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ABSTRACT:

In the framework of the quality enhancement of the hydraulic boundary conditions for sea defences, a large-scale measurement campaign in the Wadden Sea in 2003 is foreseen. The objective of this campaign is to measure the relevant physical quantities which will help in improving the wave modelling simulations in a tidal basin such as the Wadden Sea with the ultimate aim of predicting the design wave heights during extreme events along the sea dikes of the Wadden Sea.

One of the prerequisites for the campaign is a detailed measurement plan. In this plan, the exact locations of the measurement stations and the type of measurement instruments need to be defined, as well as the data format, the data post-processing and reporting. In order to write this plan the questions what, where and how should be measured need to be addressed.

In this report the "what" question has been answered with the necessary input parameters in a spectral wave model such as SWAN and the knowledge gaps in the physics of such models in mind. The physical mechanisms which are important in tidal inlet systems have been described. Furthermore, the meteorological, astronomical, bathymetric and hydrodynamical quantities which should be measured are described per geographical subdivisions of a tidal inlet system. Finally, the accuracy with which measurements are to be performed is discussed.

Once the question "Where to measure in the Wadden Sea" has been answered, it is useful to study for the particular locations the present performance of a wave model like SWAN, and to study the relative importance of swell, currents, triads, diffraction, depth-induced breaking, reflection and bottom friction for the particular locations. This could support choices which have to be made concerning the priorities of processes to be investigated.

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1 Introduction

In the framework of the quality enhancement of the hydraulic boundary conditions for sea defences, a large-scale measurement campaign in the Wadden Sea in 2003 is foreseen. The objective of this campaign is to measure the relevant physical quantities which will help in improving the wave modelling simulations in a tidal basin such as the Wadden Sea with the ultimate aim of predicting the design wave heights during extreme events along the sea dikes of the Wadden Sea.

One of the prerequisites for the campaign is a detailed measurement plan. In this plan, the exact locations of the measurement stations and the type of measurement instruments need to be defined, as well as the data format, the data post-processing and reporting. In order to write this plan the following three questions need to be answered first:

1. What physical quantities need to be measured?
2. Where should the measurement stations be located?
3. How, i.e. by what method, should these quantities be measured?

In this report the first question (the "what" question) is addressed. This question will be answered with the necessary input parameters in a spectral wave model such as SWAN and the knowledge gaps in the physics of such models in mind. The "what" question cannot be answered while ignoring the other two questions, which means that recommendations for those modules will also be given.

The report is composed as follows: in Chapter 2 the physical mechanisms are described, which are important in tidal inlet systems but which are not modelled satisfactorily. In Chapter 3 the meteorological, astronomical, bathymetric and hydrodynamical quantities which should be measured are described per geographical subdivisions of a tidal inlet system. In Chapter 4 the accuracy with which measurements are to be performed is discussed.

2 Relevant physical processes in the Wadden Sea

The ultimate goal of the foreseen measurement campaign is to improve the quality of the determined hydraulic boundary conditions near the sea defences in the Wadden Sea. The hydraulic boundary conditions along every sea defence in the Wadden Sea can be obtained in a number of ways. First of all, the wave conditions can be measured at a distance of 50m from the dike, every 100m. Extrapolation of these results towards 1/4000yr conditions will give accurate measures for the hydraulic boundary conditions. Taking into account the limitations for setting up an extensive measuring campaign in terms of measurement equipment and budget, this is not a serious option. Secondly, numerical models can be used to determine the wave conditions in the entire domain of interest. Measurements of wave conditions, wind, currents and water levels are still required for purposes of calibration, validation and verification. However, the number of measurement points is significantly smaller than in the first option.

For obtaining the hydraulic boundary conditions from numerical model simulations, there are several options. The choice is between spectral wave models, time-domain models or a combination of both. The choice depends on the required accuracy of the wave conditions near the dikes, the available budget and time for obtaining these conditions, the available data, etc. Also possible developments in the future have to be taken into account. Not only the applied the hardware (PC, workstations, network) will improve, but also the models themselves. New insight into physics will result in more reliable wave predictions. Furthermore, the model may speed up significantly by improving newly developed numerical techniques.

Nowadays it is common practise to use spectral wave models, such as SWAN, to predict the wave field in the entire Wadden Sea, including the last 50 m in front of the sea defences. Spectral wave models can rather accurately predict the wave motion inside the tidal basin. However, in very shallow area, such as tidal flats and surf zones, the predictive ability decreases. Due to lack of knowledge in modelling e.g. non-linear interactions in shallow water the predicted wave conditions near the sea defences are not expected to be accurate. Improvement of these predictions can be achieved e.g. by a measurement campaign in order to gain insight in the physical processes which are poorly understood. Successively, a better understanding should lead to a better ability to model the physical processes.

The spectral models describe the wave motion in a statistical way. The wave parameters such as significant wave height and wave period are averaged measures, which are used for determining the forces on the sea defences. If more detail is required, such as overtopping by individual waves, spectral wave modelling cannot be used.

Alternatively, time-domain wave prediction models can be used. Nowadays, Boussinesq-type wave models are appropriate to determine the wave conditions in the rather shallow tidal basin of the Wadden Sea. In the future (say within 10 years from now) non-hydrostatic flow models may also form an alternative. A disadvantage is that time-domain models require significantly more computational time compared to spectral wave models for computing the wave motion in the same domain. Therefore, time domain models are restricted to smaller domains. On the other hand, we are interested in the wave conditions near the sea defences, not necessarily in the entire Wadden Sea. If proper 'offshore' boundary conditions are available, time domain models can be used to determine the hydraulic boundary conditions. The offshore boundary for the time-domain model is located inside the tidal basin of the Wadden Sea, but far away from the dikes. The boundary conditions can be obtained from measurements. The locations of the measurement sites should not be in areas with rapid spatial and temporal changes in the wave field; E.g. the bathymetry must not vary rapidly.

The pros and cons of spectral and time domain models can be combined. Time domain models provide accurate wave predictions in the region near the sea defences, whereas the wave field in the rest of the tidal basin can be obtained with a spectral model. Consequently, by coupling the two models reliable results might be predicted for the entire Wadden Sea. Realisation of the coupling is relatively simple. Spectral information, obtained from the spectral wave model, at the 'offshore' boundary of the time domain model must be transformed to time series, which are input for the time domain model.

In this study we focus on the numerical modelling of the hydraulic boundary conditions by applying spectral wave modes. The wave conditions near these sea defences depend on the incoming wave field through the tidal inlets, the wave processes in the Wadden Sea and the propagation of the waves towards the dikes. Three trajectories can be distinguished to characterise wave propagation and related processes in the Wadden Sea:

- From the tidal inlet around the heads of the Wadden Islands towards the sea defence of these islands.
- From the tidal inlet through the tidal channels towards the dikes of the main land.
- From the tidal inlet over the tidal flats towards the dikes of the main land.

By following the waves along these trajectories a number of physical processes are encountered:

- Propagation of swell into tidal basin.
- The effect of currents on the wave motion in tidal channels.
- Non-linear wave interactions in shallow areas (triad wave interaction).
- Dissipation of wave energy due to bottom friction in shallow areas.
- Diffraction of waves around the heads of the Wadden islands.
- Reflection on dikes.
- Depth-induced wave breaking on tidal flats and near sea defences.

For all of these processes we will describe the deficiencies that are encountered of modelling them in wave prediction models, what needs to be measured for a proper calibration and validation of these models and along which trajectories measurements have to be carried out for verification.

2.1 Swell and wind waves

Under extreme storm conditions typical low-frequency waves in the Wadden Sea have a peak period of the order 16s. These waves are generated at the North Sea. Ocean waves with peak periods significantly larger than 20s do not penetrate into the Wadden Sea. In the continuation of this study we will refer to swell as the waves generated at the North Sea and penetrating into the Wadden Sea.

In the presence of swell the wave height of wind waves changes more rapidly. This effect not only occurs in deeper areas of the Wadden Sea, but also in the shallow areas. Furthermore, the presence of swell may strongly increase the wave period. It is important to know how swell waves propagate through the tidal basin and if they reach the sea defences. The swell waves will mainly propagate through the tidal channels in the Wadden Sea. Over tidal flats the swell wave energy will be significantly reduced due to bottom friction. To verify that the amount of swell energy is dominant in deeper areas, wave measurements should be carried out in and around tidal channel and on tidal flats. Since this is already suggested in Section 2.2 and 2.3 extra measurements are not required. Along the trajectories suggested in these sections the amount of swell energy should be studied accurately.

Another deficiency concerning swell occurs in the formulation of whitecapping (steepness-induced wave breaking), when swell and wind waves interact. The formulation for dissipation by whitecapping as implemented in most numerical models is based on the pulse-banded description of Hasselmann (1974). In many third-generation models, the average wave steepness is computed from the energy based on significant wave height and some average wave frequency. The addition of small amounts of low frequency energy to the wave spectrum can have a large influence on the average wave period and thus significantly decrease the computed wave steepness. In this way, the low frequency energy has a large influence on a process that is occurring in the high frequency part of the spectrum. When a small amount of swell energy is added to a wind sea, the computed average wave number decreases and the computed steepness decreases. As a result the dissipation by whitecapping will be reduced, which is thus an undesired characteristic of this formulation.

This reduction in wave steepness is sometimes so significant that dissipation by whitecapping becomes an order of magnitude smaller and leads to excessive growth of wave energy at high frequencies. This behaviour is reported by various authors (see e.g. Hurdle, 1998; Holthuijsen *et al.*, 2001). Wave growth may be enhanced when some swell is present. The simple approach using a mean wave steepness in the pulse-banded model for whitecapping, which has also been implemented in SWAN, allows the presence of swell to accelerate the wave growth due to wind, being opposite to the effect expected from field observations.

In the Wadden Sea double-peaked spectra occur. Waves generated in the offshore area and propagating through the tidal inlet into the Wadden Sea will be longer than the wind waves generated locally in this area. Since whitecapping mainly occurs at deeper water, the whitecapping problem manifests in the deeper parts of the Wadden Sea. Consequently, the underestimation of the wave periods at deep water may be due to the whitecapping problem in the model.

In the deeper parts of the Wadden Sea, the complete two-dimensional wave spectra should be measured, in order to verify whether double-peaked spectra occur. Furthermore, the effect of whitecapping can be investigated. Due to the whitecapping problem in numerical models, the wave growth at higher frequencies should be significant. It is probably sufficient to measure the two-dimensional spectra at only one location in the tidal basin.

2.2 Influence of currents

Wave propagation is affected by the presence of a current, resulting in refraction or blocking of wave energy. The influence of currents has been incorporated in spectral models in the action density equation through the wave propagation velocity, in either geographical and spectral space. In the absence of a current the propagation velocity in frequency space is zero. Only a few tests have been carried out to verify the effect of currents on the wave propagation. The waves will refract on oblique currents and might even be blocked by opposing currents.

For verification purposes two-dimensional situations are required in which the effect of wave-current interaction can be investigated. In the Wadden Sea current velocities are significant in the tidal channels. Here the wave field will be affected. A spectral wave model requires a (spatially varying) current and water level field, which can be determined with a hydrostatic flow model. At several locations in and around the channel current and water level data must be gathered, which are used for calibration and validation of the flow model. Wave data must be obtained to validate the modelling of the current effect in the spectral wave model.

To investigate the influence of the current on the wave spectra computed by the spectral model, two runs should be made: one including the current velocity and one without current. The results of the two computations should not only be compared in the vicinity of the channel, but on an entire trajectory through the flood channel to the sea defence at the main coast. To verify the model results, wave statistics are required along that same trajectory. Current measurements have to be carried out only in the neighbourhood of the channels, as mentioned above.

2.3 Triad wave interactions

Presently, there is a lack of complete understanding of the physical mechanism of three-wave interactions (triads), not to mention the interaction of triads with other physical processes. The modelling of the shift of energy towards higher and lower frequency ranges is based on strong assumptions. Consequently, a strongly simplified formulation for the effect of three wave interactions in shallow areas is implemented in the present models.

E.g. in SWAN triads are modelled by the so-called Lumped Triad Approximation (LTA). One of the major deficiencies of this formulation is the overestimation of the amount of wave energy that is shifted towards higher frequencies. Since the LTA formulation is based on self-self interaction (interaction of waves with same frequency and same direction), an irrealistic spectral shape is obtained. In reality long-wave energy is generated by the interaction between waves with a small difference in frequency. The shift of wave energy to frequencies significantly lower than the peak frequency is not modelled in SWAN.

Triad wave interactions occur in shallow areas. In the Wadden Sea the tidal flats are sufficiently shallow for the triads to have a significant impact on the spectral shape of the wave energy density. Consequently, the wave period will be affected. The effect of the triads can only be quantified accurately from the measurements if the entire two-dimensional wave spectrum is measured. For verification the evolution of the wave spectrum along a trajectory from the tidal inlet, over a tidal flat towards the sea defence at the main land, should be measured. On the tidal flats the generation of higher harmonics can then be visualised. The measured and computed amount of wave energy at e.g. twice the peak frequency must be compared, in order to get a feeling for the overestimated shift of wave energy towards higher frequencies that will probably be predicted by SWAN. The resulting wave period will thus be underestimated by SWAN. By studying the measured wave spectra along the trajectory, not only the shortcoming of the LTA formulation will be highlighted, but also insight will be gained in the physical mechanism of triads.

2.4 Bottom friction

In the Wadden Sea, bottom friction is an important dissipative process. Due to strong variations in depth the effect of bottom friction is very local. The bed of the Wadden Sea is almost entirely covered with sand. Only in a strip of approximately 20m to 100m in front of the sea dikes and behind the Wadden Islands, silt covers most of the bed. The roughness of silt is smaller than the roughness of sand. Furthermore, vegetation plays a role for bottom friction. However, the vegetation is also contained in the same coastal strip.

Since bottom friction is important in the entire Wadden Sea, velocities at the bed should be measured in the entire area. Furthermore, samples of the bottom should be taken in order to determine the material on the bed, its grain size and the resulting bottom roughness. However, it will be sufficient to confine to the trajectories mentioned in the beginning of Section 2.

2.5 Diffraction

Diffraction has not yet been implemented in a standard version of SWAN. Recently, a formulation for diffraction has been implemented at Delft University of Technology in a research version of SWAN. A limited number of verification tests have been carried out and reported in Holthuijsen et al. (2002). Further validation and verification for field situations is required.

Diffraction in the Wadden Sea occurs around the heads of the islands. Mainly long waves will bend behind the islands. Near the head the short wind waves diffract as well. In order to validate and verify the diffraction patterns, the wave trajectory from the inlet, around the head of an island, to the sea defence of that island should be monitored. It is sufficient to determine the significant wave height, mean wave period measures and mean wave direction along this trajectory. Nevertheless, more information would be obtained by HF-radar techniques, which will visualise the bending of the wave crests.

2.6 Reflection on dikes

The dikes on the main land are relatively steep. The short wind waves will break and dissipate on the slope of the dike, but the long waves will be reflected. The long wave energy consists of swell wave energy and low-frequency energy generated by non-linear wave interaction. Since the region is relatively shallow the non-linear wave interaction will be mainly due to triads, rather than quadruplets. Four wave interaction manifests more in deeper water.

The reflected long waves affect the wave energy spectrum related to the incoming waves. The presence of low-frequency energy near the dikes increases the wave period. Furthermore, wind waves will steepen on the oppositely propagating reflected waves. Measurements near the dikes should not only be focussed on the significant wave height (energy of incoming and reflected waves) at one position. in order to separate incoming and reflected wave energy, either directional wave energy spectra or the significant wave height at locations forming a triangle must be obtained.

2.7 Depth-induced wave breaking

Dissipation of wave energy due to wave breaking is either due to whitecapping (steepness-induced) or due to the fact that the wave height exceeds a depth-related level (depth-induced). Depth-induced wave breaking occurs in shallow areas. Not only near the sea defences on the main land and behind the Wadden Islands, but also on the tidal flats, depth-induced wave breaking decreases the amount of wave energy.

The dissipation rate due to wave breaking can be measured by collecting wave data along the three trajectories mentioned earlier in this report. The end of these trajectories must be close to the dikes, inside the surf zone, where wave breaking forms a significant part of the total dissipation rate.

2.8 Priorities in measuring processes

Not all of the processes mentioned in sections 2.1 to 2.7 are equally important to consider for the measurement campaign. Nevertheless, some of them can be combined with others. Two criteria will be used for prioritising the physical processes. Firstly, the impact of the particular process on the hydraulic boundary conditions will be taken into account. Secondly, the lack of knowledge of the mechanism of the processes and the modelling of these processes will be considered.

The Wadden Sea is a system of tidal flats and channels. In the channels wave-current interaction and swell propagation are the dominant processes. On the tidal flats triad interactions, bottom friction and depth-induced breaking play an important role. In the coastal strip near the sea defences, reflection, depth-induced wave breaking, bottom friction with spatially-varying bottom roughness and triad wave interactions affect the wave field. The presence of swell may also strongly influence the wave period. As already mentioned, one must not only consider the physical processes in front of the sea defences, but also critically observe and study the wave behaviour in the other parts of the Wadden Sea. In the next chapter we will focus on the physical processes per geographical area.

The deficiencies in the modelling of the processes within a spectral wave model lead to the greatest uncertainties for the processes of swell propagation, interaction between swell and wind waves, triad interactions and wave-current interaction. The modelling of the other processes is less critical. On the other hand, if measurements for e.g. triad wave interactions can easily be combined with those for depth-induced wave breaking or bottom friction, this should be done. Furthermore, the present spectral wave models have a tendency to underestimate the wave period not only near the sea defences, but also on the tidal flats. Due to the whitecapping problem also in deep water the predicted wave period is smaller than the measured wave period. Processes having a major effect on the underestimation of the wave period are swell propagation, triad wave interaction and reflection of long waves.

Here we propose to focus the measurements on swell propagation, wave-current interaction and triad wave interactions. Depth-induced wave breaking and reflection can be considered simultaneously. Diffraction and bottom friction may be less important to consider, although diffraction highly determines the amount of wave energy reaching the coast line of the lee side of the Wadden Islands.

Once the question "Where to measure in the Wadden Sea" has been answered, it is useful to study for the particular locations the present performance of a wave model like SWAN, and to study the relative importance of swell, currents, triads, diffraction, depth-induced breaking, reflection and bottom friction for the particular locations. This could support choices which have to be made concerning the priorities of processes to be investigated.

3 Physical quantities per geographical area

3.1 Introduction

A tidal inlet system such as the Wadden Sea consists of a number of very distinct geographical areas in which different physical processes are important. In a typical tidal inlet system the components are the offshore area outside the tidal inlet, the ebb tidal delta, the barrier island coasts, the tidal basin with channels and flats, and the basin shoreline, which in the Netherlands consists mostly of sea dikes. See Figure 1 for a schematic overview of a tidal inlet system. Per area the physical processes are listed which are important for spectral wave modelling.

3.2 Entire tidal inlet system

For all the components of a tidal inlet system the following astronomical, meteorological and bathymetric quantities should be measured.

3.2.1 Astronomical data

Astronomical data (tides) can be taken from the Admiralty Tide Tables at nearby stations. A hydrostatic flow model may be used to compute the tides in the tidal inlet system based on the tidal constituents from these stations.

3.2.2 Meteorological data

The total water depth in which the waves propagate is not only affected by the tide but also by the atmospheric and wind set-up. These effects are caused by the barometric pressure and the local wind velocity (magnitude and direction). These quantities can be obtained from local or nearby measurements and downscaled to the sea surface, or may be obtained from atmospheric models operated by the KNMI. The effect of wind and air pressure on the water level needs to be evaluated using a hydrostatic flow model for the entire system such as Delft3D, Triwaq. In the offshore area these effects may be negligible relative to the depth, but in shallower waters they will be as important as the tide.

3.2.3 Bathymetric data

For a correct prediction of the wave field, knowledge of the exact location of the bed is of utmost importance. Wave propagation and dissipation processes strongly depend on the local water depth. The bathymetry may be obtained from nautical charts and by local measurements using ships in deeper water or at high tide or vehicles in the intertidal area. The frequency of measurements depends highly on the time scale of the morphology in the different areas. In order to determine the orientation and depth of the tidal channels and flats, bed loadings in the ebb tidal delta and on the barrier island coasts should preferably be carried out periodically and at least after each major storm. In the interior of the tidal basin the morphological changes are much slower. There, it is important to determine the channel depth and orientation correctly. Additionally, samples of the tidal channel bottom and tidal flats' surface should be taken in order to determine the sediment diameters and the bottom roughness, if this information is not yet available.

3.3 Offshore area

The offshore area of a tidal inlet consists of the sea shelf with depths of up to 30m, which is the depth limit of the area of interest. The seaward boundary of a spectral wave model will normally be located in this area, which means that the hydrodynamical and meteorological boundary conditions need to be obtained in this area. Since part of the computational domain is located in this area, the bathymetry of this area also needs to be known.

The following hydrodynamical data in the offshore region which are needed to drive a spectral wave model are:

1. the significant wave height H_{m0};
2. the spectral distribution as a function of frequency (spectral shape);
3. the mean direction;
4. the spectral distribution as a function of direction (directional spreading).

These components may be obtained with a wave buoy (such as a directional wave rider) provided that the instrument can resolve typical swell and wind sea conditions (in the frequency range of 0.04 to 0.5 Hz). Alternatively, these parameters may be obtained from the nearest node of a wave hindcasting model such as the NEXT model operated by Oceanweather/DHI. These two sources may also be used in conjunction: the numerical data may be used as the boundary condition, while data from a single buoy location just inside the domain may be used for verification purposes.

Depending on the choice of boundary, the hydrodynamical conditions along the boundary may vary. This variation on the boundary may be implemented using a linear interpolation of the hydrodynamical conditions between instrument locations or nodes.

3.4 Ebb tidal delta and tidal inlet gorge

The ebb tidal delta is the protrusion of sand seaward of the gorge of the tidal inlet. This delta is formed by a number of processes, among which are tidal currents in the channels and along the perimeter of the delta, and waves incident from the sea. This area is highly complex and dynamical. Morphological changes occur on the time scale of storms (bulldozer effect of the waves) and decades (slow clockwise evolution of the channels). For the present purposes, the ebb tidal delta may be regarded as a filter which will block some offshore wave conditions and transmit others. This means that we are not primarily interested in the processes on the ebb tidal delta itself but that we will need to focus on the effect of the ebb tidal delta on the hydrodynamical processes just shoreward of the delta in the main tidal gorge, such as the wave properties (wave height, spectral distribution, directional distribution) and currents.

The hydrodynamical data just seaward of the ebb tidal delta may be obtained from the wave buoy mentioned in the previous section. The data obtained just inward from the ebb tidal delta (i.e. in the main tidal inlet gorge) should include

1. the significant wave height H_{m0};
2. the spectral distribution as a function of frequency (spectral shape);
3. the mean direction;
4. the spectral distribution as a function of direction (directional spreading);
5. current velocities (magnitude and direction).

The first four quantities may be obtained with a directional wave rider. The currents in the gorge are of a very complex nature: they are driven by tidal forcing, density gradients of concentration, temperature and salinity, etc. It is not likely that the currents will be uniform over the cross-section of the tidal gorge or will even be in the same direction from point to point. Therefore, ideally the currents should be measured "everywhere". This is hardly feasible with fixed equipment. However, it would be possible to measure with a limited number of current meters, which are fixed in space but measure continuously, and perform periodic measurements over the entire cross-section.

This has been done in the case of the Texelstroom measurements performed by NIOZ, who deployed two upward-looking ADCP frames on the bottom of a tidal channel. These instruments take vertical line measurements of two horizontal velocities. Additional measurements with an ADCP from the TESO ferry measurements in the Marsdiep/ Texelstroom inlet are taken to achieve a greater cross-sectional detail.

The current measurements can be used to calibrate a hydrostatic flow model which in turn would provide the discrete input flow field for the SWAN model.

3.5 Barrier island coasts

Of the barrier island coasts the "island heads" are the most important in the tidal inlet system because these sandy areas can accrete or erode at relatively small time scales. The shoreline erosion and accretion both on the seaward and inlet side of the islands will affect the secondary (or flood-dominated) channels which run near the coast. The island heads are also suitable locations from which to observe wave patterns in the nearby tidal channels.

The hydrodynamical data which should be obtained near the island heads is:

1. the significant wave height H_{m0};
2. the spectral distribution as a function of frequency (spectral shape);
3. the mean direction;
4. the spectral distribution as a function of direction (directional spreading);
5. current velocities;
6. wave patterns.

These data may be obtained with a directional wave rider(s). The current velocities may be obtained with conventional propeller instruments or with an ADCP located on the bottom which measures the horizontal velocities in a vertical line upward. Wave patterns (wave crests) may be visualised with HF radar(s) and will give insight in the refraction/diffraction of the swell waves around the island heads.

3.6 Tidal basin - channels

After the waves propagate through the ebb tidal delta most of the remaining wave energy will propagate towards the main land and the barrier island coast through the tidal channels. In these channels the waves will be affected by local winds which will generate more wave energy. Furthermore whitecapping and current refraction change the wave field. The wave spectra will evolve on the trajectory from the tidal gorge towards the main land and the barrier islands. We therefore recommend to collect data along two trajectories: along the centreline of the main tidal channel from the tidal gorge to the main land and along the centreline of the tidal channel from the tidal gorge to the island shoreline.

The following hydrodynamical data should be obtained in the channels in a number of locations:

The hydrodynamical data which should be obtained near the island heads is:

1. the significant wave height H_{m0};
2. the spectral distribution as a function of frequency (spectral shape);
3. the mean direction;
4. the spectral distribution as a function of direction (directional spreading);
5. current velocities.

The first four quantities may be measured with a directional wave rider. However, wave directions and directional distributions may not be important in this part of the basin because the wave direction is in many situations likely to be parallel to the channel axis so that non-directional wave riders may suffice. This is not valid at the intersection of two or more channels. The wave propagation direction and directional spreading are relevant at these locations. The current velocities may be obtained using bottom-mounted ADCP's with additional transect measurements from ships.

The results by Dunsbergen (1995) for the Friesche Zeegat show that the wave spectra change significantly along the centreline of the main tidal channel, and that the buoy spacing of approximately 5 km is not small enough to capture the variations. We therefore recommend a spacing of at least 1 km, but this needs to be investigated further using accurate bathymetry, wind and current velocity information.

3.7 Tidal basin - flats

While most of the wave energy will propagate through the channels towards the main land, some energy will also propagate over the channel flats. This will occur mostly during high water. Under storm conditions the water depth over the flats may be a few meters above the flats' bed level. The wave spectra will undergo a profound change in shape when encountering relatively shallow waters. Besides dissipation due to depth-limited breaking and whitecapping, some energy will be transferred to higher harmonics, and some to lower harmonics through triad wave interactions. These interactions will redistribute the energy over the spectrum and affect the mean period of the spectrum. We recommend that the wave spectra should be measured at a number of locations covering at least a trajectory from the tidal inlet gorge to the mainland, over the tidal flat.

The following data should be obtained:

1. the significant wave height H_{m0};
2. the spectral distribution as a function of frequency (spectral shape);
3. the mean direction;
4. the spectral distribution as a function of direction (directional spreading);
5. current velocities.

In order to determine the (significant) effect of directional spreading on the transfer of energy from lower and higher harmonics, it is necessary to measure the directions as well. Because the locations are intertidal, it is not possible to use a wave rider but it would be possible to use an array of elevated pressure sensors in combination with a flow meter. The individual arrays should be spaced with a distance about 1 km along the trajectory, since relevant changes in the spectrum are to be expected within that range.

3.8 Basin shoreline

The boundary condition for the sea defence design is located 50 meters from the toe of the structure. The measured data will be used as verification of the model results at that location. The following properties should be measured there:

1. the significant wave height H_{m0};
2. the spectral distribution as a function of frequency (spectral shape);
3. the spectral distribution as a function of direction (directional spreading);
4. the tidal elevation.

The first two quantities may be measured with a wave staff or with pressure sensors. The directional spectrum will be used to gain insight in the amount of reflected wave energy.

3.9 Other physical quantities

In order to properly model the structure of the currents in a tidal inlet system, data on the salinity, the temperature and the silt concentration should also be available. However, this might increase the collection effort dramatically.

4 Accuracy of measurements

In this section the required accuracy for the measurements of wave data, bathymetry, wind data, and current data are discussed. We remark that the required accuracy of the measurements is hard to estimate. For reliable estimations sensitivity studies should be carried out. The sensitivity of errors in bathymetry, current velocity, water level and wind velocity for wave field predictions must be studied. By comparing spectral model runs in which one of the quantities above is varied, conclusions can be drawn.

4.1 Wave data

In the offshore region and in deeper water, wave measurements should have the following accuracy.

The surface elevation should be collected with an accuracy of O(1cm). The instruments should be able to resolve waves with frequencies between 0.02Hz and 0.5Hz. However, in the Wadden Sea waves with frequencies lower than 0.04Hz have not been measured in the past. Therefore, the lower bound can be set at 0.04Hz. Due to the upper bound of 0.5Hz, the sampling frequency in deeper water should therefore be at least 1Hz. The signal should preferably be continuous but at least should not be less than 2 hours in order to achieve a frequency resolution of 0.01Hz after averaging. The directional resolution should at most be 10 degrees, and the instruments should be able to resolve waves from all directions.

In the shallower areas, and especially on the tidal flats, the same accuracy applies but the data should be collected at a sampling frequency of at least 2Hz in order to resolve the generation of higher harmonics.

The spacing of the instruments in the trajectories in the tidal channel and on the tidal flats should be at least O(1km) but this needs to be assessed with more information, for example from a numerical flow model.

We recommend that the original time series should be stored along with the integral parameters. Awkward values for the integral parameters might be explained from certain deficiencies in the time series.

4.2 Bathymetry

The resolution in space is determined by the scale of the spatial characteristics of the bed geometry that affect the evolution of the wave field in the computational domain. For spectral wave models the spatial resolution does not have to be smaller than a typical wave length for that area. This means that in the offshore areas the resolution should be of the order 100m, whereas in the tidal basin the reduction in wave length requires a resolution of the order of 10 meters. However, near tidal channels the changes in depth must be represented accurately. Therefore, the resolution should be such that 10% in depth variation is represented. For typical channel slopes of 1:20 and a depth variation (highest minus lowest depth value in channel) of 10m, 10% variation results in a resolution of 20m. This is even more than the typical wave length. The advised resolution for bathymetry sampling is therefore of the order 10m.

Not only the spatial resolution is important, but also the time that the bathymetry is measured must be considered carefully. The bathymetry varies in time. The variation during a storm may even be very strong. When storm condition are hindcasted with a wave model, the bathymetry that is used as input, should be measured directly after a storm.

4.3 Wind input

As mentioned in Section 3.2.2. wind input for the spectral models can be obtained from measurements or from atmospheric models. In either case these wind velocities should be hourly-averaged at a height of 10m above the water surface, since the formulations for wind wave generation in stationary versions of a spectral model such as SWAN requires these quantities. Measurements are only required for driving the atmospheric models. Wind station located near the Wadden Sea can deliver these data.

If not digitally available, atmospheric models should be used to obtain wind fields. Therefore, the wind velocity should be measured at a number of wind stations. KNMI has developed 'downscaling' techniques to obtain the wind velocities from the HIRLAM model at any required resolution. The local roughness of the sea surface is taken into account. The land-sea transition can be represented accurately. The lower limit for accurate downscaling results is 500m. This is an optimal resolution, since spatial variations of wind fields less than 500m are not likely to be important, even on the transition from land to sea.

4.4 Current and water level

To obtain realistic computational results from a flow model, accurate current measurements must be obtained. Especially near the tidal channels sufficient information should be available to calibrate, validate and verify the flow model. In and around the tidal channels the character of the current is highly three-dimensional. The current velocity should be measured along the channel, but also across the channel. In a cross-section of the channel the flow can be directed downstream on one side, whereas the direction may be opposite on the other side. Data at one location in the channel are probably not representative for the entire cross section. We advise to carry out measurements along rays along and across the channel. The accuracy of the current measurement should be of the order 10%. For typical velocities of 1m/s in the channel this means that an accuracy of the order of 10cm/s is sufficient.

Furthermore, most spectral wave prediction models need the depth-averaged current velocity as input. Therefore, at each location the vertical profile must be measured (e.g. by an upward-looking ADCP), such that the depth-averaged velocity can be determined afterwards. Due to the highly three-dimensional character of the flow, measuring the current velocity at only one point in the vertical is insufficient.

5 Conclusion

In this study a proposition has been made for measurements in the Wadden Sea. With these measurements the quality of the hydraulic boundary conditions for the sea defences is aimed to be increased. Furthermore, the measurements are focussed on the physical processes in spectral wave models such as SWAN that are insufficiently understood and modelled.

The entire Wadden Sea has been subdivided into typical areas. Per area the physical processes are listed and the required wave data in these areas are listed. For the entire tidal system astronomical data, meteorological data and bathymetric data have to be gathered to drive a spectral wave model.

We have proposed to make a selection out of the wave processes affecting the wave conditions in the Wadden Sea. The wave data to be measured are wave height, wave period and two-dimensional wave spectra. We have proposed the following processes along indicated trajectories:

1. The propagation of swell wave energy (from the tidal inlet towards the sea defences at the main land and at the barrier islands, mostly through the tidal channels).
2. The effect of a current (along tidal channel towards the main land).
3. Triads (over a tidal flat towards the main land).
4. Diffraction (around the head of the islands towards the barrier island coast).

Finally we have discussed the required accuracy of the data to be obtained.

The present study is entirely focussed on the wave dynamics in the Wadden Sea. The expertise of morphologists has not been used and experts in the field of wind and water motion, including effects of density and temperature, have not been consulted. To have a broader view of the mechanics involved in the Wadden Sea and to include them into the foreseen measurement campaign we recommend to consult the mentioned experts as well.

6 Recommendations

The required accuracy of the measurements is hard to estimate. For reliable estimations sensitivity studies should be carried out. The sensitivity of errors in bathymetry, current velocity, water level and wind velocity for the computed wave conditions must be studied. By comparing spectral model runs in which one of the quantities above is varied, conclusions can be drawn.

The 1/4000yr storm conditions will probably not be measured during the foreseen measurement campaign. Nevertheless, the spectral models will be calibrated and validated on the storms that are measured. To determine the hydraulic boundary conditions the model must run under conditions for which it has not been calibrated. The validity of the model is uncertain and should be checked. Furthermore, the transformation of the condition from storm conditions to super storm conditions must be validated.

Once the question "Where to measure in the Wadden Sea" has been answered, it is useful to study for the particular locations the present performance of a wave model like SWAN, and to study the relative importance of swell, currents, triads, diffraction, depth-induced breaking, reflection and bottom friction for the particular locations. This could support choices which have to be made concerning the priorities of processes to be investigated.

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A Figure

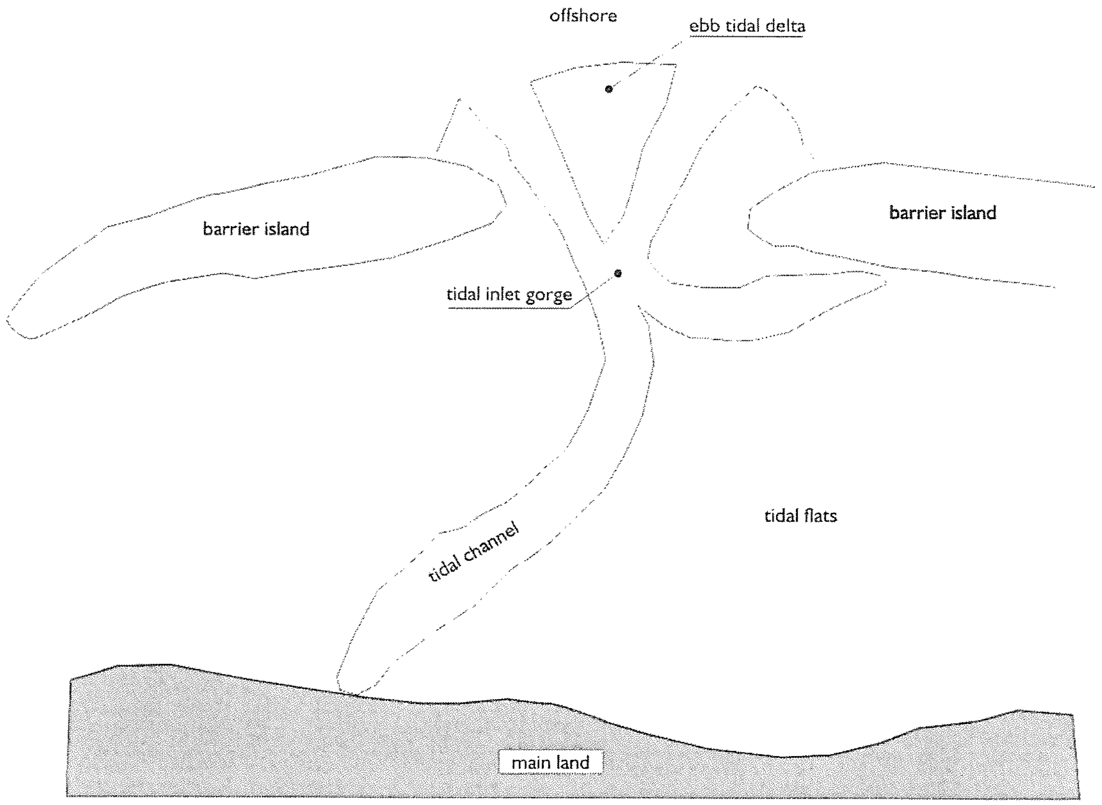
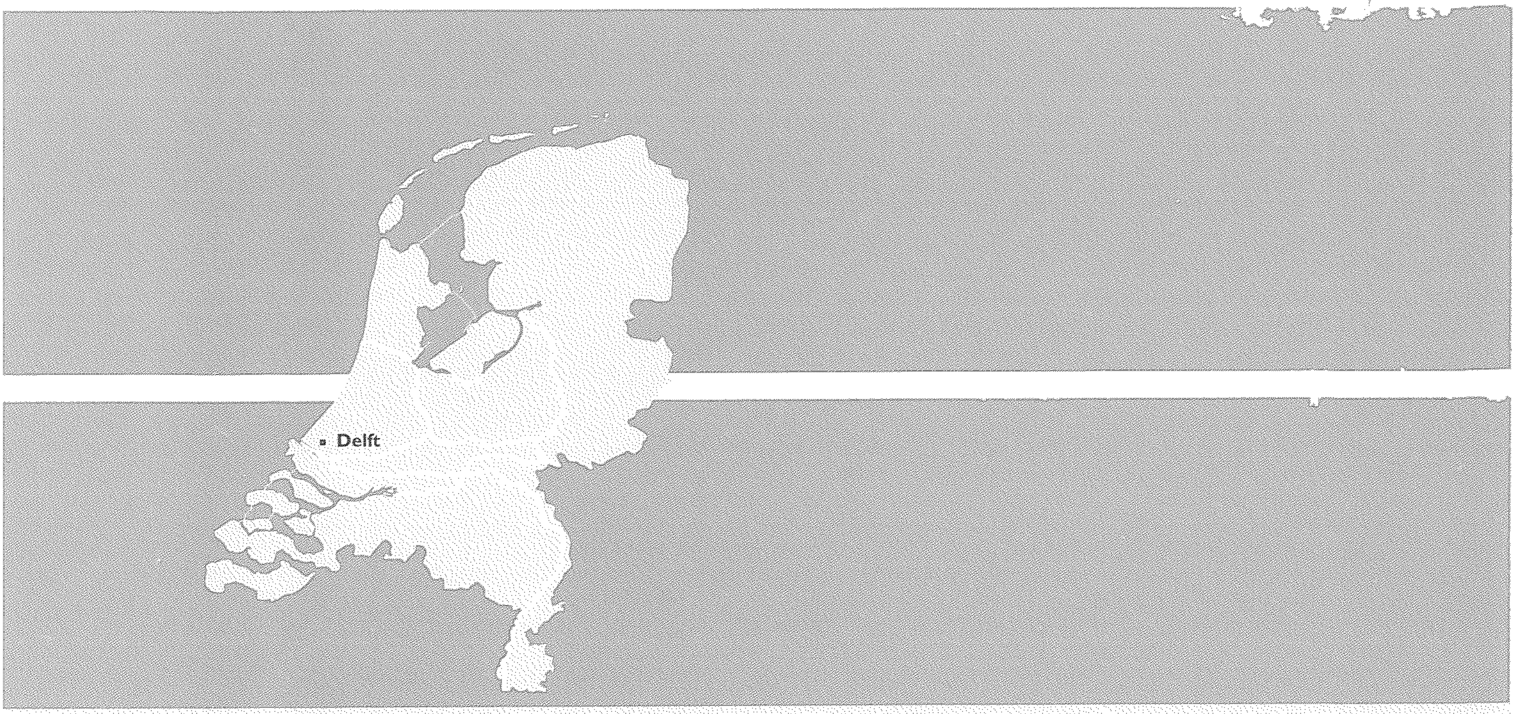


Figure 1 Schematic drawing of a tidal inlet system



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