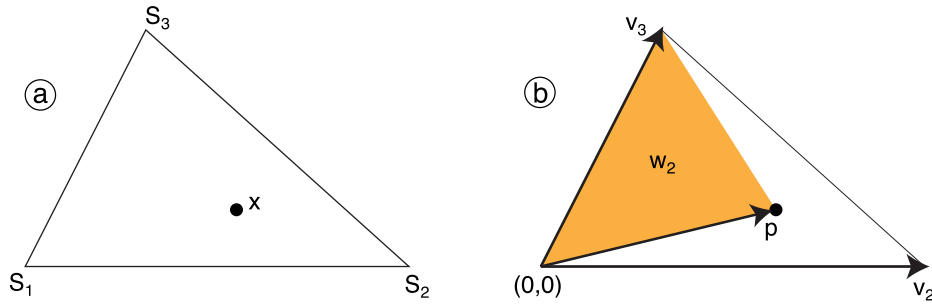


Figure 5.3. A triangle formed by three tidal gauge stations. The water level at a point inside the triangle is calculated as a weighted average of the station levels. The coloured fraction of the triangle surface area is the weight w_2 for station S_2 .

Using $w_1 = 1 - w_2 - w_3$ this is equivalent to

$$\vec{x} = w_1 \vec{S}_1 + w_2 \vec{S}_2 + w_3 \vec{S}_3.$$

With these three weights the water level L_P in point P is then found as

$$L_P = w_1 L_1 + w_2 L_2 + w_3 L_3, \quad (5.2)$$

in which L_1 , L_2 en L_3 are the three measured levels.

5.2.1 The three weights

For finding the three weights Equation (5.1) is written as

$$\begin{cases} p_x = w_2 v_{2x} + w_3 v_{3x} \\ p_y = w_2 v_{2y} + w_3 v_{3y} \end{cases}$$

with solution

$$\begin{cases} w_2 = \frac{(p_x v_{3y} - p_y v_{3x})}{(v_{2x} v_{3y} - v_{2y} v_{3x})} \\ w_3 = \frac{(v_{2x} p_y - v_{2y} p_x)}{(v_{2x} v_{3y} - v_{2y} v_{3x})} \end{cases}$$

De numerator of the expression for w_2 is twice the surface area spanned by the vectors \vec{p} en \vec{v}_3 . The denominator is twice the surface area of the triangle. Hence, the weight w_2 is equal to the fraction of the triangle surface area covered by the coloured part of Figure 5.3b. The third weight w_1 is found from $w_1 = 1 - w_2 - w_3$. If all three weights are positive, point P lies inside the triangle.

5.3 Interpolation inside a quadrangle

The four defining stations of a quadrangle could be used to define two triangles, but sometimes this looks a bit awkward and interpolation inside a quadrangle seems more natural. For a quadrangle, however, there is no straightforward linear interpolation between the water levels at the four defining stations, simply because the four levels at the corners do not define a single plane. This is solved by assigning an orientation to the quadrangle.

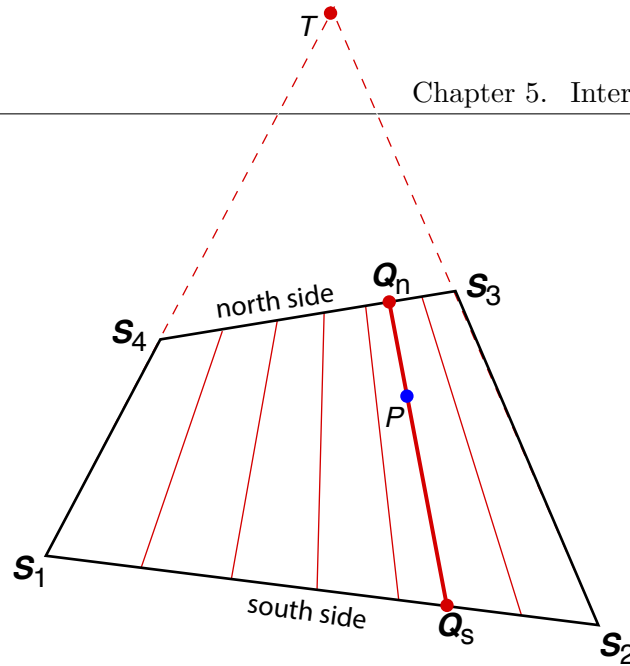


Figure 5.4. Quadrangle of 4 stations used for interpolation. There is no plane through the 4 station levels but after choosing a "north-south" direction a water level can be calculated for any point P inside the quadrangle.

The quadrangle in [Figure 5.4](#) has a "north side" between stations 3 and 4 and a "south side" between stations 1 and 2. The water level for a point P inside the quadrangle is found as follows:

- The sides $[S_1, S_4]$ and $[S_2, S_3]$ intersect at some point T .
- The line $[T, P]$ intersects the north and south side of the triangle at Q_n and Q_s respectively.
- The water level at Q_n is found by linear interpolation between S_3 and S_4
- The water level at Q_s is found by linear interpolation between S_1 and S_2
- The water level at P is found by linear interpolation between Q_n and Q_s .

The last three steps result in 4 weights for the water levels at the four stations. All waterlevels inside the quadrangle do not form a plane, but there is a smooth transition between the levels along (S_1, S_4) and those along (S_2, S_3) .

5.4 Interpolation along a line segment or "edge"

For a point P *not being inside a quadrangle or a triangle*, the water level is estimated by interpolating along a nearby line segment between two tidal stations. [Figure 5.5](#) and [Figure 5.6](#) illustrate the situation.

A line segment has an orientation derived from its two defining stations. Going from the first to the second station, only points at the right hand side of the segment are "valid points" for water level calculation. If points at both sides are allowed, the segment has to be declared twice in the configuration file for the InterTides region, as (S_1, S_2) and as (S_2, S_1) .

[Figure 5.5](#) illustrates the simple interpolation method. The station levels at S_1 and S_2 are linearly interpolated along the line segment. The values are then simply shifted sideways to a parallel line through the point P .

Usually several connected line segments form a sort of edge. [Figure 5.5](#) shows three segments, the middle one used to find a water level for point P . A difficulty arises

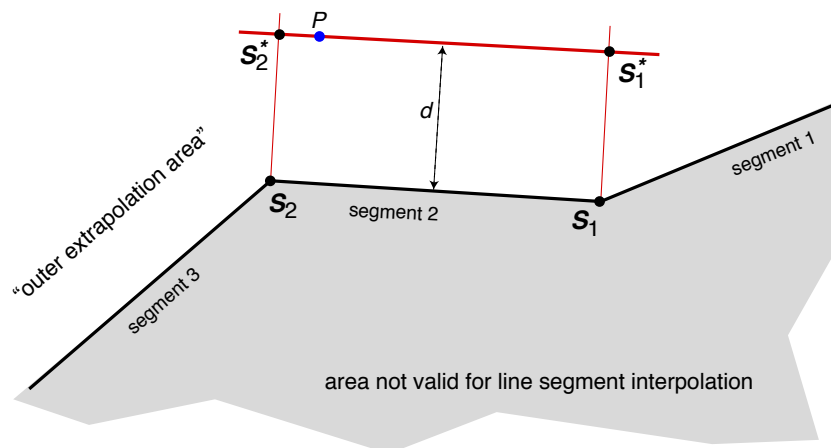


Figure 5.5. Interpolation along a line segment between two tidal stations S_1 and S_2 . Moving from S_1 to S_2 , valid points P lie at the right hand side of the segment. Linearly interpolated water levels between S_1 and S_2 are simply shifted to the parallel line on which a point P lies. A difficulty arises if several line segments are not in a straight line.

if the segments do not lie in a straight line. The areas assigned to segment 1 and segment 2 will overlap near station S_1 . This leads to a discontinuity in calculated levels, which gets larger at larger distances d . Near station S_2 the method does not fill space. There will be points P for which no segment is found and to which, as a last resort, the level at the nearest station is assigned.

This difficulty is solved by a correction illustrated in Figure 5.6. At station S_1 a bissectrice divides the area between segment 1 and segment 2. Interpolated levels are still shifted over a distance d to point P , but the interpolated values now lie between S_1^* and S_2^* . The segment $[S_1^*, S_2^*]$ is stretched or shortened in order to fit in between the bissectrices. And very much like in the uncorrected case, the distances from P to S_1^* and S_2^* determine the weights assigned to the station levels at S_1 and S_2 .

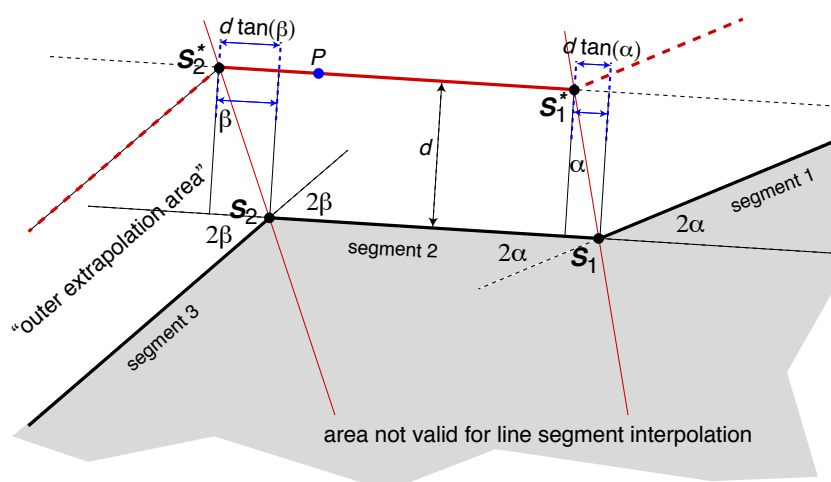


Figure 5.6. Line segment interpolation with angle correction. The bissectrices at each station define the areas assigned to each line segment and the line segment with interpolated water levels is stretched or shortened in order to fit in between the bissectrices at distance d from the edge.

5.5 Phase differences

The most simple situation is a tidal wave of uniform amplitude moving through the region. In [Figure 5.7](#) there are two waves with a delay of 2 hours between station 2 and station 1. Now we apply simple linear interpolation to a point in the middle between the two stations and we get the red curve in [Figure 5.7](#). The problem is that the amplitude of this red curve is smaller than the amplitude at the two tidal stations. For a larger phase difference between the stations this damping effect will increase.

The size of this damping effect can be estimated for the simple situation in [Figure 5.7](#). For a delay of α hours we calculate the amplitude of the interpolated tidal wave $w(t)$. With equal amplitude A at the two stations we get¹

$$\begin{aligned}
 w(t) &= \frac{A}{2} \left[\sin\left(\frac{2\pi t}{12.421}\right) + \sin\left(\frac{2\pi(t-\alpha)}{12.421}\right) \right] = \\
 &= A \cos\left(\frac{2\pi\alpha/2}{12.421}\right) \times \sin\left(\frac{2\pi(t-\alpha/2)}{12.421}\right) = \\
 &= A \left[1 - 2\sin^2\left(\frac{\pi\alpha}{24.842}\right) \right] \times \sin\left(\frac{2\pi(t-\alpha/2)}{12.421}\right) = \\
 &= A [1 - \epsilon] \times \sin\left(\frac{2\pi(t-\alpha/2)}{12.421}\right).
 \end{aligned} \tag{5.3}$$

The interpolated sine wave $w(t)$ shows a delay $\alpha/2$ relative to station 1, which is fine. Its amplitude, however, is not equal to A , but it is reduced. In [Equation \(5.3\)](#)

¹This uses $\sin(x) + \sin(x - 2y) = 2\cos(y)\sin(x - y)$, in which y is half the phase difference. This can be shown as follows: $\sin(x) + \sin(x - 2y) = \sin(x) + \sin(x)\cos(2y) - \cos(x)\sin(2y)$. With $\cos(2y) = 2\cos(y)\cos(y) - 1$ and $\sin(2y) = 2\sin(y)\cos(y)$, the first term cancels and we have $2\sin(x)\cos(y)\cos(y) - 2\cos(x)\sin(y)\cos(y)$, which is equal to $2\cos(y)\sin(x - y)$.

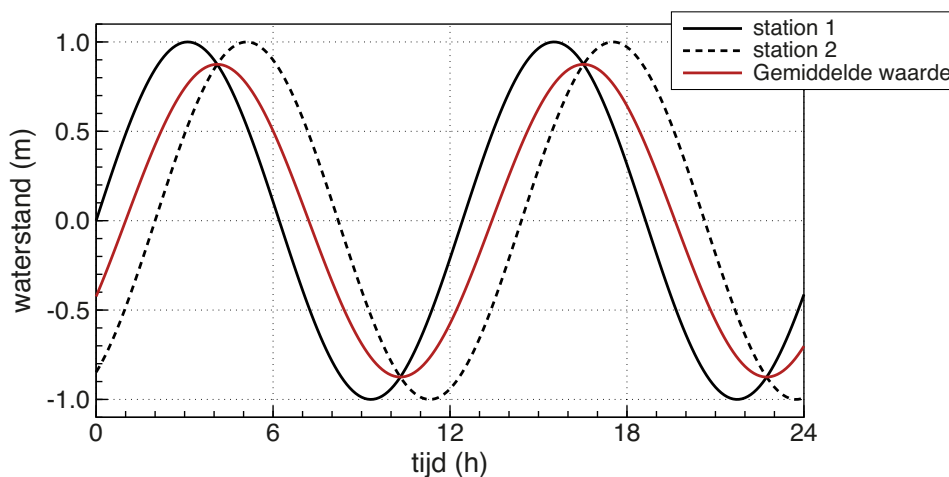


Figure 5.7. The curves for station 1 and station 2 describe a tidal sine wave which needs two hours to move from station 1 to station 2. The red curve is the interpolated water level halfway. The amplitude of the interpolated tide is 13% too small due to the phase difference of 2 hours.

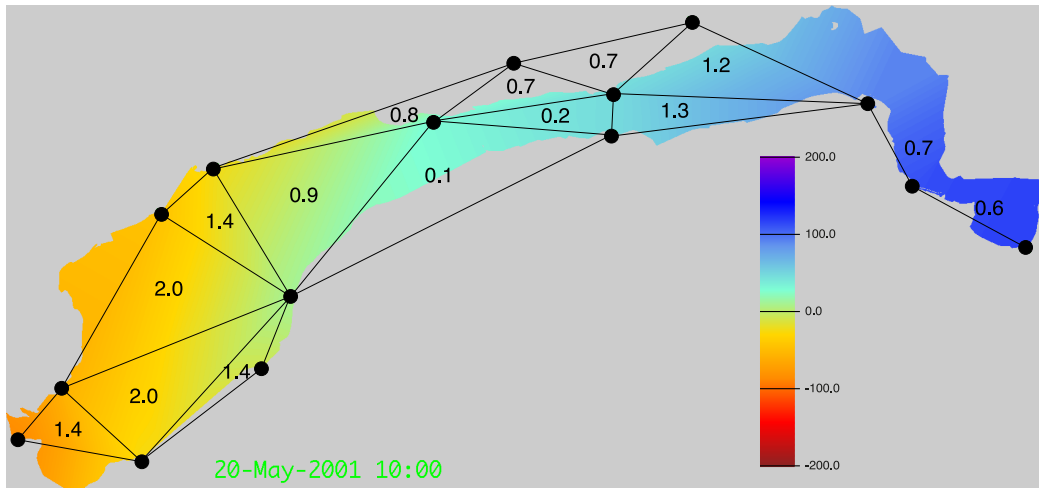


Figure 5.8. Maximum M2 phase difference in hours between two corners of the interpolation triangles for region Wadden Sea.

the amplitude of $w(t)$ is written as $A(1-\epsilon)$ with ϵ as relative amplitude reduction. From the derivation in [Equation \(5.3\)](#) we can write for ϵ

$$\begin{aligned}\epsilon &= 2 \sin^2\left(\frac{\pi\alpha}{24.842}\right) \approx \\ &\approx 2 \left(\frac{\pi\alpha}{24.842}\right)^2 \approx \frac{\alpha^2}{31.3}.\end{aligned}\tag{5.4}$$

The last two steps are an approximation valid for delays α not exceeding about 3 hours. [Equation \(5.4\)](#) shows that the amplitude reduction increases quadratically with the phase difference between the stations. For $\alpha = 0.5$ hour the deviation is merely 0.8%. For $\alpha = 1.5$ hour the deviation reaches already 7%.

The tidal phase of each station is estimated as the phase of the M2 component of the tide. M2 is the principal lunar, semi-diurnal tidal constituent. It is calculated by harmonic analysis of the tidal gauge data (see [Chapter 7](#)). [Figure 5.8](#) shows for each of the triangles the maximum delay between any two corners of the triangle. The delays exceed 1 hour for the area west of Harlingen and between Schiermonnikoog and Rottum. The damping errors will be largest there. For the mudflats near Terschelling, Ameland and Engelsmanplaat, these errors will be small.

The damping effect can be largely avoided by synchronising the tidal gauge data before interpolating them. As an example, [Figure 5.9a](#) shows again the water levels from [Figure 5.2](#). In [Figure 5.9b](#) the curves are shifted using the phase of the M2 constituent.

5.6 Interpolation with correction for phase differences

Finally, we need to figure out how to use synchronised stations for the calculation of an interpolated level at a specific point and a specific time. The basic method remains the same. The water level of a point P at time t is found by interpolating between two, three or four water levels at nearby tidal stations. The calculations of the weights remains unchanged.

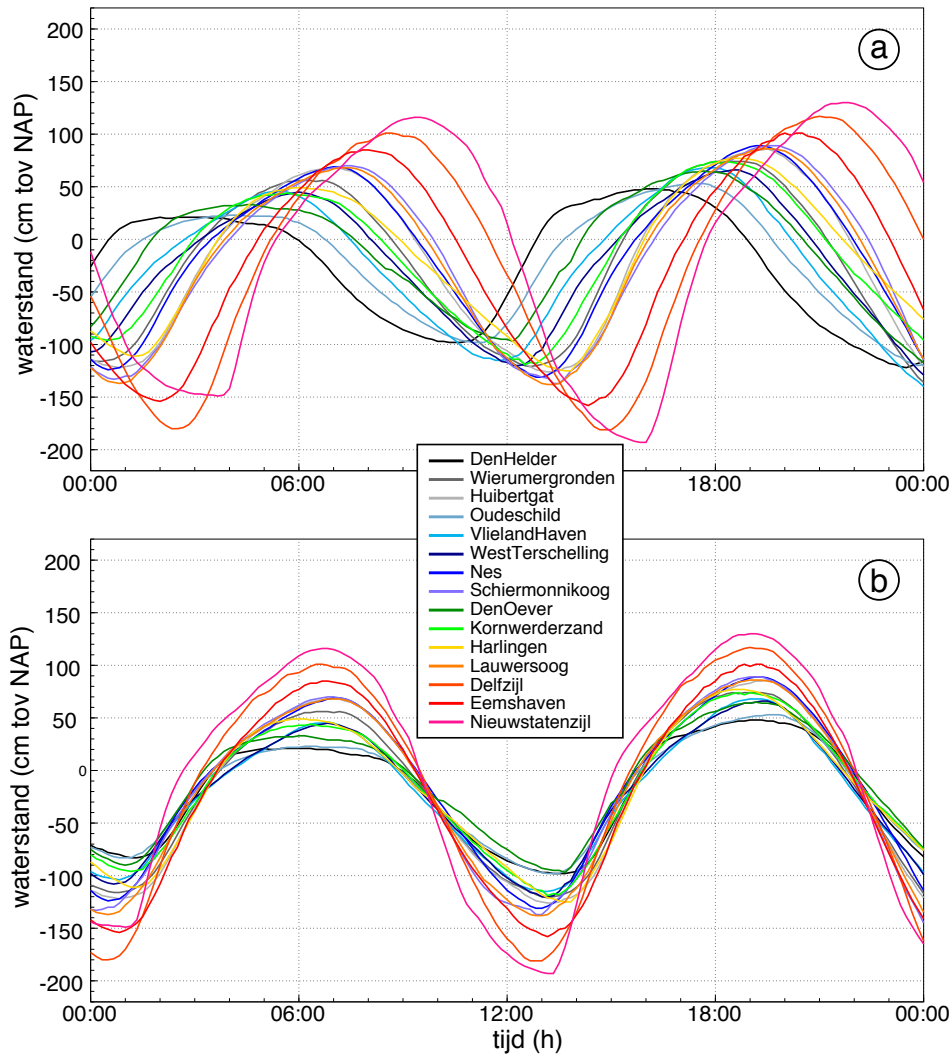


Figure 5.9. Water levels measured at 24 april 2006. (a) As measured by the 15 tidal gauge stations of Rijkswaterstaat, (b) Shifted with the phase of the M2 constituent of the station (M2 is the principal lunar, semi-diurnal tidal constituent).

We write the station weights as w_i , and the water levels as functions of time $W_i(t)$. Without synchronisation we would write for the water level $W_P(t)$ at point P

$$W_P(t) = \sum_i w_i W_i(t). \quad (5.5)$$

The correction makes use of delayed levels $W_i(t + d_i)$ in which d_i is the time delay belonging to station i . The water level at point P is then found as

$$W_P = \sum_i w_i W_i(t + d_i). \quad (5.6)$$

But for which time this is the level at point P ? A consistent approach is to assume that not just the levels, but also the delays can be interpolated. So the water level W_P in Equation (5.6) actually is the water level at time $t + d_P$ in which d_P is the

delay at point P estimated by

$$d_P = \sum_i w_i d_i. \quad (5.7)$$

We now can add the time to W_P in [Equation \(5.6\)](#) and get

$$W_P(t + d_P) = \sum_i w_i W_i(t + d_i), \quad (5.8)$$

which, by subtracting d_P from the time t is equivalent to

$$\begin{aligned} W_P(t) &= \sum_i w_i W_i(t + (d_i - d_P)) = \\ &= \sum_i w_i W_i(t_i^*) \end{aligned} \quad (5.9)$$

in which t_i^* is the phase corrected time for station i , defined as $t + (d_i - d_P)$. Without any phase differences the d_i are zero, then also $d_P = 0$ and [Equation \(5.9\)](#) reduces to [Equation \(5.5\)](#).

[Equation \(5.9\)](#) shows that we first have to calculate d_P by interpolating between the tidal station delays using [Equation \(5.7\)](#). Then we can find the phase corrected times t_i^* for the stations as $t + (d_i - d_P)$.

Note that the weighted sum of the phase corrections $\sum_i w_i (d_i - d_P) = \sum_i w_i d_i - \sum_i w_i d_P = d_P - d_P = 0$ and that the $(d_i - d_P)$ are the *local phase differences*, the differences between the point phase d_P and the phases d_i of the nearby stations. Clearly, in local interpolation only local phase differences should play a role.

5.7 Exposure time map corrected for phase differences

The damping effect will affect also exposure times since these are calculated from a large series of interpolated levels. A too small tidal amplitude will cause points with a large height to be flooded less often. This leads to an overestimated exposure time. On the other hand, points with a low height will be exposed less often than by tides with a larger amplitude, which corresponds to an underestimate.

As an illustration of this effect, [Figure 5.10a](#) shows an exposure time map calculated with phase correction, [Figure 5.10b](#) without phase correction and [Figure 5.10c](#) is the difference map. The largest deviations indeed occur west of Harlingen and near Rottum, where we would expect them according to [Figure 5.8](#).

InterTides can use different types of delays, based on the lunitidal intervals for high tide, low tide, the averages of those two, or based on the phase of the M2 constituent calculated for the stations². The different delays estimated lead to very similar results, since a small remaining phase difference will have a negligible effect on interpolated values (e.g. [Equation \(5.4\)](#)).

The use of virtual stations in InterTides 1.3 can only be combined with correction based on the M2 phase. The use of lunitidal intervals should be regarded as an obsolete feature available only for interpolation schemes without virtual stations.

²M2 is the moon tide responsible for most of the tidal wave. This tidal constituent is known as the "principal lunar semi-diurnal" and has an astronomical speed of 28.984104 degree per hour, which corresponds to a period of 12.420601 hours.

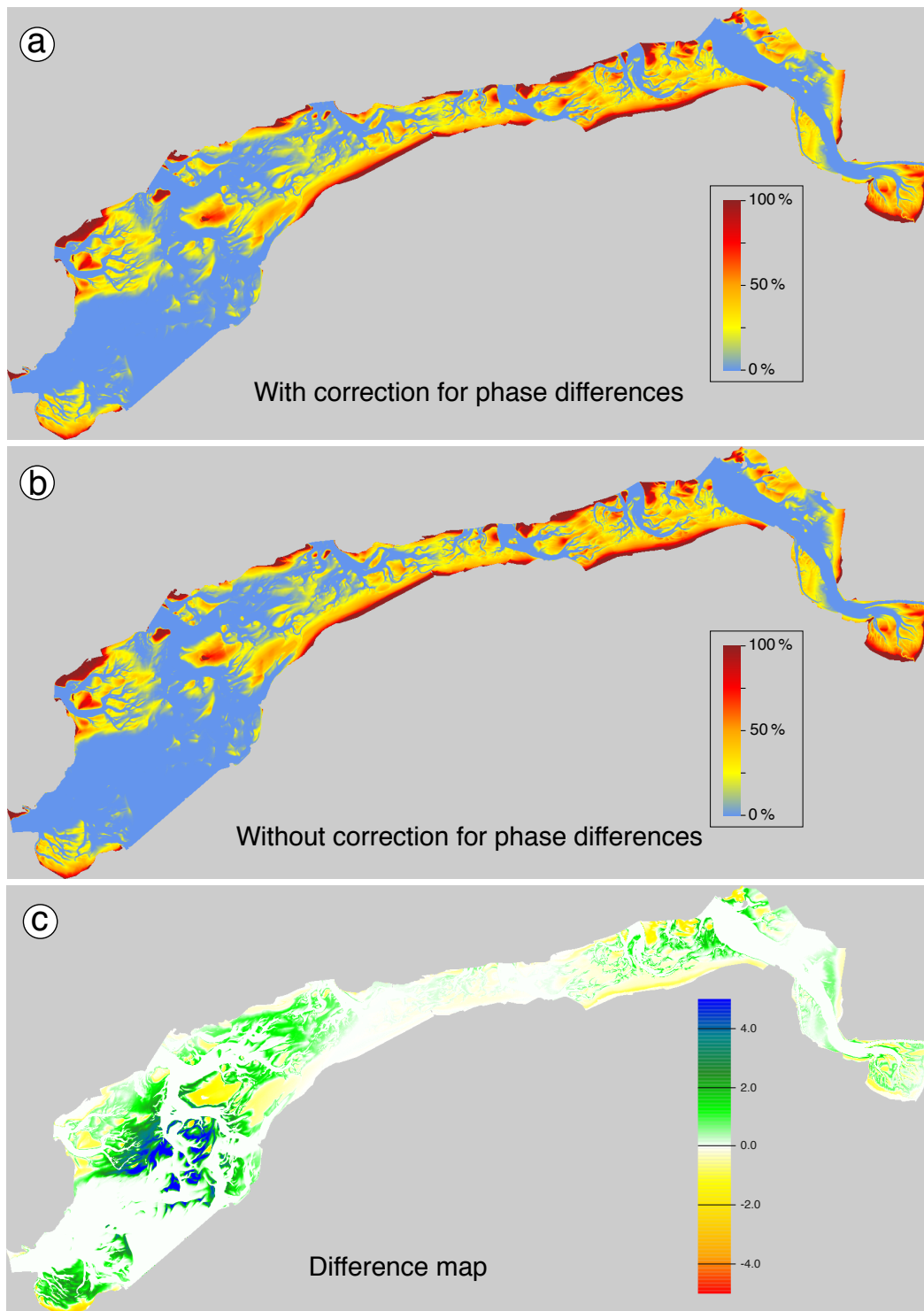


Figure 5.10. Effect of synchronization of tidal gauge stations on a calculated exposure time map. (a) Exposure time as a percentage of time calculated for M2-synchronised tidal stations like those in Figure 5.9b, (b) The same for non-synchronised stations like those in Figure 5.9a, (c) The difference map in the same units, percentage of time. Positive values (green-blue) mean a larger exposure time with synchronization. Note that 4% of time means $0.04 \times 24 \times 60 \approx 58$ minutes per day.

5.8 Normalisation

The increase of the tidal amplitude from the open sea towards the end of an estuary is a well known phenomenon. This is a large effect which dominates also the tides in the Eastern Scheldt and the Western Scheldt.

If there are several tidal gauge stations along the estuary this effect will certainly be present in interpolated water levels. The geometrical pattern of the amplitude increase, however, is not necessarily represented very well by the positions of the tidal gauge stations.

This problem can be solved if the following maps are available

- A map \mathcal{M} of the mean sea level.
- A map \mathcal{A} of the tidal amplitude. This map may be a *relative* map, just showing the pattern of amplitude increase in the estuary, for instance relative to the open sea value at the estuary mouth.

Then, instead of interpolating between waterlevels W_i at the tidal gauge stations, we use reduced (or normalised) water levels r_i which are defined as

$$r_i = \frac{W_i - z_i}{A_i} \quad (5.10)$$

where z_i is the mean sea level read from map \mathcal{M} and A_i the tidal amplitude read from map \mathcal{A} at the location of the tidal station i .

Reduced levels can replace the actual levels in all interpolation equations above, also in [Equation \(5.9\)](#) which corrects for phase differences. For each stations, the reduced levels are calculated using a constant z_i and a constant A_i , and the phases of the tidal constituents of the station will not change.

The result of interpolation will be a reduced water level r_P at point P which is transformed into a real water level by using the values z_P and A_P read from the maps at location P . Hence, $W_P = z_P + A_P \times r_P$. For the water level $W_P(t)$ at time t , using [Equation \(5.9\)](#) for the interpolated level r_P , this looks like

$$\begin{aligned} W_P(t) &= z_P + A_P r_P(t) = \\ &= z_P + A_P \sum_i w_i r_i(t_i^*) = \\ &= z_P + \sum_i w_i \frac{A_P}{A_i} [W_i(t_i^*) - z_i] \end{aligned} \quad (5.11)$$

in which t_i^* is the phase corrected time for station i , defined as $t+(d_i-d_P)$ at [page 45](#) in [section 5.5](#).

Note that the water level at point P depends on the *ratios* of A_P and the station amplitudes A_i . This implies that multiplying the amplitude map \mathcal{A} with some factor does not affect any result. Therefore the amplitude map may be a *relative* map, just showing the pattern of amplitude increase in the estuary, as stated above.

This adaptation leads to calculated water levels which are in accordance with the local mean sea level and amplitude. Weather influences remain present in interpolation results since these are still based on measured water levels which may very well exceed the average tidal amplitudes A_i .

5.8.1 Example Eastern Scheldt

Figure 5.11 shows the Eastern Scheldt M2 amplitude map provided by Rijkswaterstaat. The original map is defined on a rather coarse grid of 1000 m. In order to prevent spatial discontinuities in calculated water levels the map values are read using double linear interpolation between the cell values.

Figure 5.12a shows water levels calculated with help of the amplitude map in Figure 5.11 (The accompanying map of the mean sea level is zero everywhere). Without normalisation the levels are different and Figure 5.12b shows a map of the difference. Close to the location of a tidal gauge station i the difference is zero (white on the map), since the station weight w_i approaches 1.0 and A_P will be close to the station's A_i (e.g. Equation (5.11)).

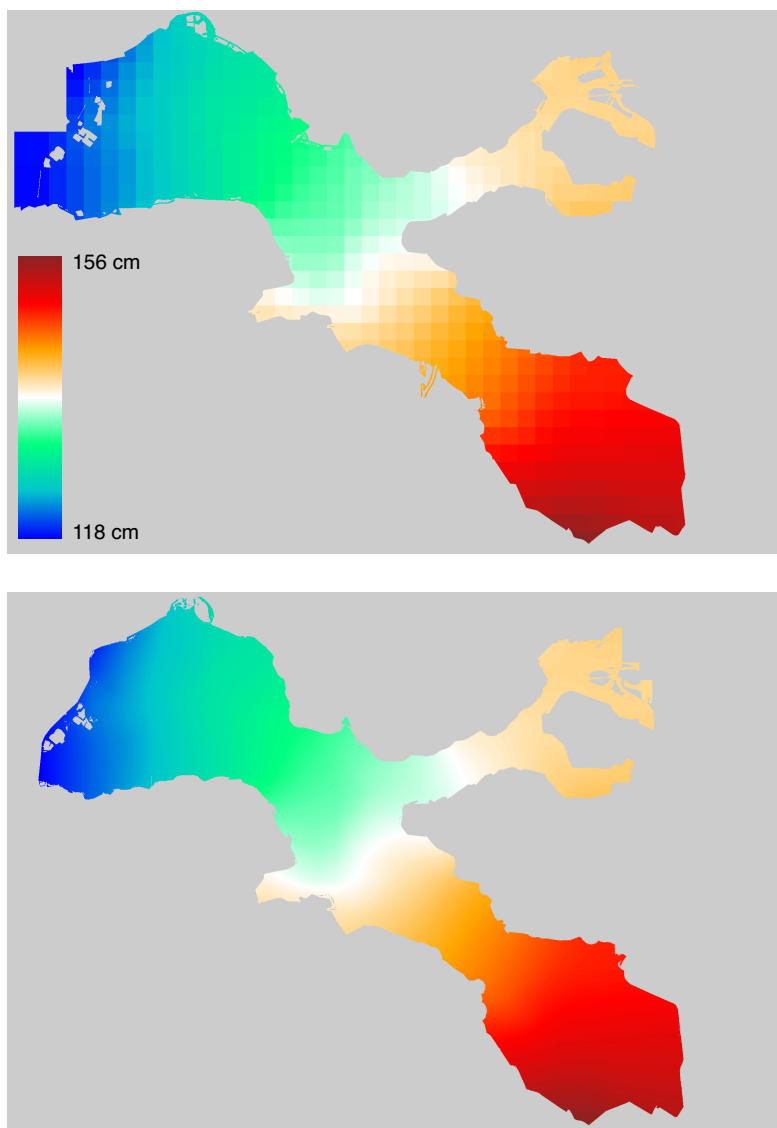


Figure 5.11. Map of the Eastern Scheldt M2 amplitude (Rijkswaterstaat). (top) The original map at a 1000 m grid. (bottom) The same map with a double linear interpolation between the original grid cells. This interpolation prevents discontinuities in calculated water levels.

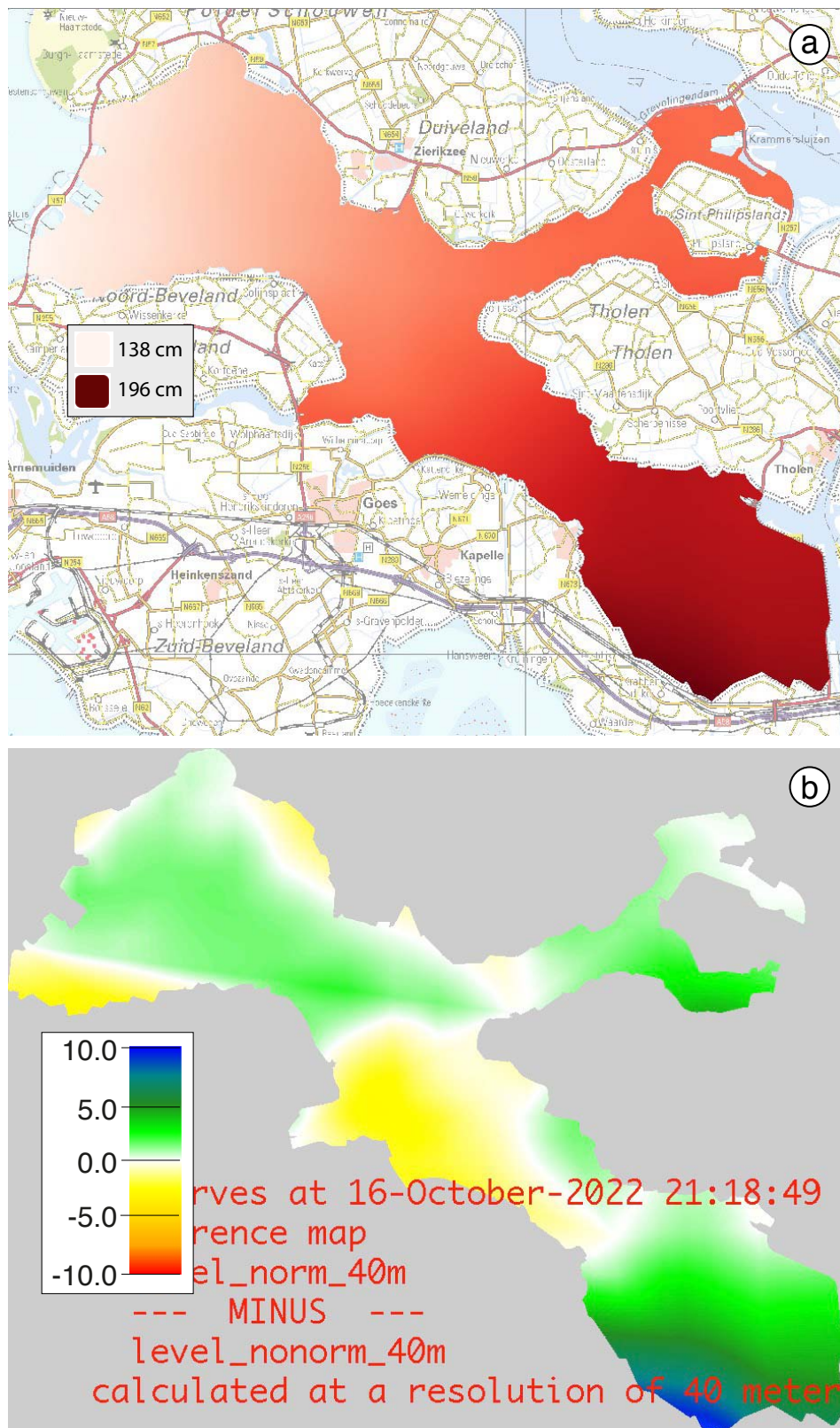


Figure 5.12. Effect of normalisation on Eastern Scheldt water levels. (a) The water levels at May 20, 2015, at 15:00 calculated using normalisation. The levels range from 138 cm just behind the storm surge barrier to 196 cm in the south eastern end of the estuary. (b) The difference (in cm) with water levels calculated without normalisation.

The effect of normalisation reaches 10 cm at the south eastern end of the estuary. The reason is that there is no tidal station at the far end of the Eastern Scheldt. *Without normalisation* the levels at the south eastern end are then estimated as the level at the nearest station. *With normalisation* the reduced level r_P is still estimated as the reduced level at the nearest station, but then r_P is multiplied by the tidal amplitude at point P . At the south eastern end of the area, the final estimate of the water level W_P may exceed all measured levels closer to the open sea.

5.9 Virtual stations

Virtual tidal stations are stations that do not actually exist. Their water levels are calculated by interpolation between nearby physical stations. Phase differences between these physical stations are taken into account, just like in finding water levels for an arbitrary point (see [section 5.6](#)).

Virtual stations need to be defined in the configuration file for an InterTides region and the two or three physical stations they depend on are explicitly listed. Virtual stations then can be used as any physical station in the definition of interpolation quadrangles, triangles or edges.

Virtual stations are used only in region "Waddengebied" (Wadden Sea Area) in order to deal with the North Sea coastal zone and the tidal inlets between the Wadden islands.

5.10 Indirect sides of a quadrangle

The north or south side of a quadrangle may be marked as "indirect" in the configuration file for a region. The levels along such an indirect side are not found by linear interpolation between the two corners but they are derived from nearby edge segments (e.g. [section 5.4](#)). This solves a problem with discontinuous water levels in case the edge segments are not parallel to the side of the quadrangle.

Indirect sides are used only in the interpolation scheme for region "Waddengebied" (Wadden Sea Area). Some more remarks on this topic can be found in [Chapter 6.5](#).

Configuration of the Regions

For five InterTides regions the tidal gauge stations are listed and an interpolation scheme is shown. An interpolation scheme is a map covering the region and consists of line segments, triangles and quadrangles with tidal stations at their corners. Along the line segments (or "edges"), and inside the triangles and quadrangles, water levels can be interpolated according to the description in [Chapter 5](#).

For some regions subareas are defined which can be selected in the user interface.

For region Wadden Sea Area ([section 6.5](#) for "Waddengebied") the interpolation scheme is more complicated due to requirements with respect to the islands and the tidal inlets. Some extensions to the methods of [Chapter 5](#) are explained.

6.1 Eastern Scheldt

This section describes the interpolation scheme for the Eastern Scheldt (Oosterschelde). This region is available in online InterTides.

The water levels installed refer to the period from 1990 onwards. The interpolation uses reduced water levels ("normalisation", e.g. [section 5.8](#)) based on a map of the M2 amplitude by Rijkswaterstaat ([Figure 5.11](#) at [page 48](#)). The M2 constituent or the "principal lunar semi-diurnal" has a period of 12.420601 hours. InterTides with the Eastern Scheldt amplitude map has been used in ([Rappoldt and Ens, 2013](#)) for simulating foraging birds.

[Table 6.1](#) lists the tidal gauge stations used for the interpolation and [Figure 6.1](#) shows the triangles and edges used in the interpolation.

For the black parts in [Figure 6.1](#) the water level at the nearest station is used (either Krammersluizen in the north or Bergesediepsluis in the south-east). Due to the use of an amplitude map water levels calculated in the black parts may still exceed those at "their" station (see [Figure 5.12](#) at [page 49](#)).

6.1.1 Subareas

There are no subareas defined for this region.

6.1.2 Height maps

There are 5 pre-installed height maps for this region. Maps `bodem_1990`, `bodem_2001` and `bodem_2010` have been used in a simulation study with Deltares ([Rappoldt and Ens, 2013](#)). Further documentation will be added here as soon as possible.

The height maps `bodem_os_2016` and `bodem_oosterschelde_2021` originate from Rijkswaterstaat. These maps have been used for exposure time calculations with InterTides which are part of ecotope map construction. The height maps will be documented by Rijkswaterstaat in "Toelichting ecotopenkaart 2016" and "Toelichting ecotopenkaart 2021", both documents are in preparation.

Table 6.1. Tidal gauge stations used for region Eastern Scheldt (Oosterschelde). The positions are in EPSG 28992 coordinates (Amersfoort or RD new).

X	Y	Name
37216	404735	Roompot
49440	396100	Kats
59300	401630	Stavenisse
69000	408570	Krammersluizen
63910	391613	Yerseke
70210	392080	Bergsediepsluis

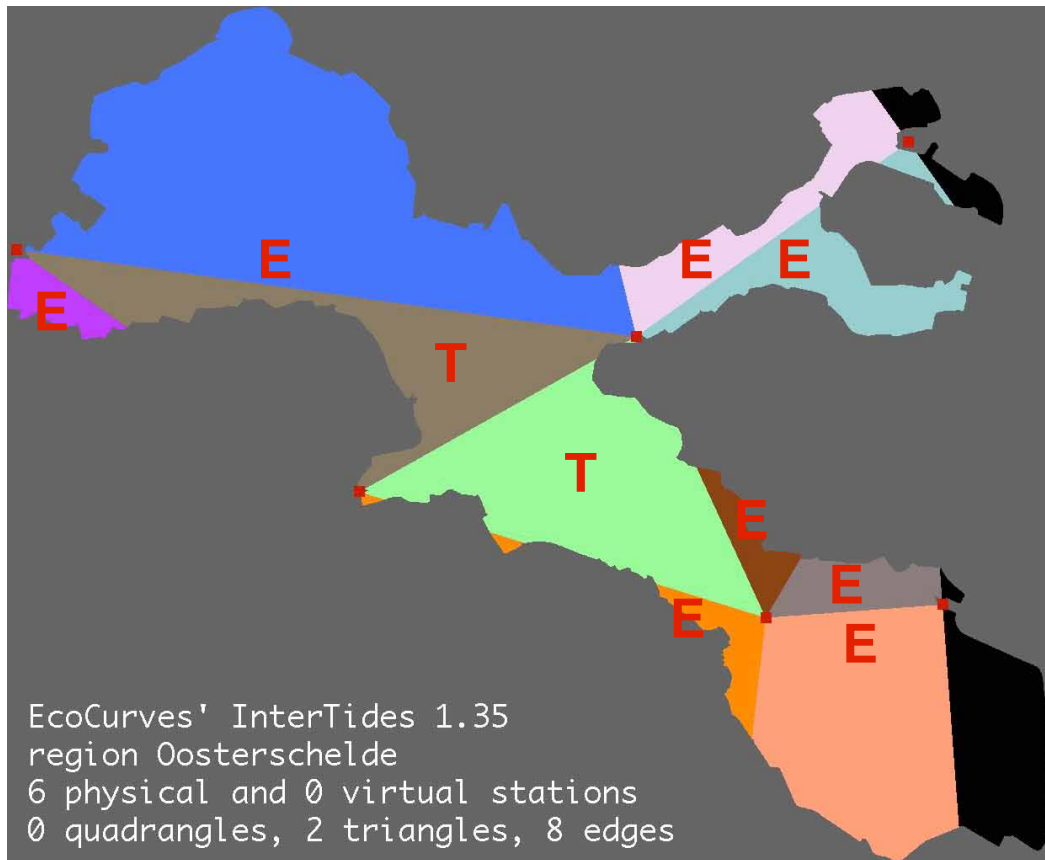


Figure 6.1. Eastern Scheldt interpolation scheme consisting of 2 Triangles and 8 Edges. For black parts the water level at the nearest station is used.

6.2 Western Scheldt

This section describes the InterTides configuration for the region Western Scheldt (Westerschelde). This region is not (yet) available in online InterTides.

The water levels installed refer to the period from 1995 onwards. The interpolation uses reduced water levels ("normalisation", e.g. [section 5.8](#)) based on a map of the M2 amplitude by Rijkswaterstaat. The M2 constituent or the "principal lunar semi-diurnal" has a period of 12.420601 hours. The map of the mean sea level is zero everywhere.

[Table 6.2](#) lists the tidal gauge stations used for the interpolation and [Figure 6.2](#) shows the quadrangle, triangles and edges used in the interpolation.

6.2.1 Subareas and height maps

There are no subareas defined for this region.

Table 6.2. Tidal gauge stations used for region Western Scheldt (Westerschelde). The positions are in EPSG 28992 coordinates (Amersfoort or RD new).

X	Y	Name
65541	375998	Baalhoek
73080	379550	Bath
41652	381517	Borssele
27200	381000	Breskens
15010	378610	Cadzand
59050	384960	Hansweert
56042	380549	OverloopHansweert
76872	372913	Prosperpolder
69909	377234	SchaarNoord
45780	373060	Terneuzen
6083	392714	VlakteRaam
30480	385220	Vlissingen
60290	379692	Walsoorden
19870	394300	Westkapelle

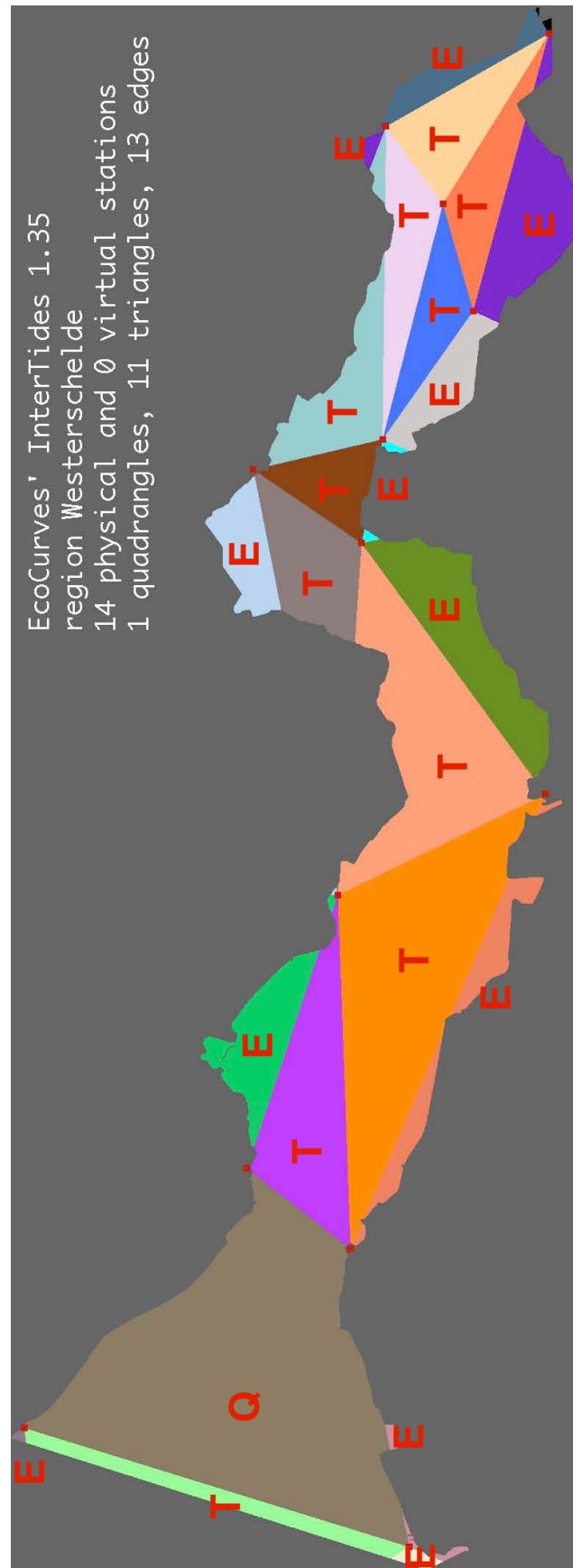


Figure 6.2. Western Scheldt interpolation scheme consisting of 1 Quadrangle, 11 Triangles and 13 Edges. For the small black part in the east the water level at the nearest station (Prosperpolder) is used.

6.3 Voordelta en Vlakte van de Raan

This section describes the interpolation scheme for coastal area between the Belgian border and the port of Rotterdam (Voordelta en Vlakte van de Raan). This region is not (yet) available in online InterTides.

The water levels installed refer to the period from 2001 onwards. No normalisation is used. [Table 6.3](#) lists the tidal gauge stations used for the interpolation.

[Figure 6.3](#) shows the quadrangles, triangles and edges used in the interpolation. Note that stations Europlatform, HoekvanHolland and Scheveningen lie outside the map in [Figure 6.3](#).

6.3.1 Subareas and height maps

Two subareas are defined for this region, "Voordelta" and "Vlakte van de Raan". There are no pre-installed height maps for this region.

Table 6.3. Tidal gauge stations used for region "Voordelta en Vlakte van de Raan". The positions are in EPSG 28992 coordinates (Amersfoort or RD new).

X	Y	Name
15010	378610	Cadzand
6083	392714	VlakteRaan
27200	381000	Breskens
30480	385220	Vlissingen
19870	394300	Westkapelle
36920	404796	Roompotbuiten
37853	408772	Oosterschelde04
36761	416146	Oosterschelde14
32824	421369	Brouwershaven2
46197	419184	Brouwershaven8
9960	447600	Europlatform
36775	438792	LichteilandGoeree
49862	431612	Haringvliet10
61680	427360	Stellendammbuiten
67930	444000	HoekvanHolland
78010	457350	Scheveningen

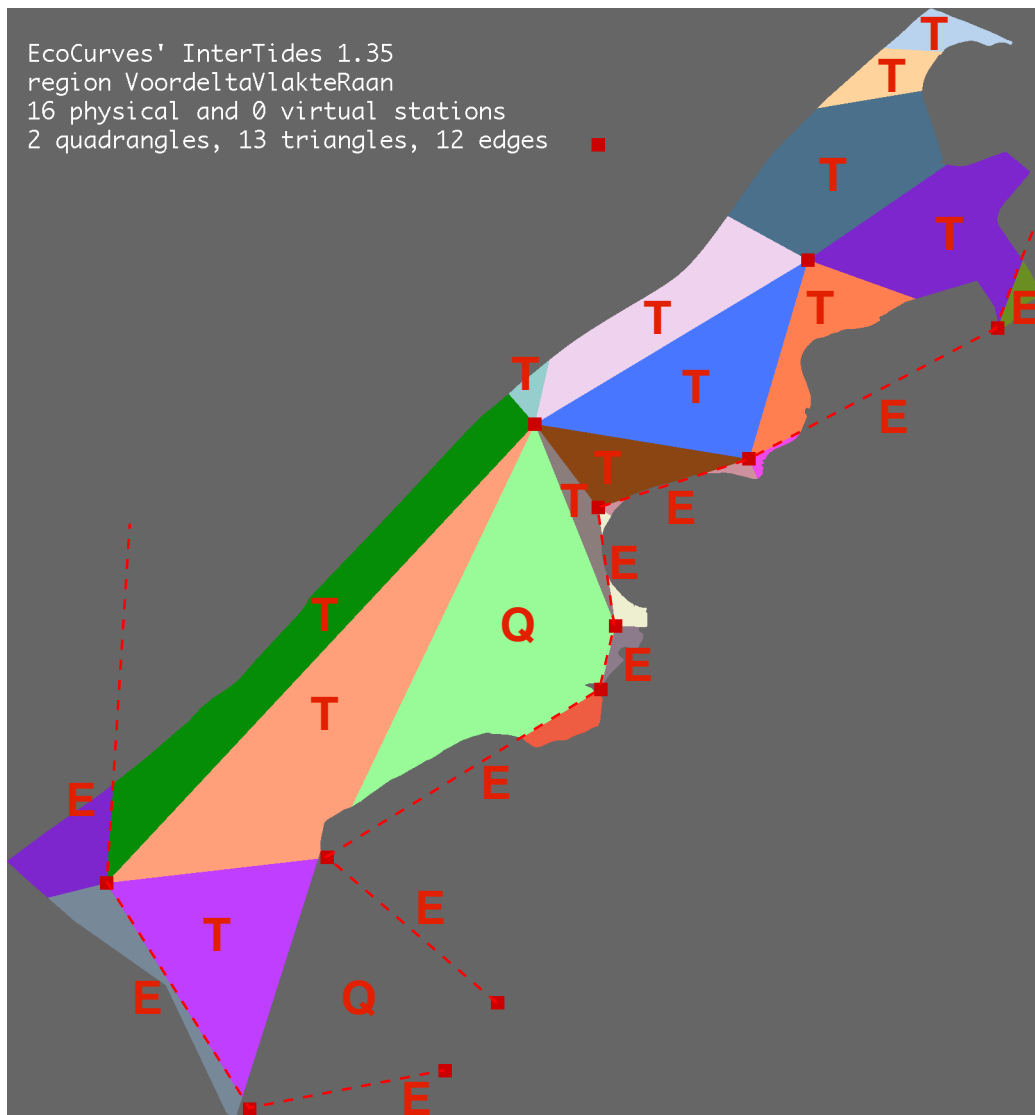


Figure 6.3. Voordelta en Vlakte van de Raan interpolation scheme consisting of 2 Quadrangles, 13 Triangles and 12 Edges. Stations Europlatform, HoekvanHolland and Scheveningen lie outside this map.

6.4 Wadden Sea

This section describes the interpolation scheme for the Wadden Sea (Waddenzee). This region is available in online InterTides.

The water levels installed refer to the period from 1981 onwards. [Table 6.4](#) lists the tidal gauge stations used for the interpolation. No normalisation is used. [Appendix B](#) explains why a map derived from a dynamic simulation by [Nauw et al. \(2017\)](#) is not used.

[Figure 6.4](#) shows the triangles and edges used in the interpolation. For the black parts in [Figure 6.4](#) (tiny areas near Den Helder and Nieuwstatenzijl) the water level at the nearest station is used.

The edges are indicated as a dashed red polygon. Starting from Den Helder, each line segment connects two stations and is used as an "edge" for points at its right hand side. In the Eems-Dollard area the edges Eemshaven-Delfzijl and Delfzijl-Nieuwstatenzijl are used at both sides, The two stations are declared as "edge" in reverse order as well.

The Wadden Sea is also a subarea of region "Wadden Sea Area" (Waddengebied) described in [section 6.5](#). Near the tidal inlets between the islands the results of two interpolation schemes wil differ. These differences reflect the uncertainties involved in estimating water levels in the tidal inlets by means of interpolation. **Therefore water levels calculated in the neighbourhood of the tidal inlets should be used with care.**

6.4.1 Subareas and height maps

The tidal basins ("kombergingen") listed in [Table 6.6](#) at [page 66](#) are available as subareas for region Wadden Sea as well. Two subareas in that table, however, do not exist for region Wadden Sea: "Noordzeekustzone" lies outside the region and "Waddenzee" is the entire region.

The height maps available for the Wadden Sea region are the same as those for the Wadden Sea Area listed in [section 6.5.6](#) at [page 67](#).

Table 6.4. Tidal gauge stations used for region Wadden Sea (Waddenzee). The positions are in EPSG 28992 coordinates (Amersfoort or RD new).

X	Y	Name	X	Y	Name
111850	553230	DenHelder	179707	604916	Nes
118980	561460	Oudeschild	208850	602790	Lauwersoog
132030	549440	DenOever	209170	609500	Schiermonnikoog
135280	590000	VlielandHaven	221990	621330	Huibertgat
143870	597420	WestTerschelling	250750	607900	Eemshaven
151610	564780	Kornwerderzand	258000	594430	Delfzijl
192882	614562	Wierumergronden	276540	584310	Nieuwstatenzijl
156480	576550	Harlingen			

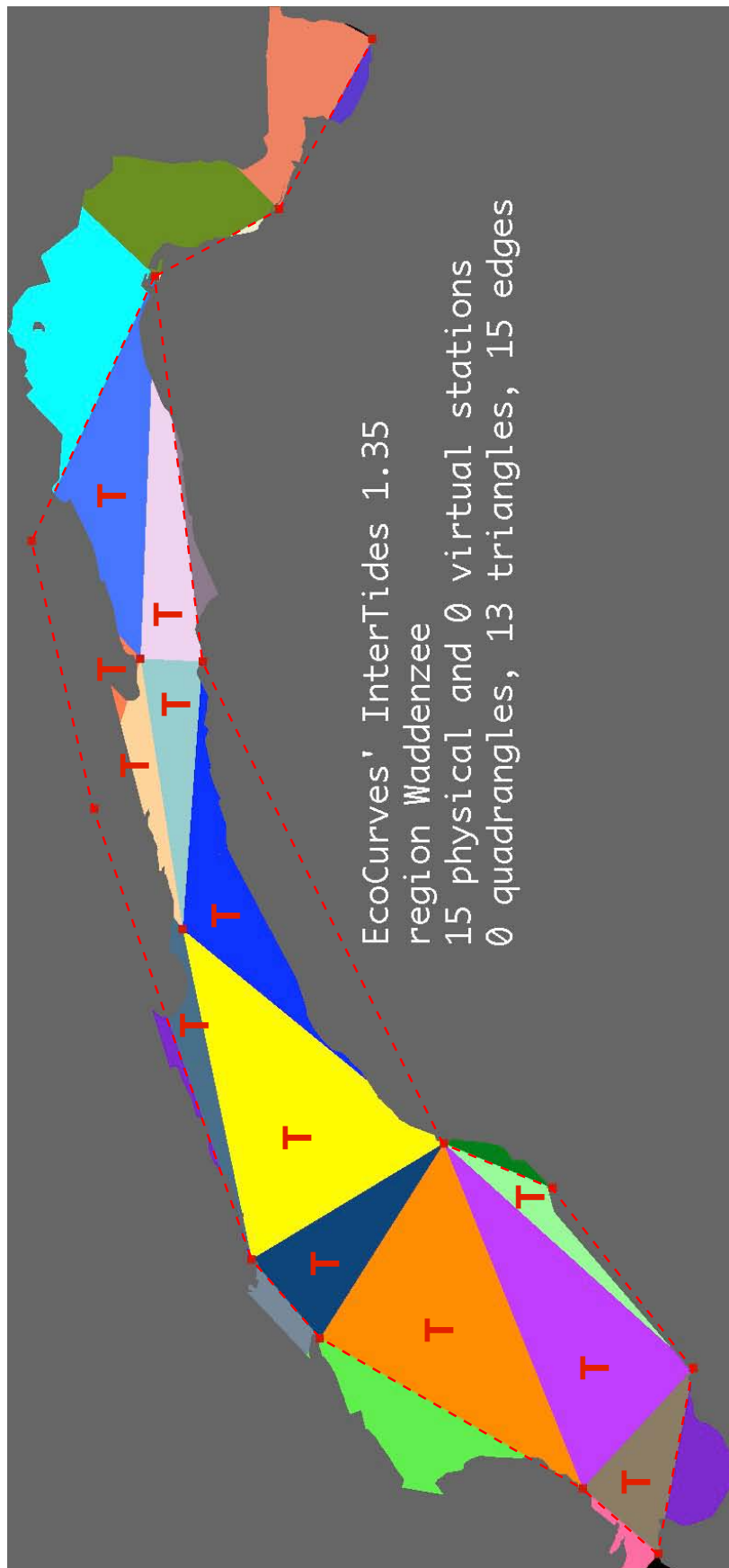


Figure 6.4. Wadden Sea (Waddenzee) interpolation scheme consisting of 13 Triangles and 15 Edges. The edge segments are shown as a red dotted line segments connecting two stations. For the small black parts near Den Helder and Nieuwstatenzijl the nearest station is used.

6.5 Wadden Sea Area (Waddengebied)

This section describes the interpolation scheme for the Wadden Sea Area (Waddenzee met Noordzee kustzone). This region is available in online InterTides. The water levels installed refer to the period from 2000 onwards. No normalisation is used. [Table 6.5](#) lists the tidal gauge stations.

6.5.1 A complex interpolation scheme

The rather complex interpolation scheme in [Figure 6.5](#) has been designed to prevent lines of interpolation crossing the large wadden islands. In this way the Wadden Sea tide and the North Sea tide are kept separate, with the tidal inlets as transition zones between the two.

Position and extent of these transition zones in [Figure 6.5](#) are rather arbitrary, however. **Therefore water levels calculated in the neighbourhood of the tidal inlets should be used with care.**

[Figure 6.5](#) shows the quadrangles, triangles and edges used in the interpolation. The corners are either physical tidal stations or virtual stations.

Edges are indicated as a dashed red line segment. Each line segment connects two stations and is used to find water levels for points at its right hand side (see [section 5.4](#)). In the Eems-Dollard area and along the North Sea coast most line segments are used two-sided. The two stations need then to be declared as "edge" in reverse order as well.

Details are explained below in [section 6.5.3](#). At first an example of calculated water levels is shown.

Table 6.5. Tidal gauge stations used for region Wadden Sea Area (Waddenzee met Noordzee kustzone). The positions are in EPSG 28992 coordinates (Amersfoort RD new).

X	Y	Name
98430	497500	IJmuidenhaven
111850	553230	DenHelder
111215	570625	TexelNZ
118980	561460	Oudeschild
132030	549440	DenOever
135280	590000	VlielandHaven
151400	606250	TerschellingNZ
143870	597420	WestTerschelling
151610	564780	Kornwerderzand
192882	614562	Wierumergronden
156480	576550	Harlingen
179707	604916	Nes
208850	602790	Lauwersoog
209170	609500	Schiermonnikoog
221990	621330	Huibertgat
250750	607900	Eemshaven
258000	594430	Delfzijl
276540	584310	Nieuwstatenzijl

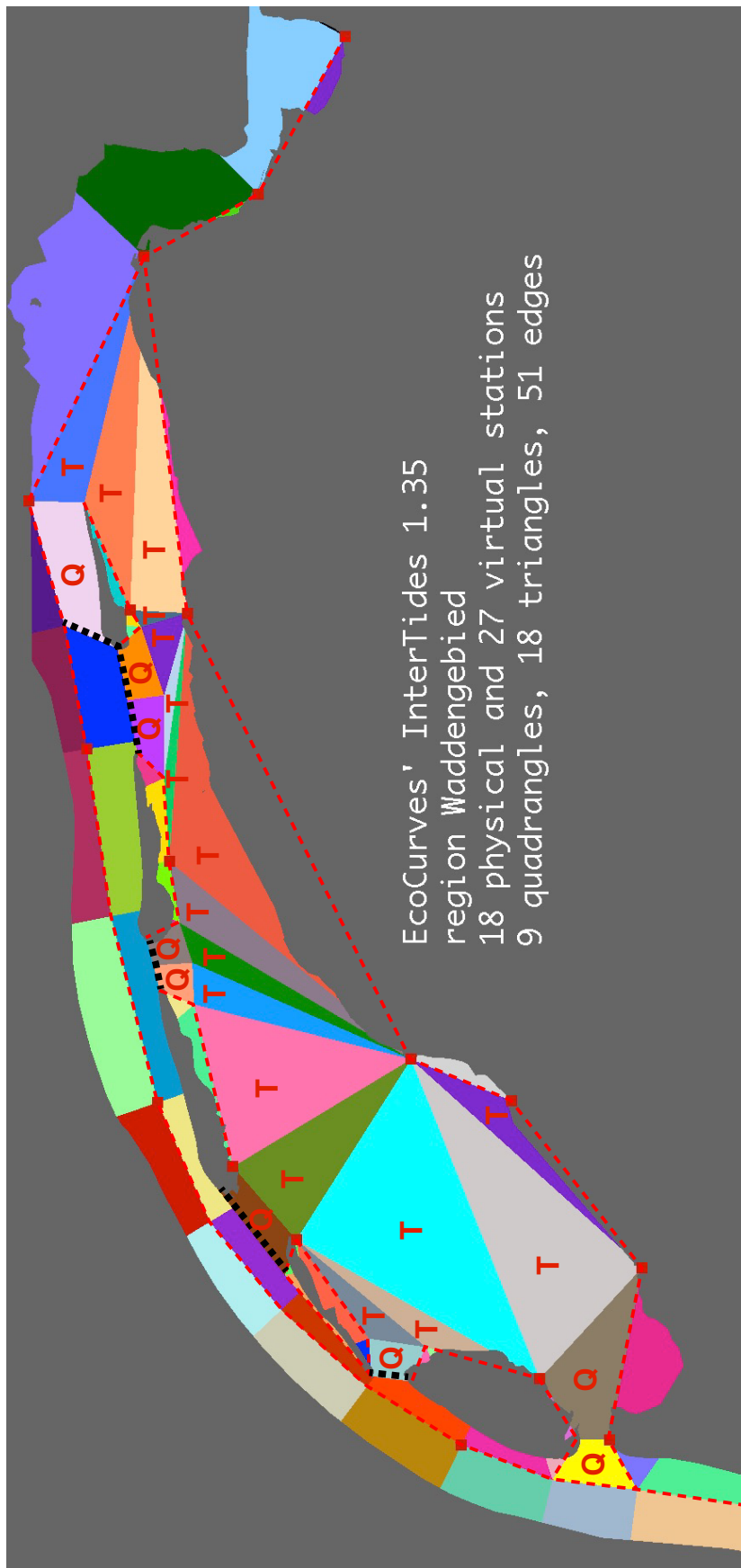


Figure 6.5. Wadden Sea Area (Waddengebied) interpolation scheme consisting of 9 quadrangles, 18 Triangles and 51 Edges. The 18 physical stations are marked with a red square, the 27 virtual stations lie at corners where no physical station is indicated. The edge segments are shown as red dotted line segments connecting two stations. A black dotted line in a quadrangle indicates indirect interpolation along that particular side. For a tiny black part near Nieuwstatenzijl the nearest station is used. Station IJmuidenhaven lies outside this map.



Movie 6.1. Wadden Sea Area levels from September 8, 2021, 22:10 to September 9, 2021, 12:00. The movie shows the gradients in the tidal inlets if level differences between Wadden Sea and coastal zone are relatively large. The animation runs for 28 s.

6.5.2 The tidal wave

The North Sea tide is driven by the ocean tide in the North Atlantic. Due to the earth rotation, a tidal wave moves south along the Scottish and English east coast, turns around in the southern North Sea and then follows the coast of Belgium, Holland, Germany and Denmark.

[Movie 6.1](#) shows an animation of the tide along the North Sea side of the wadden islands and in the actual Wadden Sea. The Wadden Sea levels are different and somewhat delayed. Quite naturally there are gradients in the tidal inlets between the islands. In the animation, these gradients are quite local and the transition zones between North Sea and Wadden Sea do not extend far into the North Sea or Wadden Sea.

The number of tidal stations allows an approximate simulation of the North Sea and Wadden Sea levels, but the dynamic details in the neighbourhood of the tidal inlets can obviously not be resolved by interpolation. The interpolation scheme near the tidal inlets is therefore rather arbitrary. Virtual stations are used to "separate" the measured levels in the North Sea from those in the Wadden Sea, with the tidal inlet as a transition zone. As a consequence, **water levels calculated in the neighbourhood of the tidal inlets should be used with care.**

6.5.3 Details of the interpolation

The starting points for designing the interpolation scheme in [Figure 6.5](#) were the following.

- 1 The tidal wave along the coast runs smoothly and is hardly affected by the Wadden Sea tidal inlets.
- 2 The interpolation scheme for the region Wadden Sea in [Figure 6.5](#) shows that water levels south of Ameland and Schiermonnikoog are calculated in triangles containing North Sea stations Wieremgronden or Huibertgat. This should be avoided except near the Eems in the east where islands are small and the Wadden Sea is relatively open to the North Sea.

- 3 The rest of the Wadden Sea interpolation scheme [Figure 6.2](#) should largely remain unchanged, with the exception of the tidal inlets.

North Sea coast

Point 1 is achieved by means of virtual stations in between the physical North Sea stations. The water levels at the virtual stations are calculated from the physical ones, using the distances to the defining stations as weights and taking into account a phase difference. These virtual stations are shown as orange dots in [Figure 6.7](#) at [page 64](#).

This results in a row of coastal stations. Edge interpolation is used to find the water levels in the coastal zone (see the interpolation scheme in [Figure 6.5](#)).

Tidal inlets

Point 2 and 3 are achieved by defining virtual stations around the tidal inlets. These virtual stations are shown as white dots in [Figure 6.7](#) at [page 64](#). As an example, [Figure 6.6](#) shows the details between Ameland and Terschelling.

At the North Sea side the virtual levels are found by edge interpolation from the row of North Sea stations. At the Wadden Sea side they are found by interpolating between Wadden Sea stations. The water levels calculated in this way will fit smoothly in the surrounding North Sea or Wadden Sea levels. The *rather arbitrary* positions of the virtual stations determine the extent of the transition zone between North Sea and Wadden Sea.

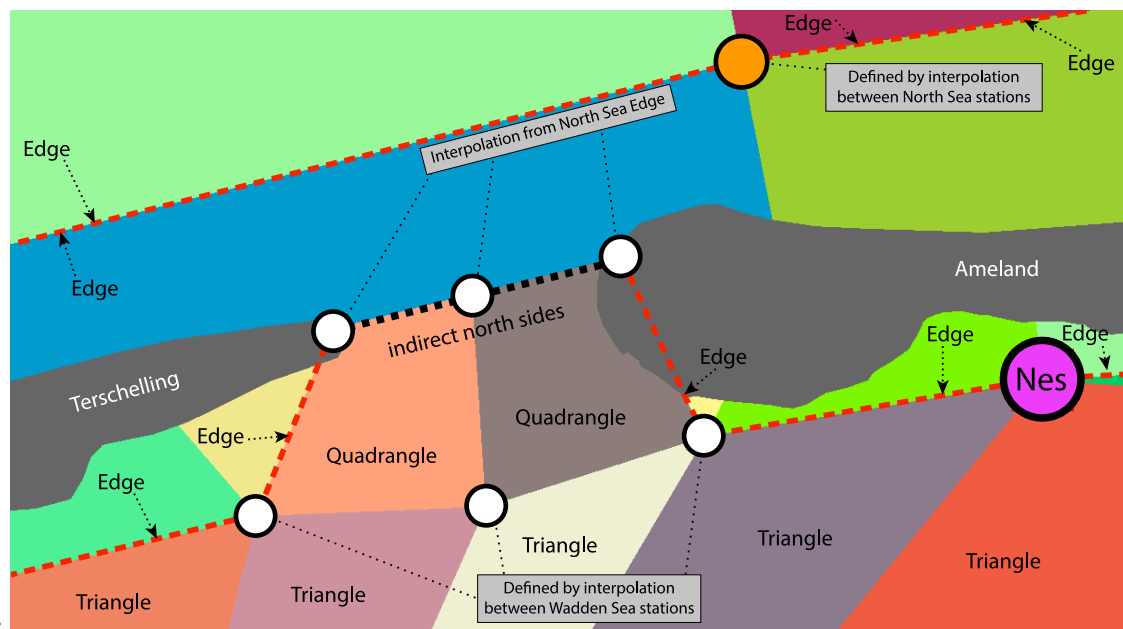


Figure 6.6. Tidal inlet interpolation. The physical station Nes is a large magenta dot. The orange dot is a North Sea virtual station defined by interpolation between North Sea measured levels. The white dots are virtual stations around the tidal inlet Borndiep. The northern ones are defined by edge interpolation from the "North Sea edge" as indicated in the drawing. The southern ones are defined by interpolation between Wadden Sea physical stations. The levels at the north side of the two quadrangles are found from the North Sea edge as well ("indirect interpolation").

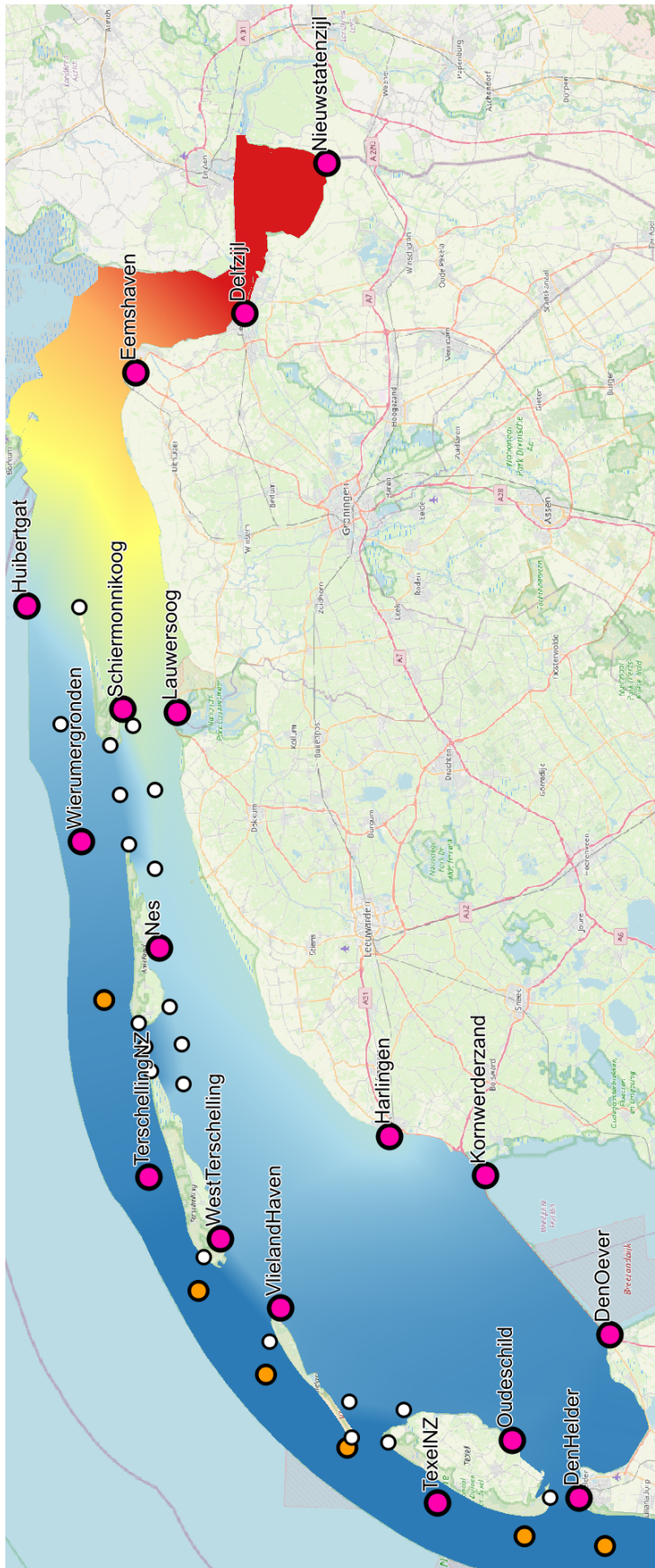


Figure 6.7. Physical and virtual tidal gauge stations in the Wadden Sea area. The physical stations of Rijkswaterstaat are shown as large magenta dots with a name. The virtual stations for improving the North Sea tide are orange dots. And the smaller white dots show the positions of the virtual stations used to separate Wadden Sea and North Sea tide. The background is a water level map for 20-May-2010 at 10:50. The interpolation scheme for the physical and virtual stations is shown in [Figure 6.5](#) at [page 61](#).

The (virtual) stations near the tidal inlets are used to define interpolation quadrangles with indirect interpolation at their North Sea side. The indirect "north side" is necessary. Otherwise a water level discontinuity would appear between the quadrangle side and adjacent North Sea points¹.

6.5.4 Waterlevels for the Wadden Sea by two regions

The InterTides region Wadden Sea (section 6.4) does not include a North Sea coastal zone and no virtual stations are used in the interpolation scheme for region Wadden Sea (Waddenzee) in Figure 6.4 at page 59. Therefore, water levels calculated for the Wadden Sea will differ from those calculated for region Wadden Sea Area (Waddengebied) with the interpolation scheme in Figure 6.5.

Figure 6.8 shows a difference map calculated for September 9, 2021, 1:40, which is about 3.5 hours after high tide and after the start time of Movie 6.1 at page 62. The tide is falling fast and the differences between North Sea and Wadden Sea levels are relatively large. The difference map has been calculated as "Levels Waddengebied" minus "levels Waddenzee".

The positive (greenish) differences mean that the "Waddengebied" interpolation is higher. This occurs just south of Terschelling, Ameland and Schiermonnikoog. The levels are no longer affected by the (at that time) lower North Sea levels.

The negative (yellow and orange) differences mean that "Waddengebied" interpolation is lower. This occurs in the tidal inlets and predominantly between Ameland and Schiermonnikoog. The levels near the inlet are affected by the already lower North Sea levels. The difference is considerable, close to 40 cm at the North Sea side of the tidal inlet.

¹Water levels found by edge interpolation do not change linearly along an arbitrary straight line if this line is not parallel to the edge. Hence, if levels along the north side of a quadrangle would be calculated by linear interpolation between the two (northern) corners, there would be a discontinuity between the quadrangle and the North Sea levels. This is resolved by finding the north side levels by edge interpolation from the North Sea stations, and *not* by interpolation between the northern corners of the quadrangle. This is called indirect interpolation.

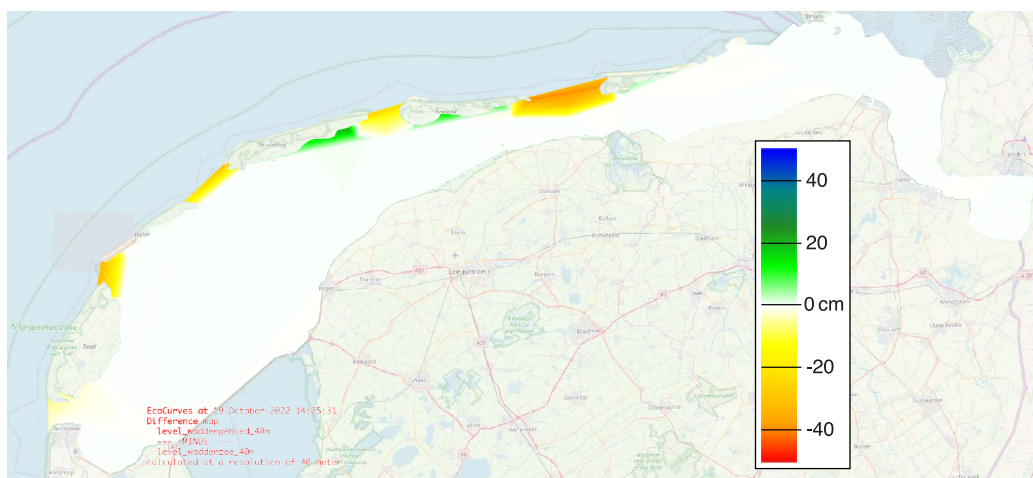


Figure 6.8. Difference between water levels calculated in region Wadden Sea Area (Waddengebied) and Wadden Sea (Waddenzee). The tide is falling, about halfway between high tide and low tide, at September 9, 2021, at 1:40.

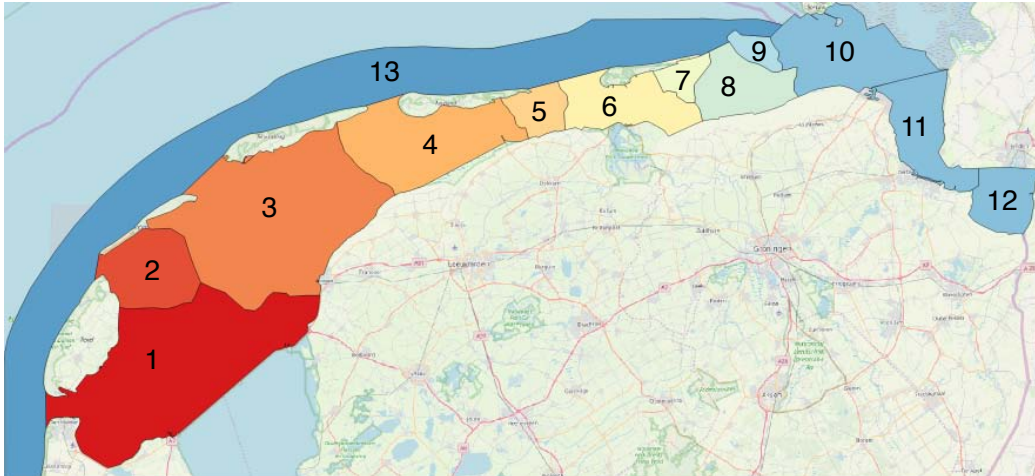


Figure 6.9. Subareas of region Wadden Sea Area (Waddengebied). The names are listed in [Table 6.6](#).

The situation considered here is fast falling tide. The uncertainty in high tide and low tide levels will be less pronounced. Nevertheless we state once again that **water levels calculated in the neighbourhood of the tidal inlets should be used with care**. This holds for both regions, "Waddenzee" and "Waddengebied" and clearly also for a derived quantity like the exposure time.

6.5.5 Subareas

[Table 6.6](#) lists the tidal basins ("Kombergingen") of the Wadden Sea as subareas. The numbers point to the map in [Figure 6.9](#). A few combinations of tidal basins are also available as subareas, Pinkegat+Zoutkamperlaag and Waddenzee. The latter consists of all tidal basins.

Two additional subareas n2k_noordzeekustzone and n2k_waddenzee are the official "Natura-2000" nature reserves. These nature reserves may contain dunes and salt marshes which are not part of the InterTides region map. Such places will be set at NODATA by InterTides calculations.

Table 6.6. Subareas of the InterTides region Wadden Sea Area (Wadengebied). The numbers refer to the map in [Figure 6.9](#). The subareas n2k_noordzeekustzone and n2k_waddenzee are the official "Natura-2000" nature reserves.

On map	Name	On map	Name
1	Marsdiep	9	Schild
2	Eijerlandse_Gat	10-12	Eems_Dollard
3	Vlie	13	NoordzeeKust
4	Borndiep	5-6	Pinkegat+Zoutkamperlaag
5	Pinkegat	1-12	Waddenzee
6	Zoutkamperlaag	12	Dollard
7	Eilanderbalg	-	n2k_noordzeekustzone
8	Lauwers	-	n2k_waddenzee

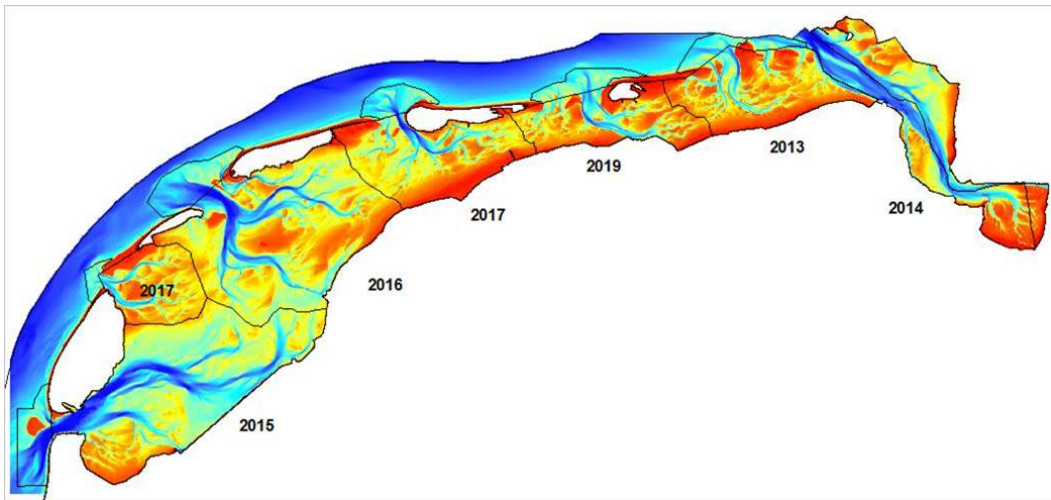


Figure 6.10. Measurement years for the height map Wadsea_2013_2019.

6.5.6 Height maps

The five height maps documented in [Elias and Wang \(2013\)](#) have been installed for use by InterTides. These maps are named "wadsea_cycle1" (1981–1989) to "wadsea_cycle5" (2006–2012) and cover 5 height measurement cycles carried out by Rijkswaterstaat. It takes several years to cover the entire area.

The height map used for the Wadden Sea Ecotope map 2017 ([Paree et al., 2021](#)) is available as Wadsea_2013_2019. The measurement years are indicated in [Figure 6.10](#).

Harmonic analysis

The following background operations of InterTides make use of the harmonic analysis of tidal data.

- **Missing values.** Water levels for the period between 1985 and 1990 are available as hourly values only¹. The easiest way of dealing with this is to calculate the five missing values per hour as the sum of the "predicted", astronomical level and the interpolated hourly residuals (the difference between measured level and predicted level).
- **First and last day.** Synchronization of the tidal wave at the various stations requires time-shifted water levels. Such a time shift leads to missing data at either the begin or at the end of the entire time series. Harmonic analysis is used to extend the measured time series over an additional day at the begin and at the end of the time range.
- **M2 phase.** One of the synchronization options of InterTides is based on the phase of the M2 constituent (the primary lunar tide). This phase is calculated for each station from the measured water levels in the year 2000.
- **High and Low tides.** The calculation of realised high tide and low tide times and levels by just searching for minimum and maximum water levels is *not* reliable due to storm tides. A better way is to use the tides predicted from harmonic analysis and to search for the real maximum (or minimum) around the astronomical prediction.

In order to accomplish these tasks, InterTides uses a basic form of harmonic analysis as a tool. Since InterTides is not a program dedicated to tidal prediction, the result of the module for harmonic analysis is not available for output. Nevertheless, the InterTides implementation of harmonic analysis will be briefly described.

7.1 Short introduction to harmonic analysis

The periodic change in water level is described as the sum of a series of cosine functions. Each cosine function has an amplitude, a frequency and a phase. The frequencies are known and fixed and the unknown amplitudes and phases need to be determined by harmonic analysis.

¹The use of a 10-minute interval started around 1990 at different dates for the various tidal gauge stations.

The frequencies depend on a handful of basic astronomical periods (e.g. [Kowalik and Luick, 2013](#); [Pugh and Woodworth, 2014](#)) related to earth rotation and the orbits of earth and moon. However, the number of cosine functions (or tidal constituents) required for a satisfactory description of the tide is much larger than the number of basic astronomical periods. There are two reasons for that.

The first reason is that the various astronomical effects do not lead to additive and independent tidal waves. The amplitude of principal lunar tide, for instance, changes periodically due to the fact that the orbit of the moon is an ellipse and not a circle. Mathematically a cosine function with a slowly but periodically changing amplitude is equivalent to the sum of *three cosine functions* with constant amplitudes and slightly different frequencies. Such interactions between the various astronomical periods lead to tens of larger and smaller tidal constituents.

The second reason is that the shape of the tidal wave changes in shallow water like the North Sea coast and the Wadden Sea. If a cosine function changes in shape it obviously is no longer a cosine function, but its frequency f is preserved. Mathematically this means it can be described as the sum of cosine functions with frequencies f , $2f$, $3f$, $4f$, etc. Analogous to the overtones in music, the additional higher frequency constituents are known as "shallow water overtones". The higher order constituents become smaller and smaller.

Harmonic analysis means that the amplitudes and phases of the important constituents are determined from a series of measured water levels. Once we have these amplitudes and phases a water level can be calculated for a time in past or future by just calculating all constituents for that time and summing them. Hence, the prediction of tides is little more than solving a fitting problem and an easy way is by linear regression analysis.

The important tidal constituents have been named and classified by [Doodson \(1921\)](#). His system has been extended, but is still in use today (e.g. http://www.iho.int/mtg_docs/com_wg/IHOTC/IHOTC_Misc/TWLWG_Constituent_list.pdf).

7.2 Harmonic analysis by InterTides

The constituents used are the same as in the predefined list for a year of data in <http://apps.helpdeskwater.nl/downloads/extra/simona/release/doc/usedoc/tidegui/a872r1r11.pdf>. This list contains the average water level and 94 tidal constituents.

Each constituent (cosine function) with unknown amplitude and phase can be rewritten as the sum of a sine and a cosine function, both with an amplitude only (e.g. [Kowalik and Luick, 2013](#)). This allows us to write the harmonic analysis as a linear regression problem with $1 + 2 \times 94 = 189$ unknown parameters. In order to solve this problem InterTides calls Lapack² subroutine "gelss" from the Math Kernel Library of Intel (<https://software.intel.com/en-us/mkl>). This subroutine calculates the least squares solution after singular value decomposition of the coefficient matrix.

All calculations are carried out with the time in days starting at 31-dec-1899 00:00:00³. Table 7.1 at page 71 gives an example of the results. It shows the harmonic constituents calculated for station Den Helder for the year 2000.

²Linear Algebra Package

³This zero point can also be set in Excel spreadsheets, but we skip 29-feb-1900 as a day and Excel does not (in Excel the year 1900 is incorrectly treated as a leap year).

Table 7.1. Harmonic analysis for Den Helder for the year 2000 using the 94 Rijkswaterstaat constituents. The fitted mean sea level was 2.8 cm +NAP and the residual error of the regression analysis is 24 cm. The phases are in degrees.

Constituent Name	Speed (deg/hr)	Amplitude (cm)	Phase (deg)
1 Sa	0.0411	10.8	338.0
2 SM	1.0159	2.2	65.0
3 Q1	13.3987	2.9	49.1
4 O1	13.9430	9.7	169.0
5 M1C	14.4921	1.4	323.0
6 P1	14.9589	3.4	12.9
7 S1	15.0000	1.2	144.4
8 K1	15.0411	6.9	6.7
9 3MKS2	26.8702	1.1	146.5
10 3MS2	26.9523	1.9	306.9
11 OQ2	27.3417	0.4	294.9
12 MNS2	27.4238	1.4	130.9
13 2ML2S2	27.4967	1.0	232.9
14 NLK2	27.8861	3.1	62.7
15 mu2	27.9682	8.0	219.7
16 N2	28.4397	10.1	74.1
17 nu2	28.5126	3.8	155.4
18 MSK2	28.9020	1.0	142.3
19 MPS2	28.9430	2.4	54.6
20 M2	28.9841	65.9	160.4
21 MSP2	29.0252	0.6	264.1
22 MKS2	29.0662	0.2	145.1
23 lambda2	29.4556	3.1	301.3
24 2MN2	29.5285	6.3	58.9
25 T2	29.9589	1.0	215.0
26 S2	30.0000	17.9	256.8
27 K2	30.0821	4.8	76.1
28 MSN2	30.5444	1.8	138.6
29 2SM2	31.0159	2.2	122.6
30 SKM2	31.0980	1.3	311.8
31 NO3	42.3828	0.3	169.7
32 2MK3	42.9271	0.9	275.9
33 2MP3	43.0093	0.2	275.2
34 SO3	43.9430	0.3	331.1
35 MK3	44.0252	0.4	196.7
36 SK3	45.0411	0.1	319.3
37 4MS4	55.9364	0.5	310.2
38 2MNS4	56.4079	0.5	126.8
39 3MS4	56.9523	1.9	219.6
40 MN4	57.4238	3.9	71.0
41 2MLS4	57.4967	1.4	151.9
42 2MSK4	57.8861	1.0	189.5
43 M4	57.9682	11.7	158.7
44 3MN4	58.5126	1.9	56.1
45 MS4	58.9841	6.4	248.5
46 MK4	59.0662	2.1	73.1
47 2MSN4	59.5285	1.2	145.8

continued on next page

Table 7.1. *continued*

Constituent Name	Speed (deg/hr)	Amplitude (cm)	Phase (deg)
48 S4	60.0000	0.5	3.6
49 MNO5	71.3669	0.6	95.3
50 3MK5	71.9112	1.1	205.6
51 2MP5	72.9271	0.6	325.6
52 3MO5	73.0093	1.1	28.1
53 MSK5	74.0252	0.5	107.8
54 3KM5	74.1073	0.1	284.4
55 3MNS6	85.3920	0.7	234.9
56 2NM6	85.8636	1.1	67.8
57 4MS6	85.9364	1.1	313.5
58 2MN6	86.4079	3.3	161.0
59 2Mnu6	86.4808	1.1	256.8
60 3MSK6	86.8702	0.7	250.5
61 M6	86.9523	5.8	256.5
62 MSN6	87.4238	1.1	267.2
63 MKnu6	87.5788	0.2	197.7
64 2MS6	87.9682	5.5	340.3
65 2MK6	88.0503	1.5	149.5
66 3MSN6	88.5126	1.2	246.6
67 2SM6	88.9841	1.0	73.6
68 MSK6	89.0662	0.5	256.7
69 2MNO7	100.3510	0.2	161.7
70 M7	101.4490	0.2	333.1
71 2MSO7	101.9112	0.3	16.5
72 2(MN)8	114.8477	0.8	82.1
73 3MN8	115.3920	1.8	190.8
74 M8	115.9364	2.2	289.3
75 2MSN8	116.4079	1.1	290.6
76 2MNK8	116.4901	0.9	89.0
77 3MS8	116.9523	3.3	11.9
78 3MK8	117.0345	0.9	190.2
79 2(MS)8	117.9682	1.2	109.8
80 2MSK8	118.0503	0.5	300.6
81 3MNK9	130.4331	0.2	56.4
82 4MK9	130.9775	0.1	161.9
83 3MSK9	131.9934	0.2	221.8
84 4MN10	144.3761	0.7	267.5
85 M10	144.9205	0.6	16.4
86 3MSN10	145.3920	0.8	357.9
87 4MS10	145.9364	1.3	86.7
88 2(MS)N10	146.4079	0.2	146.3
89 3M2S10	146.9523	0.7	171.1
90 4MSK11	160.9775	0.1	308.9
91 M12	173.9046	0.1	97.6
92 4MSN12	174.3761	0.4	44.6
93 5MS12	174.9205	0.4	132.3
94 4M2S12	175.9364	0.4	220.4

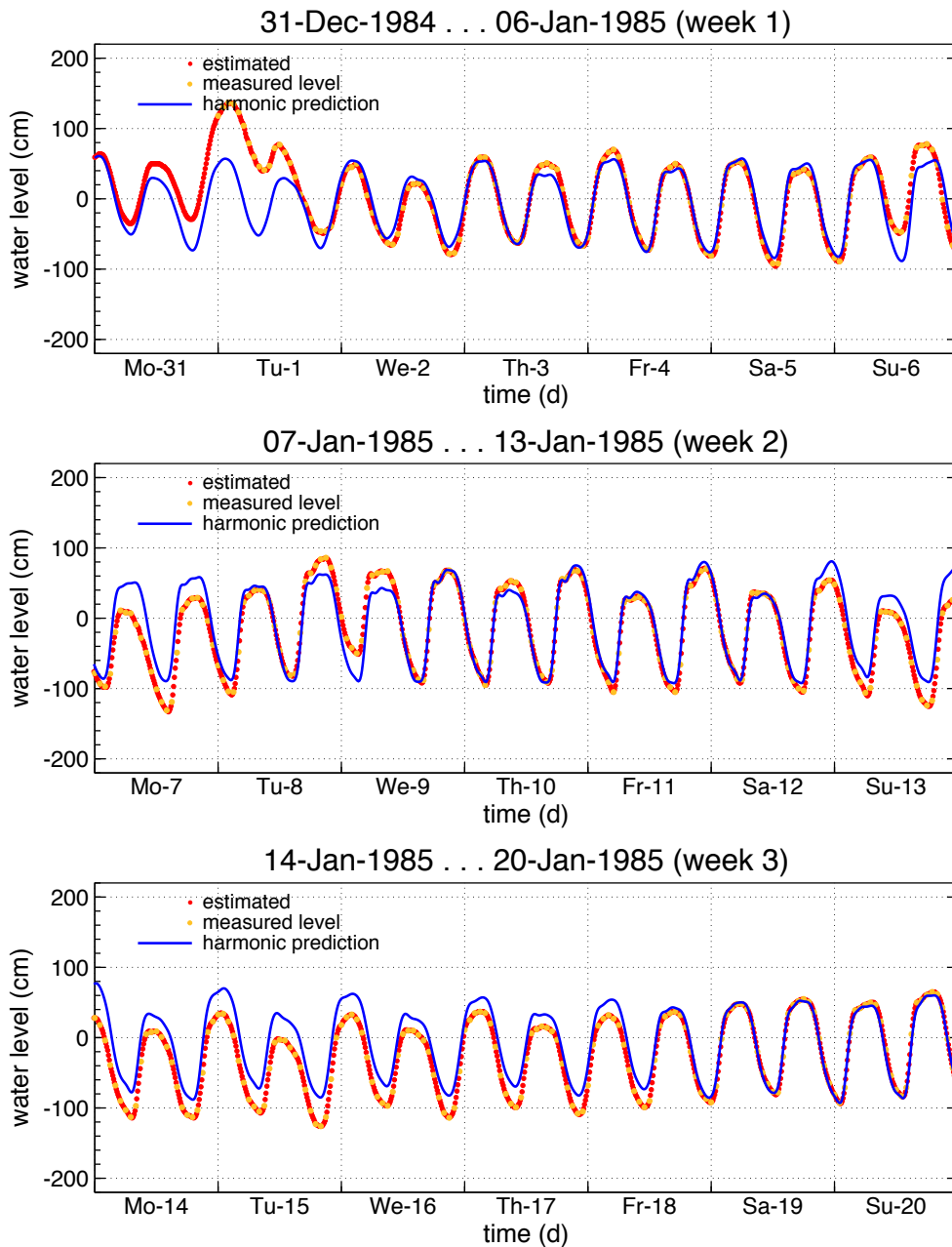


Figure 7.1. The tidal gauge time series for Den Helder begins on Tuesday January,1 1985 at 00:00. The available measured levels are hourly values and the five missing values per hour were estimated by means the calculated astronomical tide (the blue curve "harmonic prediction"). Also the levels for December,31 were estimated from the harmonic prediction).

No attempt is made to identify constituents which are not statistically significant. We just use the 94 constituents to calculate astronomical water levels at arbitrary times.

7.3 Filling gaps in the water level time series

The astronomical tide is used to fill gaps in the water level time series. [Figure 7.1](#) at [page 73](#) shows an example. The blue curve is the astronomical tide and the yellow points are measured water levels. Clearly, the measured levels deviate from the "prediction" which is mainly due to the influence of weather and atmospheric pressure. The hourly residuals can be interpolated however and added to the astronomical tide. This leads to realistic intermediate values.

An example with a larger gap is shown in [Figure 3.2](#) and [Figure 3.3](#) at [page 31](#). In case of a gap larger than 26 hours the effect of wind and atmospheric pressure is not interpolated but reconstructed from a nearby tidal station.

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Appendices

Nieuwstatenzijl sluice discharge

The tidal gauge station Nieuwstatenzijl in the Dollard is heavily affected by the sluice which drains off water from the Westerwoldse Aa around low tide. The flown out water often leads to a significant increase in the local water level which is preferably omitted in calculations for the Dollard as a whole.

Below, a few plots illustrate the problem. A solution is proposed, but has not yet been implemented in InterTides.

A.1 Disturbed low tide water levels

Figure A.1 shows the Nieuwstatenzijl levels during a number of tidal cycles in March 2020. Many tidal cycles show the sluice discharge beginning as soon as the water level drops below 0 NAP (the black arrows in the figure are just arbitrary examples). During a few days around March 12, there are increased water levels due to wind and it apparently has been difficult to get rid of the water. The tidal gauge level hardly drops below 0 cm NAP at low tide (with the exception of the low tide in the evening of March 12). Without sluice discharge the low tide level at Nieuwstatenzijl approaches -200 cm.

InterTides calculations for the Dollard area make use of interpolation between the Delfzijl and Nieuwstatenzijl tidal gauge stations. This implies that the local deviations caused by the Nieuwstatenzijl sluice discharge will affect calculated exposure times and mean low tide level.

The tidal periods around March 12 in Figure A.1 are a quite extreme example. The low tide level at Nieuwstatenzijl, however, is often affected by sluice discharge and especially for Dollard mudflat heights between -200 cm and -100 cm a significant effect on the exposure time must be expected.

A correction with help of the astronomical tide is not trivial since the astronomical tide calculated for Nieuwstatenzijl from a long time series will show a systematic error in the low tide level. The only solution seems to identify the tidal periods affected and remove them from the data. Then, the astronomic tide inferred from the remaining tidal periods can be used to complete the Nieuwstatenzijl time series.

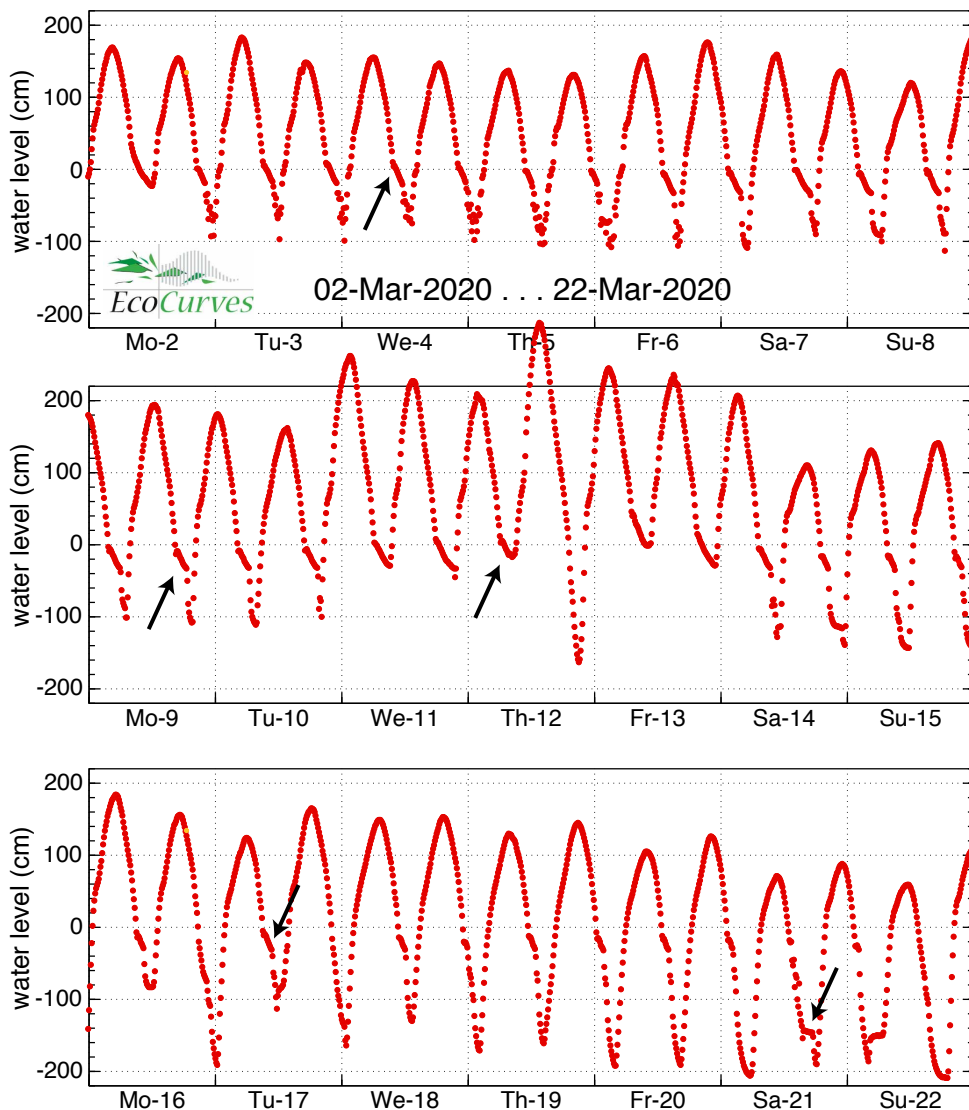


Figure A.1. Tidal gauge measurements at Nieuwstatenzijl in March 2020. Low tide levels are heavily affected by the discharge of water from the Westerwoldse Aa. Many tidal cycles show the sluice discharge beginning as soon as the water level drops below 0 NAP. The black arrows just point to arbitrary examples.

A.2 Comparison with Delfzijl

By comparing the measurements at Nieuwstatenzijl with those at the nearby station Delfzijl, the tidal periods with a large effect of sluice discharge can be identified. [Figure A.2](#) shows the daily high and low tide levels for the two stations. At most days this is the average of two levels, at some days there is just a single high tide (or low tide).

The high tide level of Nieuwstatenzijl (the upper red lines) closely follows the Delfzijl levels. On average, the high tide level at Nieuwstatenzijl is about 13 cm above the Delfzijl level, which reflects the estuarine nature of the tidal basin. We might therefore expect that the Nieuwstatenzijl low tide level is slightly below the Delfzijl one, reflecting the larger tidal amplitude further inwards into the estuary.

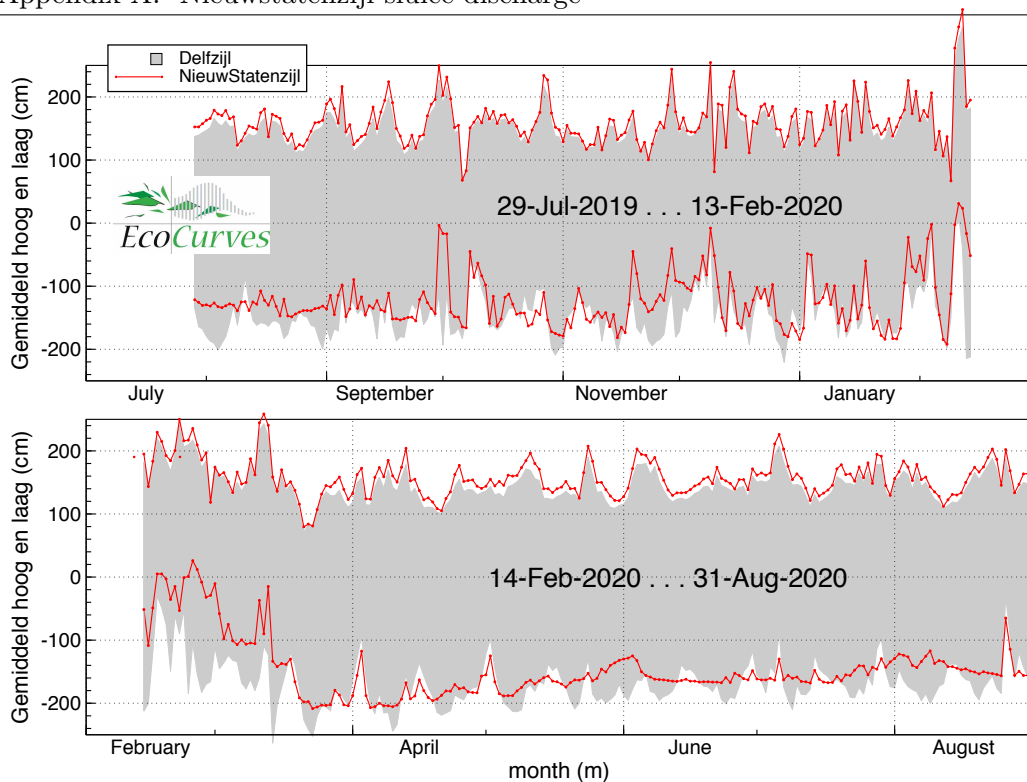


Figure A.2. Mean high tide and low tide levels for Delfzijl (grey area) and Nieuwstatenzijl (red lines) for 400 days in 2019 and 2020. For each day the average of the two tides has been plotted (sometimes one tide). The Nieuwstatenzijl high tide levels closely follow the Delfzijl ones. The low tide levels show the influence of sluice discharge.

Indeed, inspection of the tidal curves reveals at least some effect of the sluice discharge during *most of the low tide periods*. Usually the effect is moderate, as shown for instance in [Figure A.1](#) at March 19 and March 20. Sometimes the effect of sluice discharge is very large, like during the end of february and early march 2020. The high low tide levels in that period are clearly above the Delfzijl levels in [Figure A.2](#).

Hence, the tidal periods which are affected by the sluice discharge can be identified by comparing the low tide level at Nieuwstatenzijl with the one at Delfzijl. The measured levels in these periods, from high tide to the "bad" low tide and until the next high tide, are replaced by water levels calculated by harmonic analysis of the remaining "correct" tidal periods. The next section provides some details.

A.3 The correction procedure

The correction has been carried out by means of the following steps

- Calculate the astronomical tide for Delfzijl by harmonic analysis of the Delfzijl measurements.
- Calculate the effect of weather and wind for Delfzijl as the difference between the measured levels and the astronomical tide.
- Delete the data for all Nieuwstatenzijl tidal cycles (between two high tides)

with a low tide level at some threshold distance above the Delfzijl one. A threshold of 10 cm detects most of the low tides affected.

- Calculate the Nieuwstatenzijl astronomical tide from the remaining, undisturbed tidal cycles. Note that complete periods between two high tides were deleted from the time series and not just the affected levels around low tide. This prevents a bias in the harmonic analysis that would be there in the absence of low water levels only.
- "True" Nieuwstatenzijl levels can now be estimated as the sum of the astronomical tide for Nieuwstatenzijl and the Delfzijl effect for weather and wind.
- For each rejected period between two high tides, the newly estimated levels serve as a replacement. Not the full period between high tide and high tide is replaced however. Within 2.5 hours from high tide the original Nieuwstatenzijl measured levels are used. Then there is a gradual transition to the corrected levels over 1.5 hours. Hence, since a tidal period is about 12.5 hours, just the low tide part of about $12.5 - 2 \times (2.5 + 1.5) = 4.5$ hours is completely replaced by the new estimate.

The two weeks in April 2017 shown in [Figure A.3](#) required few corrections. [Figure A.4](#) shows the result for March 2020, some of the weeks also shown in [Figure A.1](#) at page 82 which were heavily affected by sluice discharge.

There is clearly some ambiguity in the correction. Another threshold for the difference with the Delfzijl low tide level would lead to less or more corrected periods and somewhat different levels. The scope of the correction can be illustrated by

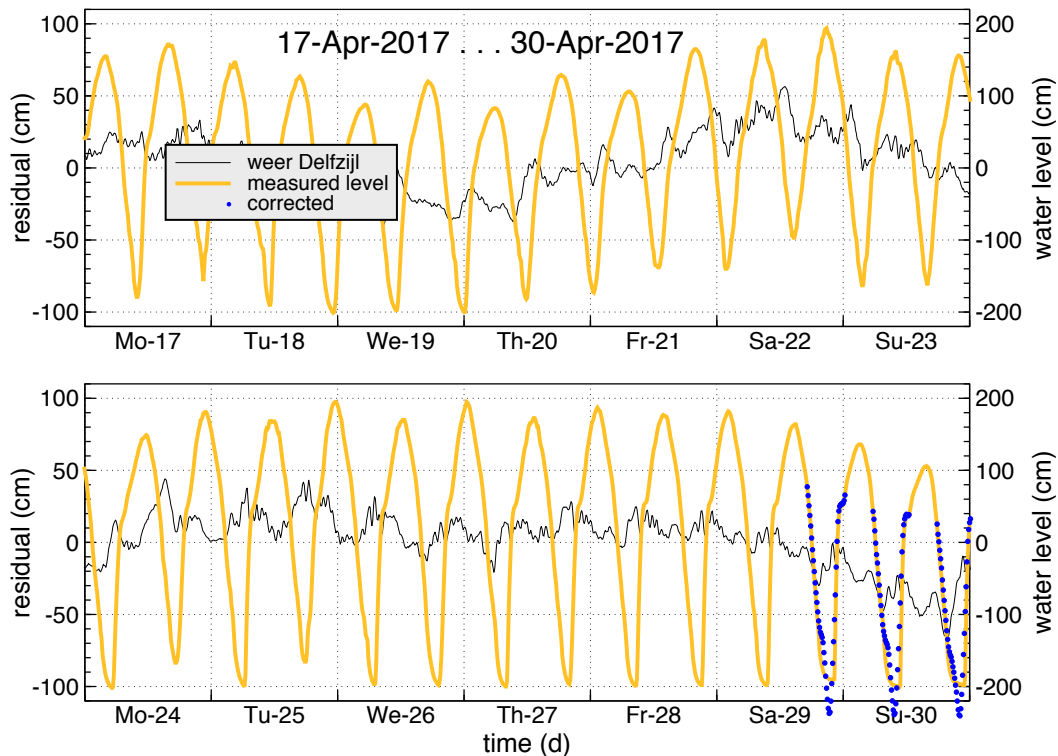


Figure A.3. Low tide periods affected by sluice discharge are corrected. These weeks in April 2017 did not require much correction.

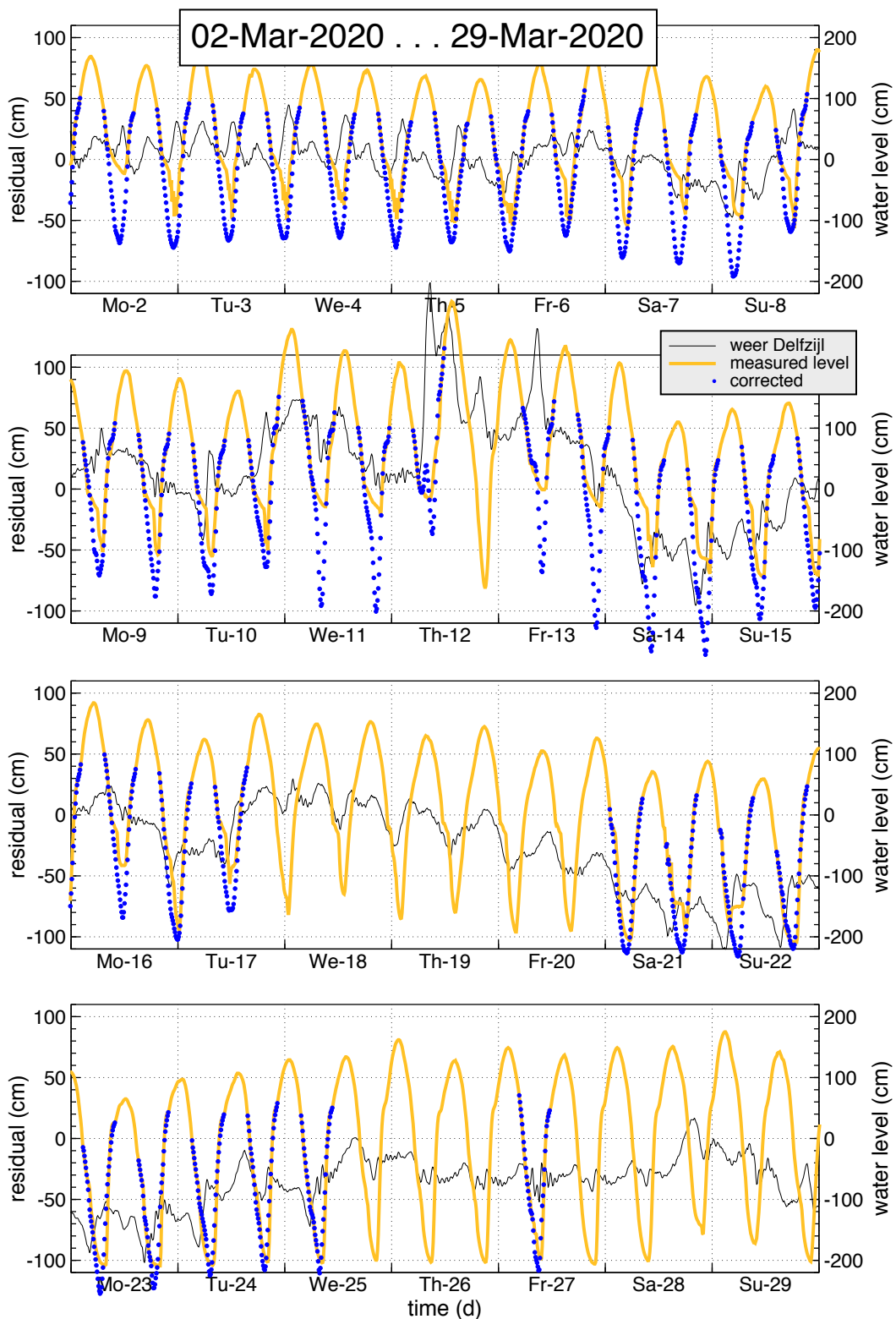


Figure A.4. Low tide periods affected by sluice discharge are corrected. The levels around high tide are always the measured levels at Nieuwstatenzijl. They are never changed (the yellow tops). A period of about 4.5 hours around an affected low tide is replaced by the sum of the Nieuwstatenzijl astronomical tide and the effect of wind and weather for Delfzijl. In between the unchanged high tide levels and the corrected low tide levels a smooth transition is calculated. This transition hours are shown blue as well.

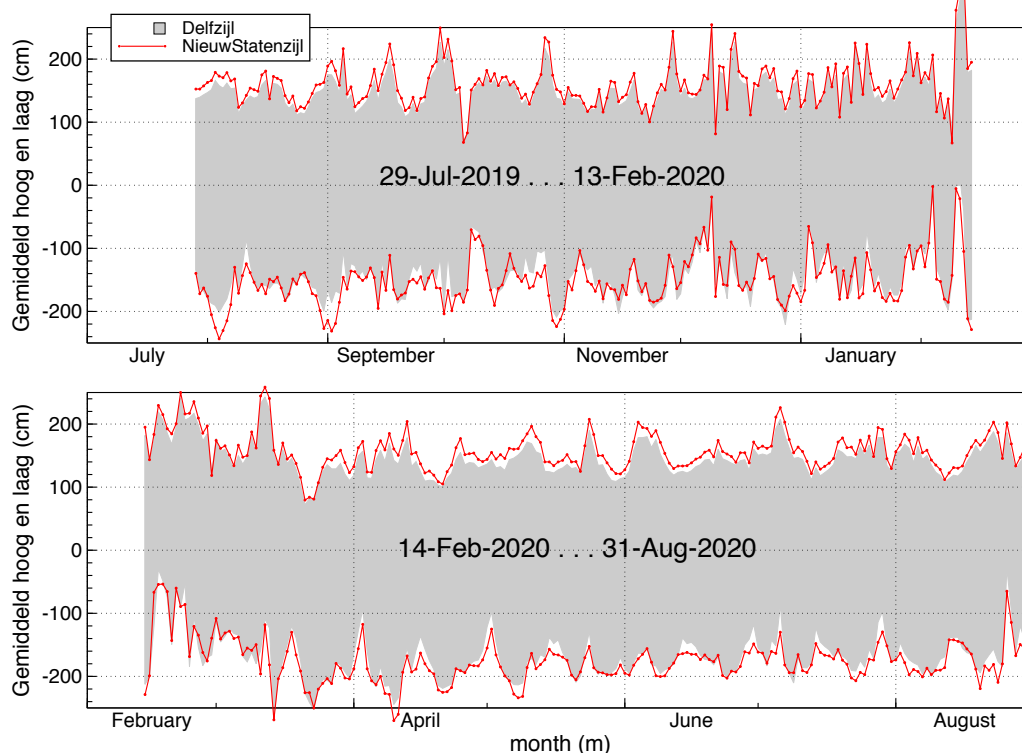


Figure A.5. High tide and corrected low tide levels for Delfzijl (grey area) and Nieuwstatenzijl (red lines) for 400 days in 2019 and 2020. For each day the average of the two tides has been plotted (sometimes one tide). The plot may be compared with [Figure A.2](#) at [page 83](#) for the uncorrected time series.

plotting once more [Figure A.2](#) at [page 83](#), now using the corrected time series. [Figure A.5](#) shows the result. The corrected low tide levels now closely follow the Delfzijl levels, similar to the high tide levels (cf. [Figure A.2](#) at [page 83](#)).

A.4 Average high and low tide levels

[Table A.1](#) shows the average and median levels at high and low tide calculated for the period 2013–2018. Note that *measured* high tide levels at Nieuwstatenzijl are about 13 cm above the levels at Delfzijl. This tide amplification in the estuary would then lead to low tide levels at Nieuwstatenzijl below the Delfzijl levels. This is *not* the case. Measured low tide at Nieuwstatenzijl is about 15–20 cm *above* the

Table A.1. Average high and low tide levels for Delfzijl and Nieuwstatenzijl calculated for the period 2013–2018. The correction for sluice discharge at Nieuwstatenzijl changes the low tide levels for that station.

	average		median	
	High	Low	High	Low
Delfzijl measured	142.2	-166.0	141.0	-171.0
Nieuwstatenzijl measured	155.4	-145.5	154.0	-157.0
Nieuwstatenzijl corrected	155.4	-170.9	154.0	-176.6

Delfzijl level, as a result of the sluice discharge. The corrected levels are indeed somewhat below the Delfzijl low tide levels. The difference is about 5 cm, less than the high tide difference, but in the expected direction.

A Wadden Sea amplitude map?

InterTides provides an adapted interpolation method in case maps are available of the (relative) tidal amplitude and the average sea level (see [section 5.8](#)). For the Wadden Sea such maps could be derived from the fluid flow simulations by [Nauw et al. \(2017\)](#). Unfortunately, the simulations suffer from a systematic error at low tide, which is explained in this chapter.

B.1 Introduction

The large scale difference in tidal amplitude from west to east will be captured sufficiently well by the 15 tidal stations used, but local differences like those in the tidal inlets could be accounted for by using maps of the tidal amplitude and the mean sea level. This would probably lead to more accurate values for the Wadden Sea than interpolation alone. The amplitude map needs to be a map of the relative amplitude only, since only ratios of amplitudes affect the final result of the equations above.

B.2 Simulated tide

[Nauw et al. \(2017\)](#) simulated the water level in the Wadden Sea for the period 2009–2011. The results were made available in the form of a harmonic analysis with 140 constituents for each of the 201584 points of the triangulation used in the numerical solution.

For each of the 201584 points the water levels have been reconstructed from their harmonic components, low tide and high tide levels have been determined and an average low tide level and an average high tide level have been calculated. From these averages maps have been made.

Figure [B.1](#) shows the map of the average high tide level. The map shows the expected increase from west to east, but there are also local differences south of the barrier islands. These are the differences that might improve the interpolated levels calculated by InterTides.

Figure [B.2](#) shows the map of the average low tide level. This map is more patchy than the map for the high tide level. The reason is the much larger role of the mudflats at lower water levels. Some observations:

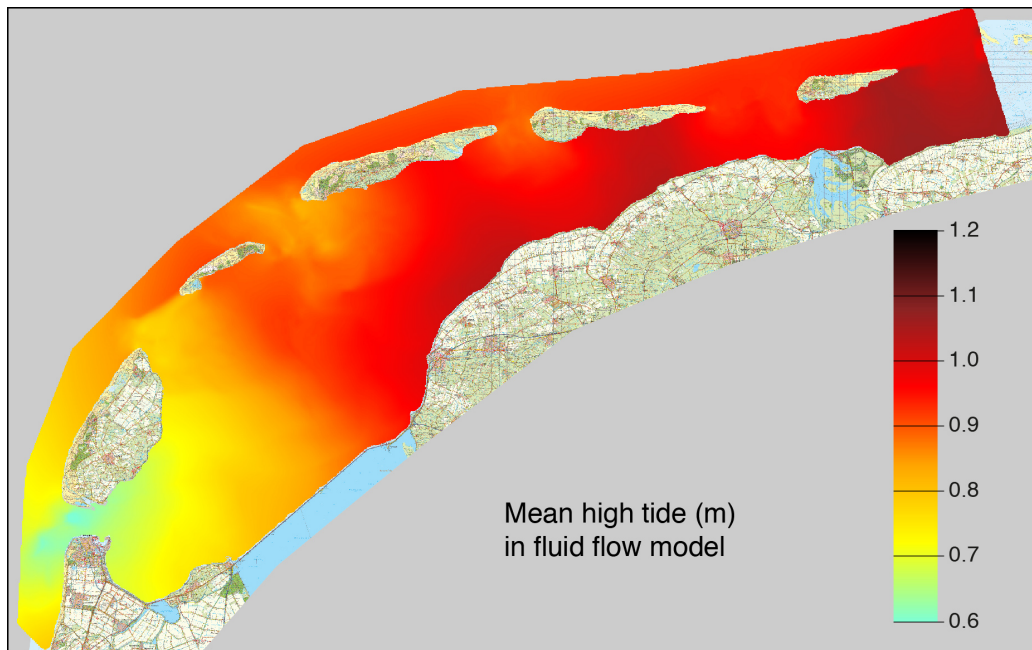


Figure B.1. Map of the average high tide level in 2009–2011 calculated from the simulations by [Nauw et al. \(2017\)](#).

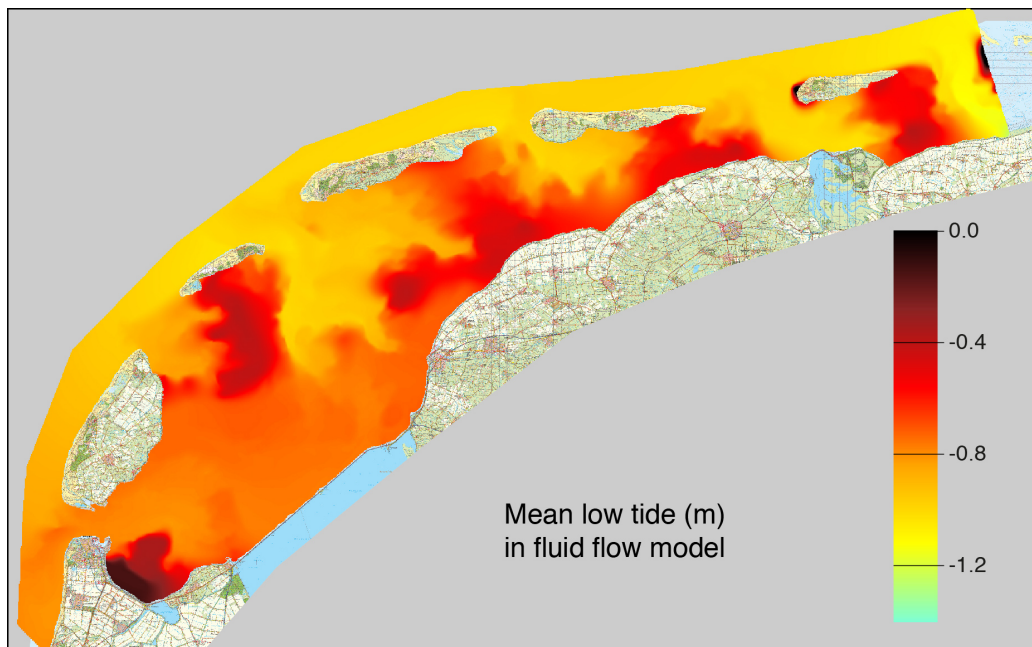


Figure B.2. Map of the average low tide level in 2009–2011 calculated from the simulations by [Nauw et al. \(2017\)](#).

- Along the North Sea coast there is a gradual decrease from west to east. This corresponds to measured levels at the tidal stations.
- Behind the larger islands two tidal waves meet, the flow velocities are relatively small, there are few gullies, and the extensive mudflats are relatively high. The simulated low tide levels behind Vlieland, Terschelling, Ameland and Schiermonnikoog are around 0.6 m below NAP.
- None of the tidal stations of Rijkswaterstaat is on a location for which these low tide levels can be verified directly.

An average low tide level of 0.6 m below NAP seems quite high, however. Therefore some plots have been made in which the simulated levels are compared with measured ones. A week has been selected (week 32 in 2010) in which the astronomical tide and the measured levels are close, so without large effects of wind and atmospheric pressure. Figure B.3 shows curves for the stations Den Helder, Nes and Schiermonnikoog.

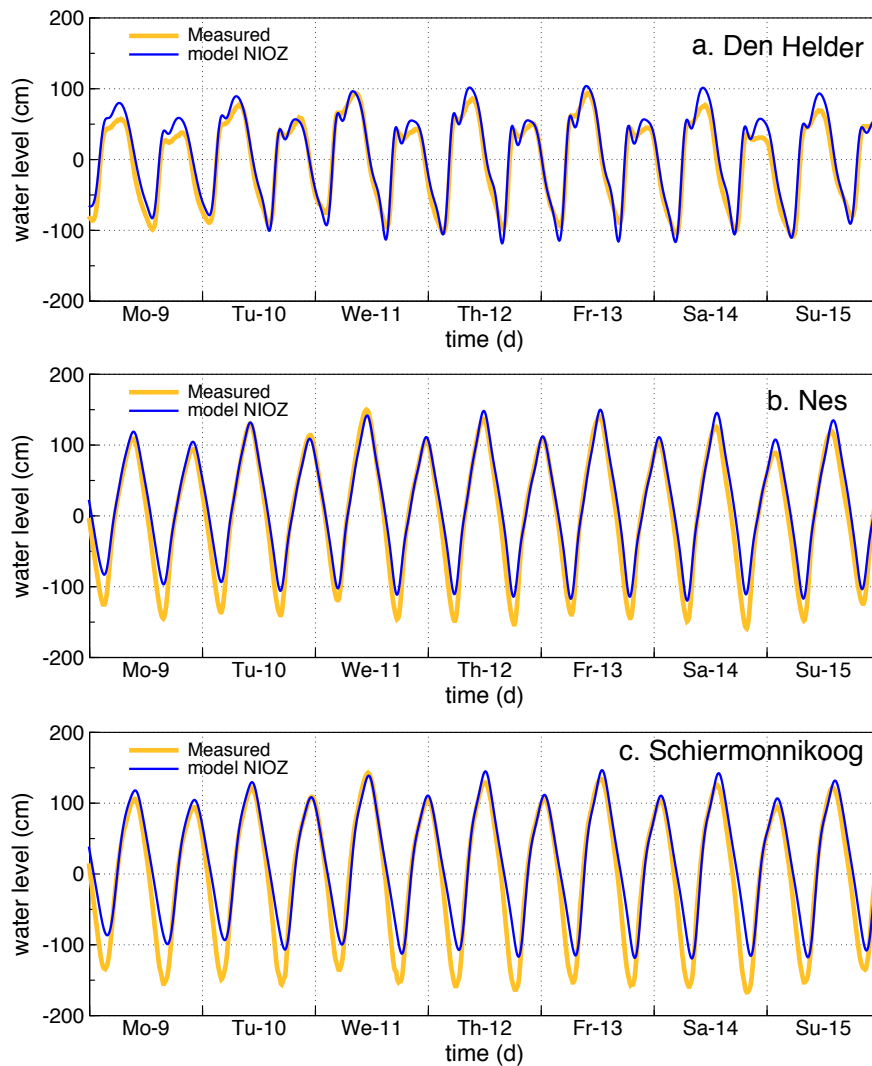


Figure B.3. Tidal curves for week 32 of 2010 (august 9 to 15). The measured values are those from the Rijkswaterstaat tidal stations. The values for "model NIOZ" were calculated from the simulations by [Nauw et al. \(2017\)](#).

In Figure B.3a for Den Helder the differences between the simulated and measured curves are small. In Figure B.3b for Nes en Figure B.3c for Schiermonnikoog, however, there is a *systematic* difference between the simulated and measured low tide level. For the high tide levels there is agreement.

Hence, for the stations Nes and Schiermonnikoog the simulated low tide levels are too high. The positions of these stations on the low tide level map in Figure B.2 is "in the yellow area", with a low tide level of about 1 m below NAP. East these stations, the low tide level on Figure B.2 increases to about 0.6 m below NAP and the question arises whether or not this is realistic. In order to check that we made use of measurements near the ferry terminal of Holwerd.

The problem with station Holwerd is that we do not have simulated water levels for the period in which measurements are available. Therefore, in Figure B.4 we first made a comparison between measured levels and levels calculated by InterTides from the measurements at Lauwersoog, Nes and Harlingen. The two curves are in good agreement. The measured low tide levels are slightly lower than the interpolated values, but if we keep that in mind, the InterTides levels can be used as an approximation for station Holwerd.

Finally a comparison has been made between InterTides and the levels in the simulation by Nauw et al. (2017), again for week 32 of 2010. Figure B.5 shows the result. There is a striking difference in low tide levels, similar to the differences in Figure B.3 for Nes and Schiermonnikoog, but much larger. The shape of the simulated (blue) curve suggests that, in the simulation, the water slowly flows down from the large mudflats east of the station until the new tide comes in.

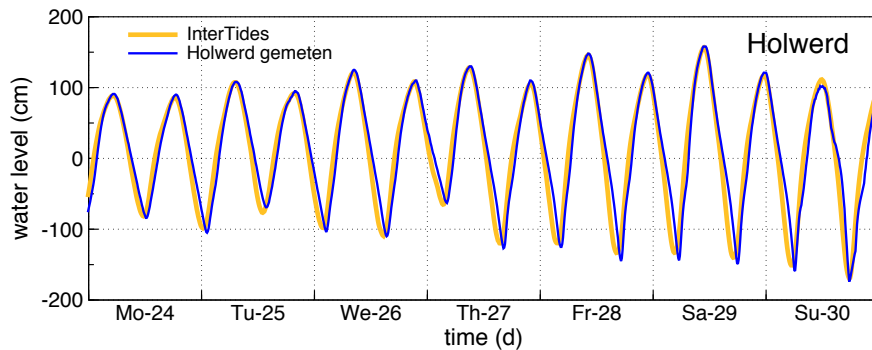


Figure B.4. Measured water levels at Holwerd for august 24–30 in 1992 together with interpolation results of InterTides (between Lauwersoog, Nes and Harlingen).

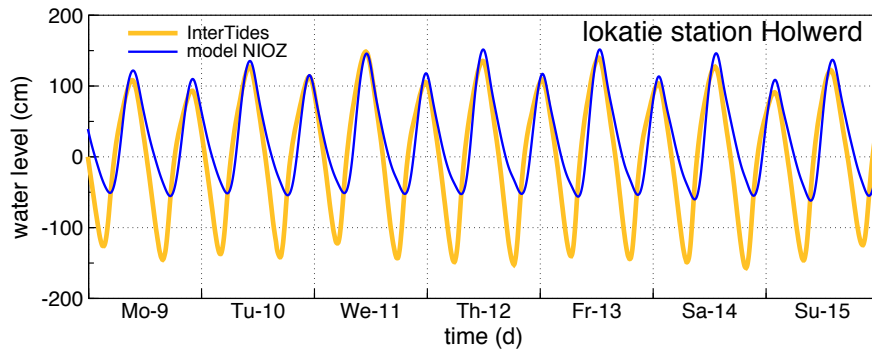


Figure B.5. Simulated levels for the location of station Holwerd for august 9–15 in 2010 (Nauw et al., 2017), together with results of InterTides calculated by interpolation between Lauwersoog, Nes and Harlingen.

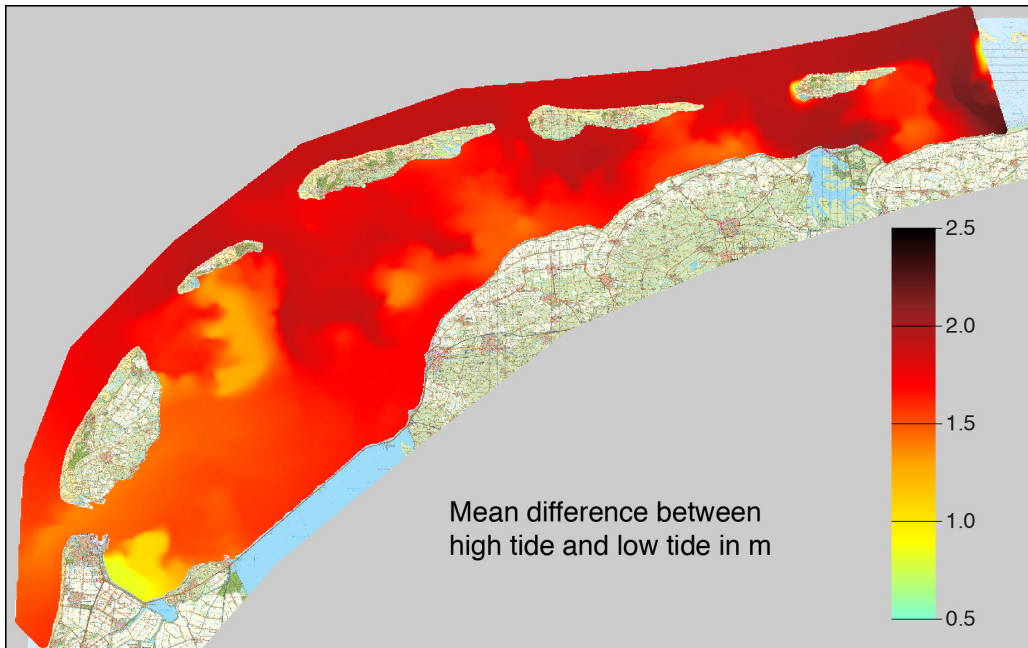


Figure B.6. Amplitude map calculated as the difference between the average high tide level (Figure B.1) and the average low tide level (Figure B.2).

B.3 The amplitude map

Figure B.6 shows the amplitude map calculated as the difference between average high tide and low tide levels.

B.4 Conclusion

The high simulated levels at low tide for the watersheds behind the barrier islands cannot be directly verified since there are no measurements available for such areas.

During the nineties, however, the water level at the ferry terminal Holwerd was measured for a few years. These levels are in good agreement with InterTides' interpolations between the stations Lauwersoog, Nes and Harlingen. Hence, InterTides is consistent with the older measurements.

There is a clear contrast, however, between the low tide levels simulated by [Nauw et al. \(2017\)](#) and the InterTides levels for the simulated period. From the shape of the simulated curves we conclude that the deviation is caused by an error in the simulation due to underestimating the flow of water from the mudflats into the gullies.

Therefore, the calculated amplitude map has not been installed with InterTides. Such a map aims to correct the interpolated levels for local differences in tidal amplitude associated with mudflats and the channels between the islands. The available map fails at the watersheds behind the islands and will therefore not be a reliable improvement.

GHW GLW kaarten voor Rijkswaterstaat CIV

Deze appendix bevat een toelichting op de aan Rijkswaterstaat geleverde GHW kaarten van gemiddeld hoogwater en GLW kaarten van gemiddeld laagwater. De kaarten zijn berekend voor de Waddenzee, de Noordzeekustzone, de Oosterschelde, Westerschelde en voor de combinatie van Vlakte van de Raan en Voordelta. Voor methodische details wordt verwezen naar de documentatie elders in dit rapport.

C.1 InterTides

InterTides berekend waterstanden door interpolatie van gemeten waterstanden tussen getijdestations. Het belangrijkste is de lineaire interpolatie binnen een driehoek van getijdestations ([paragraaf 5.2](#)). Daarmee kan het beschouwde getijdegebied echter niet helemaal worden afgedekt zodat ook langs lijnen tussen twee getijdestations wordt geïnterpoleerd ([paragraaf 5.4](#)).

De gebruikte interpolatieschema's van driehoeken, lijnstukken en hier en daar ook vierhoeken ([paragraaf 5.3](#)) kunnen worden bekeken in [Hoofdstuk 6](#).

Nu is het op de verschillende getijdestations niet op hetzelfde moment hoogwater en laagwater, er zijn faseverschillen. Het is dan "niet eerlijk" om direct tussen twee gemeten waterstanden te interpoleren. Bij de interpolatie wordt daarom voor deze faseverschillen gecorrigeerd ([paragraaf 5.5](#)).

In de Oosterschelde en Westerschelde hebben we verder te maken met een landinwaards oplopende getijslag. De interpolatie wordt in die regio's verbeterd met behulp van een kaart van de amplitude van het getij ([paragraaf 5.8](#)).

C.2 De geleverde kaarten

Alle GHW en GLW kaarten bestrijken een periode van 3 kalenderjaren. In [Tabel C.1](#) zijn de gebruikte perioden T0 en T1 te vinden. Voor elke gridcel van de kaart zijn alle waterstanden in T0 of T1 berekend. Vervolgens zijn daaruit de hoog- en laagwaterstanden bepaald waarvan dan het gemiddelde op de GHW respectievelijk GLW kaart is te vinden. Alle kaarten zijn geleverd in ASCII grid format dat kan worden ingelezen in elk GIS.

Tabel C.1. Geleverde kaarten. De kaarten zijn berekend voor de gemeten waterstanden in de periodes T0 en T1. De periodes T0 en T1 zijn aangegeven als het eerste en het laatste van drie kalenderjaren. De waterstanden zijn berekend in cm ten opzichte van NAP voor het midden van de gridcellen van 20×20 m. De linker onder hoek van elke gridcel heeft een even tental als X en Y coördinaat (0, 20, 40, 60, 80, 100, 120, 140, 160, ...).

Gebied	Periode		Grid (m)	Stelsel
	T0	T1		
Waddenzee	2008–2010	2015–2017	20×20	EPSG:28992
Noordzeekustzone	2004–2006	2015–2017	20×20	EPSG:28992
Oosterschelde	2006–2008	2012–2014	20×20	EPSG:28992
Westerschelde	2008–2010	2015–2017	20×20	EPSG:28992
Vlakte vd R + Voordelta	2008–2010	2015–2017	20×20	EPSG:28992

C.3 Gebiedsgrenzen

InterTides is geconfigureerd voor de "regio's" Waddengebied (Waddenzee + Noordzeekustzone), Oosterschelde, Westerschelde en de Zeeuwse kustzone (Vlakte van de Raan en Voordelta). Gebiedsgrenzen vallen dus vrijwel samen met die van de gelijknamige Natura 2000 gebieden, maar er zijn verschillen:

- Landsgrenzen worden door InterTides genegeerd en in plaats daarvan worden de grenzen van het intergetijdegebied gebruikt zoals dijken en duinen. Het betreft hier delen van het Eems-Dollard gebied, het Zwin en het uiterste oosten van de Westerschelde.
- Hetzelfde geldt voor havens en sommige stranden die buiten de Natura 2000 gebieden liggen, maar wel in het intergetijdegebied.
- Inlagen of kleine polders die slechts via een duiker, sluis, vistrap of een andere smalle doorgang verbonden zijn met de rest van het gebied liggen buiten de "regiokaart" van InterTides. De waterstanden op dit soort plekken worden sterk beïnvloed door de beperkte aanvoer en afvoer en kunnen niet fatsoenlijk met interpolatie worden geschat.
- InterTides rekent ook niet voor hoge kwelders en duinvalleien. De waterstanden op zulke plekken worden in hoge mate bepaald door de lokale topografie, oeverwallen van slenken en drempels, door de weerstand van de vegetatie en door lokale effecten van harde wind.

Hieronder nog wat details met betrekking tot de berekende kaarten.

C.3.1 Waddenzee

De T0 en T1 kaarten voor de Waddenzee zijn berekend met de Natura 2000 Waddenzeekaart als "subarea" van de InterTides regio Waddengebied. Dat betekent dat de geleverde kaart ophoudt bij de grenzen van het Natura 2000 gebied, maar ook dat hoge kwelders en duinvalleien zullen ontbreken omdat InterTides daar niet voor rekent.

C.3.2 Noordzeekustzone

De T0 en T1 kaarten voor de Noordzeekustzone zijn berekend met de Natura 2000 kaart van de Noordzeekustzone als "subarea" van de InterTides regio Waddengebied. Dat betekent dat de geleverde kaart ophoudt bij de grenzen van het Natura 2000 gebied, maar ook dat hoge kwelders en duinvalleien zullen ontbreken omdat InterTides daar niet voor rekent.

C.3.3 Oosterschelde

De T0 en T1 kaarten voor de Oosterschelde zijn berekend voor het intergetijdegebied achter de stormvloedkering. Zoals in [paragraaf C.3](#) aangegeven zullen enkele inlagen ontbreken die wel bij het Natura 2000 gebied horen. Dat geldt ook voor de Rammegors die met een nauwe doorgang verbonden is met de rest van het gebied.

C.3.4 Westerschelde

Voor dit gebied geldt hetzelfde als voor de Oosterschelde. Uitbreidingen ten opzichte van het Natura 2000 gebied zijn het Belgische deel van het Zwin en enkele havens en stranden. De Hedwigepolder is (nog) niet toegevoegd aan de InterTides regio. Als alles buiten het Natura 2000 gebied ongewenst is dan moet de geleverde kaart begrensd worden.

C.3.5 Vlake van de Raan en Voordelta

Dit gebied is de combinatie van de Natura 2000 kaarten voor de Voordelta en de Vlake van de Raan.

C.4 Nauwkeurigheid

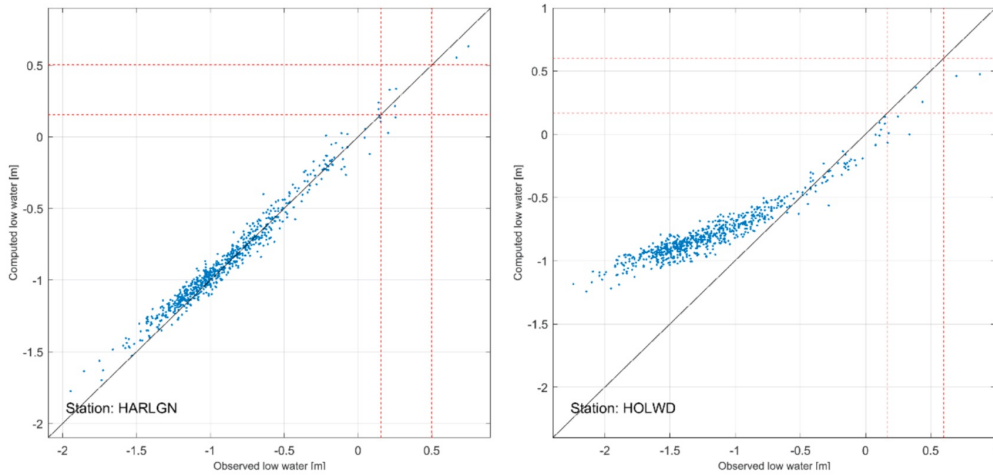
De interpolatie methode brengt met zich mee dat ter plaatse van de getijdestations InterTides de gemeten waterstanden zal reproduceren. Ook in de nabije omgeving van de getijdestations zullen de afwijkingen klein zijn.

Hoe groot de afwijkingen worden binnen de interpolatie driehoeken zal afhangen van de grootte en de ligging van de driehoeken. Er zijn geen aanvullende metingen gedaan om dit voor verschillende locaties in de Waddenzee uit te zoeken.

C.4.1 Station Holwerd

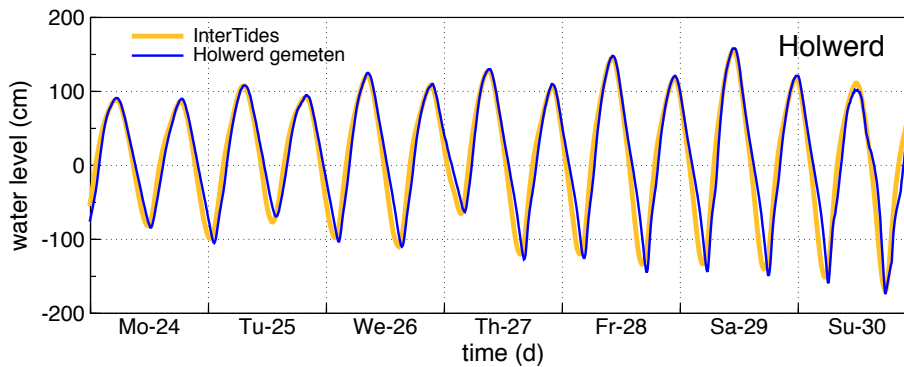
Er is één Waddenzee station, station Holwerd, waarvoor tijdreeksen beschikbaar zijn en dat door InterTides niet gebruikt wordt omdat er tussen 1999 en 2012 niet gemeten is. Op de plek van dit station werkt InterTides met de driehoek Harlingen-Nes-Lauwersoog die zich uitstrekt over verschillende wantijen.

Het getijdestation Holwerd ligt aan het eind van een smalle geul en dicht tegen een grote wadplaat, het wantij van Ameland. Van dergelijke plekken is bekend dat hydrodynamische modellen er grote afwijkingen vertonen omdat het water "op de wadplaten blijft kleven", dus relatief langzaam afstroomt en tijdens laagwater de geul blijft voeden. [Smits \(2021, Paragraaf 2.1\)](#) beschrijft dit verschijnsel en

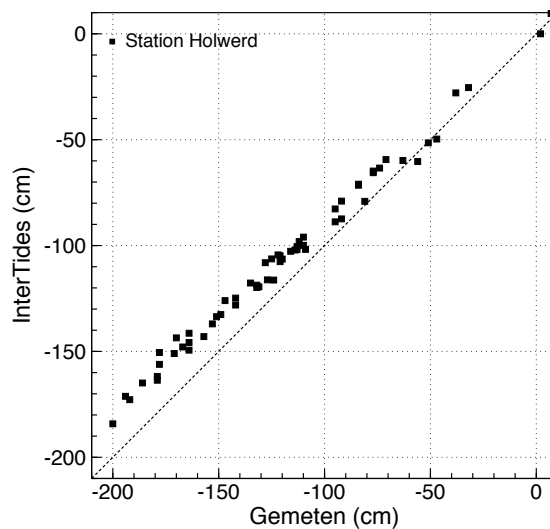


Figuur 2.2 Vergelijking van gemeten (x-as) en gemodelleerde (y-as) laagwaterstanden op MWTL-stations Harlingen (linker paneel) en Holwerd (rechter paneel).

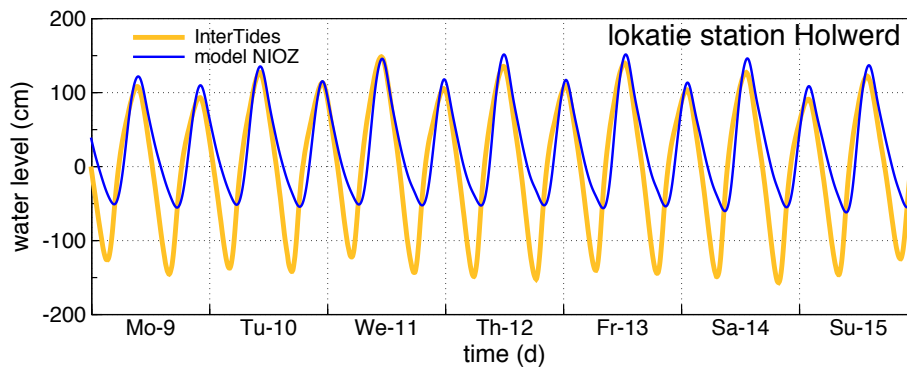
Figuur C.1. Gemeten en gesimuleerde laagwaterstanden voor Harlingen en Holwerd uit Smits (2021).



Figuur C.2. Measured water levels at Holwerd for August 24–30 in 1992 together with interpolation results of InterTides (between Lauwersoog, Nes and Harlingen).



Figuur C.3. Gemeten en met InterTides berekende laagwaterstanden voor januari 2021.



Figuur C.4. Waterstanden bij station Holwerd voor 9–15 augustus 2010, berekend uit de door [Nauw et al. \(2017\)](#) gesimuleerde waterstanden. De gesimuleerde waterstanden werden ter beschikking gesteld door Nauw (pers.comm.) in de vorm van 140 harmonische componenten voor elke van de 201584 punten van de triangulatie uit de numerieke oplossing. De InterTides curve is berekend met interpolatie in de driehoek Harlingen-Nes-Lauwersoog.

geeft grafieken met berekende en gesimuleerde laagwaterstanden voor respectievelijk Harlingen en Holwerd (gereproduceerd in [Figuur C.1](#)). Voor de lage laagwaterstanden is de afwijking ongeveer 80 cm.

[Figuur C.2](#) laat een week waterstanden zien voor station Holwerd, gemeten en berekend met InterTides. De InterTides laagwaterstanden zijn wat te hoog en wat te vroeg. [Figuur C.3](#) laat recentere laagwaterstanden zien, voor de maand januari 2021. De verschillen lijken wat groter te zijn dan in de 90-er jaren maar de afwijking bij laagste laagwaters blijft beperkt tot ongeveer 20 cm.

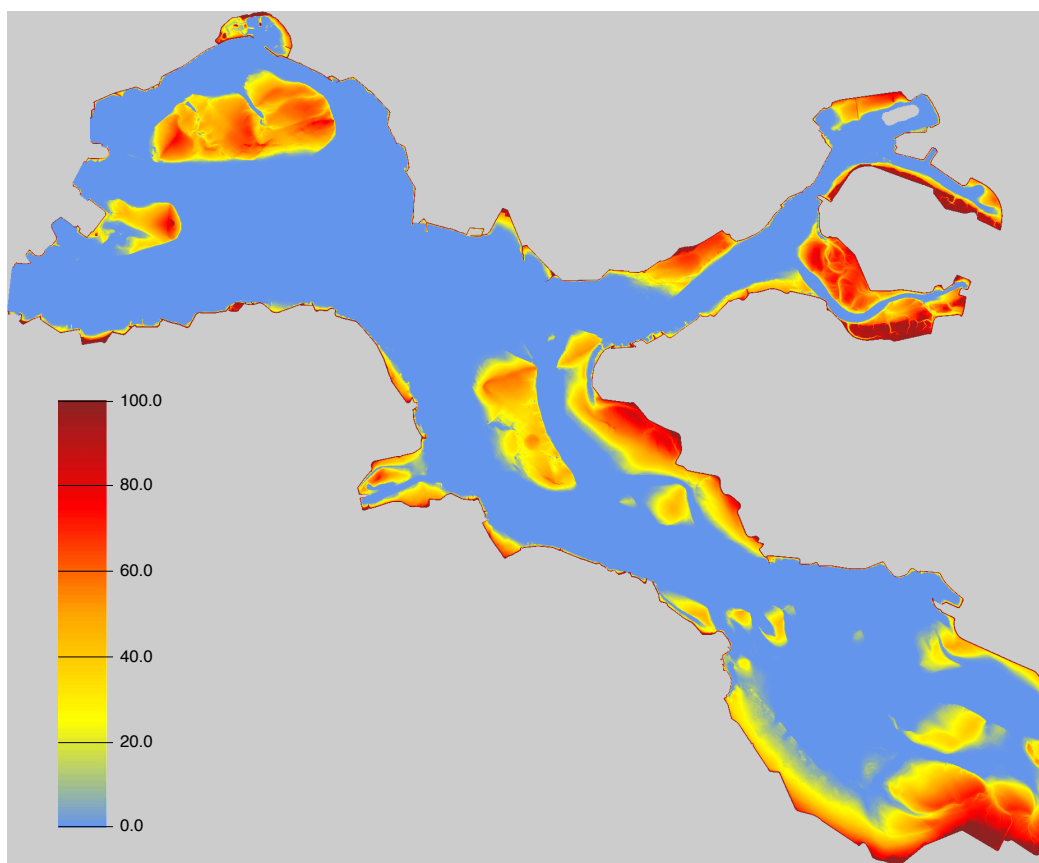
Voor de duidelijkheid wordt hier nog vermeld dat ook in de simulaties van [Nauw et al. \(2017\)](#) de grote afwijkingen bij Holwerd aanwezig zijn. De gesimuleerde getijdecures in [Figuur C.4](#) laten een geleidelijke afname van de waterstand tijdens laagwater zien en dat is precies wat door het "kleven op de plaat" wordt veroorzaakt. [Nauw et al. \(2017\)](#) hebben ten onrechte de door hen berekende RMSE waarden (root mean square error) als toevallige fouten geïnterpreteerd.

C.4.2 Zeegaten

Het Noordzee getij en het Waddenzee getij verschillen van elkaar. Interpolatie over de eilanden heen is daarom onwenselijk. Daarom worden in de InterTides configuratie voor het "Waddengebied" (de combinatie van Waddenzee en Noordzeekustzone) in de zeegaten overgangszones gelegd met behulp van virtuele getijdestations (zie ook [paragraaf 6.5](#)).

Dat de waterstanden in de Waddenzee ergens overgaan naar die op de Noordzee is duidelijk. Maar waar dat precies gebeurt kan met een interpolatie tool uiteraard niet worden vastgesteld. De waterstanden in en vlakbij de zeegaten moeten daarom met enige voorzichtigheid gebruikt worden.

Op de oostpunt van de Hon zijn door Sovon metingen gedaan aan stormvloed en in verband met onderzoek aan de overstroming van vogelnesten. De door InterTides berekende hoogwaterstanden zijn 10 à 20 cm te laag en lijken teveel onder invloed van de Noordzee te staan. Omdat het hier alleen stormvloed betreft is in InterTides niets aangepast. Metingen onder gewone omstandigheden in het Pinkegat en/of het Zoutkamperlaag zouden hier uitsluitsel kunnen geven.



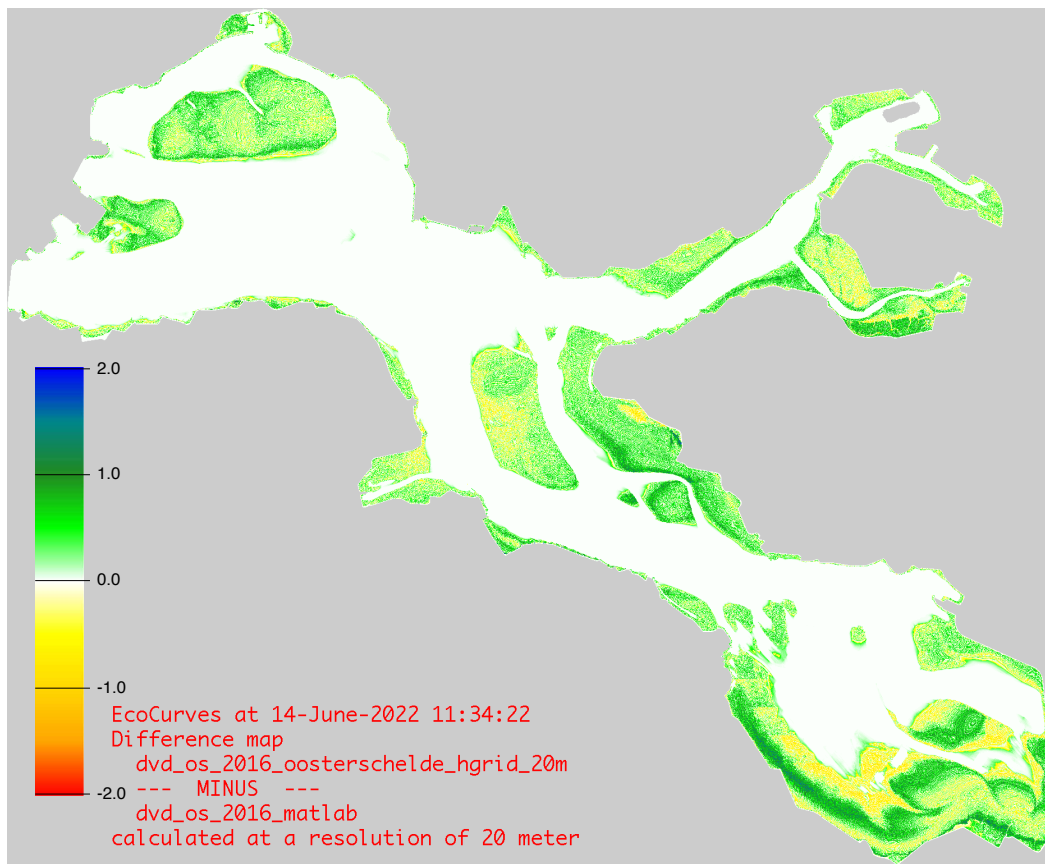
Figuur C.5. InterTides droogvalduur kaart Oosterschelde voor de periode 2013–2016 en met de bodemkaart van 2016. De droogvalduur is berekend in als een percentage van de tijd tussen 0 en 100.

C.5 Vergelijking tussen berekende droogvalduren

We vergelijken een droogvalduurkaart berekend met InterTides met een droogvalduurkaart berekend met Matlab. Beide kaarten zijn berekend voor de periode 2013–2016 voor een bodemkaart van 2016.

Van de matlab kaart (Edwin Paree, pers.comm.) zijn verder geen specificaties ontvangen.

In [Figuur C.5](#) staat de InterTides kaart afgebeeld. In [Figuur C.6](#) de verschilkaart. De verschillen blijven beperkt tot ongeveer 1% droogvalduur. Het groen-geel gestippelde karakter van enkele oppervlakken in [Figuur C.6](#) ontstaat doordat de droogvalduren op de matlab kaart zijn afgerond op gehele percentages. Dat levert op sommige plekken een verschilkaart op die geheel of gedeeltelijk bestaat uit afrondingsfouten.



Figuur C.6. Verschil tussen de InterTides droogvalduur kaart van de Oosterschelde en een kaart berekend met Matlab (Edwin Pree, pers.comm.). Het verschil is een absoluut percentage droogvalduur (een fractie van de tijd en niet een fractie van de droogvalduur).

