Prepared for:
RIKZ

Calibration tool for SWAN

Activity 8.1 & 8.2 of SBW project Waddenzee

Part 1: Analysis of requirements

Report

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TITLE: Calibration tool for SWAN. Part 1: Analysis of requirements

ABSTRACT:

The spectral wave model SWAN plays a key role in the estimation of the Hydraulic Boundary Conditions (HBC) for the primary sea defences of the Netherlands. Since uncertainty remains with respect to the reliability of SWAN for application to the geographically complex area of the Wadden Sea, a number of activities have been initiated under project H4803 "Uitvoering Plan van Aanpak SBW-RVW Waddenzee" to devise a strategy for the improvement of the model. This activity is initiated in parallel to the measurement campaign in the Wadden Sea (part of SBW-Veldmetingen). The current study considers the conceptual design of a calibration tool for SWAN, which is carried out as a separate sub-project. This project has two components: an inventory of requirements for a calibration tool for SWAN (Part 1 or Activity A), plus a subsequent literature and feasibility study on appropriate calibration techniques for such a tool (Part 2 or Activity B). The present contribution concerns the former of these topics. While the application focus is the Wadden Sea, it is understood that the calibration tool should have a sufficiently general character to be applicable to other relevant application areas as well.

After a general introduction and problem statement, the purpose of the calibration tool is formulated. The practical aspects of effectiveness and efficiency are outlined. In a further chapter the various sources of uncertainty are discussed. Aspects such effects of changes in parameterisations and user choices of model domain and resolution are argued to be separate issues. Although they affect overall accuracy, they are outside the scope of parameter calibration discussed in the present study. In a separate chapter a concise description of the processes and uncertain parameters of the spectral wave model SWAN is given, with reference to Appendix A for a more extensive treatment. Given these uncertainties, it is argued that parameter estimation should include the establishing of acceptable ranges around the best fit solution. The total number of uncertain SWAN parameters is 11 (default SWAN version 40.51). Next, the conventional SWAN calibration approach is summarised, with a full text in Appendix B. The requirements for automated calibration include a classification of parameters into the types: generic, application dependent and "dustbin"-type. Quantification of measures of calibration quality is discussed, focussing on Goodness of Fit norms and standard statistical quantities. A recommended approach for automated calibration using these concepts is presented, with focus on the Wadden Sea case. Finally, the functional requirements for the calibration tool and its recommended use are presented.

The results will be input for Part 2 of the study: literature study and feasibility of a SWAN calibration tool.

REFERENCES: Plan van Aanpak SBW Natuurrandvoorwaarden Waddenzee; contract RKZ-1697

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List of symbols
DIA Discrete Interaction Approximation
GoF Goodness of Fit
HBC Hydraulic Boundary Conditions
HR Hydraulische Randvoorwaarden
LTA Lumped Triad Approximation
PvE Programma van Eisen
RVW Randvoorwaarden
SBW Sterkte en Belasting Waterkeringen
SWAN Simulating WAves Nearshore
VTV Voorschrift op Toetsen op Veiligheid
Introduction

1.1 De Hydraulische Randvoorwaarden (in Dutch)


Vooral voor de Waddenzee is er onzekerheid over de kwaliteit van de huidige Randvoorwaarden. Dit komt omdat deze verkregen zijn uit een inconsistent set van metingen en ontwerpwaarden (WL, 2002). Voor de rest van de Nederlandse Kust (de Hollandse Kust en de Zeeuwse/Zuid-Hollandse Delta) wordt gebruik gemaakt van het golftransformatiemodel SWAN (Booij et al., 1999; SWAN website). Het acroniem SWAN staat voor: Simulating WAves Nearshore).

Er zijn op dit moment voor de Waddenzee echter onvoldoende meetgegevens voor de validatie van het golfmodel SWAN, zodat het verkrijgen van betrouwbare en gevalideerde randvoorwaarden met dit model in een gebied als de Waddenzee nog niet mogelijk is. Derhalve is het ook nog onduidelijk in hoeverre onder andere de doordringing van lange golven een rol speelt of kan spelen. Enkele stormmetingen bij de Emmapolder in Groningen hebben namelijk uitgewezen dat deining een substantiële bijdrage aan de golfhoogte (orde 30%) kan leveren (pers. comm. F. den Heijer, RIKZ).

1.2 SBW RVW Waddenzee - Project H4803 (in Dutch)

Het bovengenoemde probleem is de directe aanleiding voor de vraag van het deelproject “Sterkte en Belasting Waterkeringen (SBW) – Natuurrandvoorwaarden” aan WL|Delft Hydraulics om een Plan van Aanpak op te stellen waarin de strategie wordt bepaald voor het beantwoorden van de primaire vraagstelling: “Hoe te komen tot betrouwbare Hydraulische Randvoorwaarden voor het jaar 2011 voor het Waddengebied?” Naast het doordringings-aspect moet ook de algehele geschiktheid van het golfmodel SWAN in de Waddenzee bepaald worden en aangegeven worden welke eventuele verbeteringen noodzakelijk zijn om betrouwbare HR in de Waddenzee te kunnen afgeven (WL, 2006).

Dit Plan van Aanpak valt onder het project Sterkte en Belasting Waterkeringen (SBW, 2005) omdat dit de taak heeft de kwaliteit van de modellen en methoden waarmee de HR worden afgeleid te verbeteren zodanig dat beheerders en andere deskundigen voldoende vertrouwen hebben om deze gereedschappen te gebruiken voor de vijfjaarlijkse toetsing. Dit gebeurt o.a. door meting uit te voeren in het project SBW-Veldmetingen, en door methoden en modellen te ontwikkelen om de vertaalslag van de zogenoemde diep-water statistiek naar statistiek bij de waterkeringen te kunnen maken en door de (zwaardere) belasting op en fiaalmechanismen van waterkering te beschouwen.
Het door WL met externe partijen opgestelde en inmiddels goedgekeurde Plan van Aanpak beschouwt kort de gehele keten die gebruikt wordt om de Hydraulische Randvoorwaarden af te leiden en focust op de verbetering van de voorspelling van de golfrandvoorwaarden door het golfmodel dat nodig is om de vertaling van diep water naar waterkering te kunnen maken.


Het deelproject Calibratie-tool SWAN is hiervan een onderdeel. Het is organisatorisch-administratief afgesplitst en wordt uitgevoerd onder projectnummer X0346. Het project heeft een duidelijke relatie met de onderdelen 8.5 en 8.6 “Opstellen PvE en structuur validatie-tool en uitbreiden met testcases” van het project H4803, dat vanwege een veel latere start op de resultaten van het huidige project kan voortbouwen.


1.3 Calibration tool for SWAN - Project X0346

The spectral wave model SWAN plays a key role in the estimation of the Hydraulic Boundary Conditions (HBC) for the primary sea defences of the Netherlands. Since uncertainty remains with respect to the reliability of SWAN for application to the geographically complex area of the Wadden Sea, a number of activities have been initiated under project H4803 ‘Uitvoering Plan van Aanpak SBW-RVW Waddenzee’ to devise a strategy for the improvement of the model. This activity is initiated in parallel to the measurement campaign in the Wadden Sea (part of SBW-Veldmetingen). The current study considers the conceptual design of a calibration tool for SWAN, which is carried out as a separate sub-project. This project has two components: an inventory of requirements for a calibration tool for SWAN (Part 1 or Activity A), plus a subsequent literature and feasibility study on appropriate calibration techniques for such a tool (Part 2 or Activity B). The present contribution concerns the former of these topics. While the application focus is the Wadden Sea, it is understood that the calibration tool should have a sufficiently general character to be applicable to other relevant application areas as well.

The SWAN model is used to transform offshore wind and wave conditions to wave conditions near the dikes. These offshore boundary conditions are obtained by statistical extrapolation of measured conditions to conditions that occur on average once in 2,000, 4,000 or 10,000 years, depending on the specific area considered: the Hydraulic Boundary Conditions (HBC). For the Wadden Sea dikes the HBC criterion is 4,000 years (Schiermonnikoog, Ameland, Terschelling and Vlieland: 1:2,000 years). The SWAN model uses parameterisations of physical processes for wind-wave generation and dissipation. Each of these parameterisations has one or more tuneable parameters. The optimal choice of parameter settings for SWAN applications in the Wadden Sea is not yet known. Therefore, they need to be determined in such a way that the SWAN model can be applied to determine
the Hydraulic Boundary Conditions for all dikes bordering the Wadden Sea. For this purpose a calibration tool is envisaged.

First of all the goal of Activity A is extensively described in Section 2, putting emphasis on all the aspects that are considered. Secondly, the processes modelled in SWAN and their reliability are described in Appendix A and summarized in Section 3. As a first step towards the development of a calibration tool the conventional manual calibration procedure is outlined in Section 4 and more extensively in Appendix B. Subsequently, we consider the requirements for automating such a calibration process in Section 5, with specific application to the Wadden Sea area. Central questions in this regard are the selection of relevant parameters to calibrate, their ranges of validity, type, suitability, whether they ought to vary spatially, the quality of the data available for calibration and the criteria for measuring the quality of model evaluation, and subsequently the calibration.
2 Purpose of the calibration tool

The purpose of the calibration tool is to determine in an efficient and effective way the optimum parameter setting of the SWAN model to compute spectral wave transformation in tidal areas with complex bottom topography, notably the Wadden Sea. It should provide information on a reasonable bandwidth around the optimum setting. With the calibrated model, the Hydraulic Boundary Conditions are computed more reliably than with a non-calibrated model.

This generally formulated goal contains many elements that need to be detailed to specify the requirements of the calibration tool. To that end all words or pairs of words are discussed in detail.

2.1 Calibration tool

The description above implies that a piece of software or software environment needs to be developed in which series of model simulations can be made and evaluated for efficient and effective assessment of the effects of variations in SWAN parameter settings in a (semi-) automated, quantified, objective and reproducible way. In general, calibrating a computational model comprises of the execution of many model runs with different parameter settings and choosing a set of parameter values that produces the best fit with observational data. Since many automated and semi-automated techniques are available, a choice must be made of the best method. Some methods require a man-machine mix to guide the optimization, whereas other methods operate fully automatically. Candidate methods will be selected in Activity B.

2.2 Effective and efficient

The calibration tool is effective if the calibration methodology or strategy is such that the evaluation measures (often a combination of quantitative norms and graphical presentations) are sensitive to changes in the SWAN parameter settings, both for strongly varying and more smooth error surfaces (i.e. strong or weak response of the SWAN solution to parameter variation). In general, interdependence between parameters reduces the effectivity and should be minimised by fixing or limiting the range of one of the parameters.

Efficiency implies that a calibration of the SWAN model should be possible within reasonable time to allow different combinations of parameter sets to be evaluated. It may happen that during calibration, a calibration run leads to an optimum result for an unrealistic combination of parameter settings. Then human intervention is needed to modify the input for a calibration run. Although no precise criteria can be given, a maximum period of a few days to a week seems acceptable for the entire calibration process, comprising the model simulations and post-processing. This criterion puts requirements on various aspects of the calibration tool:

- the calibration method should use only a limited number of model runs;
• the calibration should only consider a limited number of parameters to be determined;
• a basic SWAN computation for the Wadden Sea should not take too much time.

Presently, a typical SWAN computation for the whole Wadden Sea requires an amount of CPU time in the order of 1 hour on Delft Hydraulics’ computational cluster (Hydrax). This implies that calibration methods requiring thousands of model runs are currently not feasible.

2.3 Parameter settings

To determine the parameters in the SWAN model to be calibrated, information is needed on the relevant physical processes that play a role in the Wadden Sea. Such information may limit the number of parameters to be calibrated. Often a clear hierarchy of processes can be achieved. In such cases, the calibration process may likely be separated in successive independent calibration steps as well, keeping as frozen those parameters that were calibrated in the earlier steps. The calibration tool should allow for this, but may not assume that such a hierarchy exists.

In choosing parameter sets for calibration one should be aware of physical limits of certain parameterisations. Such limitations affect the scalability of parameterizations to extreme conditions. A clear example concerns the saturation of the drag coefficient. For wind speeds higher than 30 m/s this drag coefficient seems to reach an upper limit. There are even indications that for even higher wind speeds the drag coefficient goes down again, which would suggest the need for formal adjustment of the commonly used drag coefficient parameterisation. This would then formally lead to a new version of SWAN and this is therefore not considered here.

2.4 Uncertainty and reliability

There are a number of sources of error that may affect the accuracy that can be achieved with the calibration tool. For instance, it is of no use to have a very well calibrated SWAN model (taking many iterations) when a significant error remains, due to uncertainties in, for instance, bottom topography or model forcing.

For the purpose of the calibration tool, it is practical to group the uncertainty sources systematically:

A: The domain of the application and grid resolution:
• Uncertainty related to the adequacy of the selection (primarily the geographical extent) of the model domain;
• Uncertainty related to the adequacy of the resolution in the geographical schematisation of bathymetry and geometry;
• Uncertainty related to the adequacy of the spectral and directional resolution.

The choice of model domain and (geographical) model resolution are of key importance. They are fixed at the start of the calibration and are not the subject of the calibration process. Potential inadequacies in these choices can generally not be identified explicitly in the calibration but tend to be implicitly absorbed in the calibrated parameters in a distributed sense. This may lead to physically inconsistent estimates for the model parameters, which
have no generic value, and this in turn directly affects the value of the model in its use as a predictive tool.

B: Model parameterisations, time variation and numerical parameters:
- the uncertainty in the choice of physical process parameterization (i.e. which source term description to use);
- the adequacy of the assumption of stationarity;
- the uncertainty of the numerical solution method of SWAN (related to the number of iterations).

These issues also need to be addressed explicitly before the calibration process. The choices made should themselves not be the subject of the model calibration. For the numerical parameters, a slightly conservative attitude is recommended, to avoid inadequate choices that subsequently affect the calibration process in an implicit, untraceable way.

C: Model inputs:
- the uncertainty in the bottom topography (the model input, apart from its resolution);
- the uncertainty in the wind, currents and water level fields (the model forcing);

The accuracy of the topography and model forcing strongly affects the accuracy of the wave results

D: Calibration data:
- the suitability and representativity of the calibration data (type and geographical distribution);
- the measurement uncertainty in the calibration data values.

We note that this group explicitly evokes a discussion on the possible need for further measurements, including the optimal types, locations and spatial distribution of measurements. Measurements should provide at least the following integral parameters: significant wave height ($H_{m0}$), peak period ($T_p$), wave period ($T_{m-1,0}$) and mean direction $\bar{\theta}$, but preferably also provide information on the spectral form (tail). Information on the high end of the spectrum is represented by $T_{m02}$, relevant for various fail mechanisms. The project SBW-Veldmetingen addresses the issue of measurements for the Wadden Sea.

E: The calibration method:
- the assumptions of hierarchy in the calibration (strict or no hierarchy, joint or single parameter variation, iterative or (non-)iterative approach);
- the user-definition of the Goodness of Fit (GoF) criteria;
- the uncertainty of the adopted calibration (minimisation) method.

The various sources of uncertainty will lead to optimum parameter estimates which as such are inherently uncertain. It is therefore recommended to quantify this in some way, e.g. by determining a band around the optimum, or, ideally, the probability density function for the parameter. We note that the parameter uncertainty provides an underestimation of the (unknown) model uncertainty.

By taking these groups of potential uncertainties explicitly into account, model calibration will lead to an optimal SWAN parameter setting result that is well-defined. While the result is obviously constrained by the underlying assumptions, the reliability of the result is now much clearer, as the assumptions have been addressed explicitly. The present project on the
Calibration tool will take into account uncertainties mentioned under C, D and E, assuming that the choices and assumptions under A and B are optimal (no uncertainties). The uncertainties under C and D are assumed to be available (e.g. in the form of best estimates) at the start of the calibration. Variations in the calibration method itself will allow quantification of the errors or uncertainties under E.

We note that the results formally hold for SWAN 40.51, given its specific parameterisations and numerical schemes. Introduction of new parameterisations or different numerical implementations lead to a new SWAN version, which then requires its own calibration.

### 2.5 Hydraulic Boundary Conditions (HBC)

The HBC consist of a combination of extreme water level and wave conditions near the primary sea defence. These conditions are derived by translating extreme offshore wind, wave and water level conditions to the sea defence. These extreme offshore conditions have been determined by statistical extrapolation of historical events. In practice these extrapolated extreme conditions have not yet been measured. This implies that, at least in the Netherlands, no measurements are available to calibrate the model for such extreme conditions. Strictly speaking, calibrating the SWAN model for observed storm conditions is no guarantee that it will also produce reliable results for more extreme conditions.

There are various ways to improve the applicability of a calibrated SWAN model in extreme conditions. The first way is to concentrate on a proper calibration of the parameterisations of relevant physical processes with a wide range of applicability. This requires deep insight into the (present) limits of applicability of the source terms in SWAN. The second way is to calibrate the SWAN model to comparable situations at other locations, or even to measurement locations in other areas (see next section). We note that improvements in the very parameterisations of the physical processes are expected to lead to a better foundation for applying the calibrated model in extreme conditions and to smaller ranges of the tuneable parameters.

### 2.6 The Wadden Sea; comparable other areas

The Wadden Sea is the first target area for SWAN model applications for the HBC 2011. In some areas of the Wadden Sea a certain combination of physical processes may be dominant, which can also be observed in other places. For some shallow water conditions, situations may be comparable to those observed in Lake George (Australia), Lake Sloten (NL) or Lake Tai Hu (China). The collection of useable shallow water wave data will be carried out in another sub-project of the main study. Candidate dataset are those collected in Lake Sloten, Schleswig Holstein (D), Danish Wadden Sea (DK), Lake George (Australia), Lake Okeechobee (Florida, USA) and Lake Tai Hu (China).
3 Summary of processes and uncertain parameters in SWAN

The present chapter summarises the processes in SWAN and gives an overview of the uncertain process parameters that are in principle the subject of a SWAN calibration. For the underlying and much more extensive description, including issues of numerical discretisation and solution iteration parameters, see Appendix A.

The model SWAN computes the evolution of wave action density $N(x,y,v,t)$ using the action balance equation (Booij et al. 1999):

$$\frac{\partial N}{\partial t} + \nabla \cdot \left[ \left( c_g + U \right) N \right] + \frac{\partial}{\partial \theta} \left( c_o N \right) + \frac{\partial}{\partial \sigma} \left( c_o N \right) = \frac{S_{we}}{\sigma}$$  \hspace{1cm} (1)

with

$$S_{ne} = S_w + S_{wc} + S_{nl4} + S_{bot} + S_{brk} + S_{nl3}$$  \hspace{1cm} (2)

The terms on the left-hand side represent, respectively, the change of wave action in time, the propagation of wave action in geographical space (with $c_g$ the wave group velocity vector and $U$ the ambient current), diffraction and depth- and current-induced refraction (with propagation velocity $c_o$ in directional space $\theta$) and the shifting of the radian frequency $\sigma$ due to variations in mean current and depth (with the propagation velocity $c_o$). The right-hand side represents processes that generate, dissipate or redistribute wave energy. In deep water, three source terms are used: the transfer of energy from the wind to the waves, $S_w$; the dissipation of wave energy due to whitecapping, $S_{wc}$; and the nonlinear transfer of wave energy due to quadruplet (four-wave) interaction, $S_{nl4}$. In shallow water, dissipation due to bottom friction, $S_{bot}$, dissipation due to depth-induced breaking, $S_{brk}$, and nonlinear triad (three-wave) interaction, $S_{nl3}$, are additionally accounted for.

Summarising, the processes in SWAN can be divided into three categories:
- propagation (including the influence of current; the terms on the left hand side),
- deep water processes (the first three terms on the right hand side) and
- shallow water processes (the last three terms on the right hand side).

The (default) SWAN formulations of these processes feature a total of 11 uncertain parameters, which in principle need to be calibrated, see Table 1.
We note the existence of parameterisations for the coefficient $\gamma_{BJ}$ which physically represents a wave height over depth ratio. In the present project and the table above we conform to the common practice in SWAN, in which $\gamma_{BJ}$ is considered an application dependent parameter.

<table>
<thead>
<tr>
<th>Type</th>
<th>Process</th>
<th>Nr</th>
<th>Parameter</th>
<th>Explanation</th>
<th>Literature</th>
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<tr>
<td>Propagation in geographical</td>
<td>space</td>
<td>--</td>
<td>none</td>
<td>based on linear wave theory</td>
<td></td>
</tr>
<tr>
<td>Depth- and current-induced</td>
<td>directional space $\theta$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shifting of radian frequency</td>
<td>due to variations in mean current and depth</td>
<td>--</td>
<td>none</td>
<td>based on geometric optics approximation</td>
<td></td>
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<td>Deep water balance</td>
<td>Transfer of energy from wind to waves</td>
<td>1</td>
<td>$\alpha_{in}$</td>
<td>wave growth parameter</td>
<td>Komen et al., (1984)</td>
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<tr>
<td>Dissipation of wave energy</td>
<td>due to whitecapping</td>
<td>2</td>
<td>$C_{dc,wc}$</td>
<td>proportionality constant</td>
<td>Komen et al., (1984)</td>
</tr>
<tr>
<td>Shifting of mean current</td>
<td>$q$</td>
<td>3</td>
<td></td>
<td>exponent; relative mean steepness</td>
<td></td>
</tr>
<tr>
<td>Shifting of mean wave number</td>
<td>$r$</td>
<td>4</td>
<td></td>
<td>exponent; relative mean wave number</td>
<td></td>
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<td>Nonlin. transfer of wave</td>
<td>energy due to quadruplet (four-wave)</td>
<td>5</td>
<td>$C_{nl4}$</td>
<td>proportionality constant</td>
<td>Hasselmann et al. (1985)</td>
</tr>
<tr>
<td>Shallow water balance</td>
<td>Dissipation due to bottom friction</td>
<td>7</td>
<td>$C_{db,bot}$</td>
<td>proportionality coefficient</td>
<td>Hasselmann et al. (1973)</td>
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<td>Dissipation due to depth-induced breaking</td>
<td></td>
<td>8</td>
<td>$\alpha_{BJ}$</td>
<td>measure for the breaking intensity</td>
<td>Battjes and Janssen (1978)</td>
</tr>
<tr>
<td>Nonlinear triad (three-wave)</td>
<td>interaction</td>
<td>10</td>
<td>$\alpha_{EB}$</td>
<td>proportionality constant</td>
<td>Eldéberky (1996), Janssen (2006)</td>
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<td></td>
<td></td>
<td>11</td>
<td>$f_{max,EB}$</td>
<td>high-frequency cut-off in triad computation</td>
<td>Van der Westhuysen (in prep.)</td>
</tr>
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Table 1: Process categorization and the associated 11 uncertain parameters
4 Conventional calibration procedure

The conventional SWAN calibration procedure for the 11 uncertain process parameters listed above is generally conducted along the following steps:

1. Establishing the numerical settings (these may be area dependent)
2. Calibration of deep water processes;
3. Calibration of finite-depth processes and propagation;
4. Calibration for a specific field situation.

For a further background on the step by step conventional calibration procedure, the reader is referred to the more detailed description Appendix B. The discussion is limited to the stationary mode of SWAN, since most generic calibration tests consider the time-independent model solution and also because it is anticipated that this is the model mode relevant for HBC calculations concerning the Wadden Sea application area.
5 Requirements for automated calibration

In Chapter 3 above, the main processes and parameters of SWAN were described, and in Chapter 4 the step by step conventional procedure for manual calibration of the model was summarised. In the present section these elements are combined into a proposed set of requirements for an automated or semi-automated calibration system. To this aim, firstly, the 11 uncertain calibration parameters of Table 1 are categorized into three classes, based on the degree to which they are known. Secondly, relevant quantities to be used as measure of calibration quality are considered. Finally, a system of requirements for the calibration process, ranging from elementary processes to field case application, is proposed.

5.1 Classification of parameters

In Section 3 it was shown that SWAN has a range of parameters to be calibrated, belonging to the expressions of various processes. Since some processes are better known than others, and have better quality observations associated with them, the various parameters belonging to these expressions may be categorized into classes based on the degree of uncertainty associated with each. Table 2 presents such a categorization, with the classes ‘generic’, ‘application-dependent’ and ‘dust bin’. The first category contains requirements that are generally valid and are to be demanded of any SWAN calibration. The second category contains parameters of which there is greater uncertainty, and therefore may be application dependent. As a result, these parameters typically have ranges of validity for their values, which may or may not be known with much certainty. The third category contains those parameters that belong to processes that are the least known (here the dissipation terms), and therefore used as closure terms in the various process balances.

<table>
<thead>
<tr>
<th>Characteristics of spectrum</th>
<th>Generic settings and constraints</th>
<th>Application-dependent</th>
<th>‘Dust bin’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep water balance</td>
<td>$N(x,y,z,t) &gt; 0$</td>
<td>$\alpha_{br}$, $\lambda_{nl4}$</td>
<td>$C_{ds,wc}$, $q$, $r$</td>
</tr>
<tr>
<td>Shallow water balance</td>
<td>$\alpha_{BJ} = 1$ ($depth-induced breaking$)</td>
<td>$\alpha_{EB}$, $f_{max,EB}$ ($triads$)</td>
<td>$C_{ds,bot}$ ($friction$)</td>
</tr>
<tr>
<td>Numeric (driven by convergence requirements)</td>
<td>No. iterations $&gt; N$ ($N$ to be determined for SWAN Wadden Sea calibration)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In the above table, we have set $\alpha_{BJ} = 1$, to avoid the essential interdependence that exists between $\gamma_{BJ}$ and $\alpha_{BJ}$, which was explicitly shown in Dingemans (1997). This fixing to unity is also in line with the approaches of Battjes and Stive (1985), and, more recently, Ruessink et al. (2003).

Note: For the Wadden Sea, the effect on the overall modelling results of inclusion of triads in the process description needs to be assessed explicitly, cf. the pragmatic approach for HBC SWAN applications for the western coastal zone, for which triads are presently not included (Haskoning/WL, 2005).

5.2 Selection of measures of calibration quality; GoF

The primary dependent variable solved in (1) is the action density $N$. It would therefore seem logical to compare this variable (or the variance density $E=N/\sigma^2$) to observations and to derive quality criteria based on these. At present no methods are available to evaluate model performance in terms of wave spectra, however, let alone calibrating a wave model on the basis of wave spectra. Moreover, wave spectra are multi-dimensional and observations can be noisy, so that the goodness of fit of spectra is typically only evaluated qualitatively. Quantitative evaluation is reserved for integral quantities derived from these spectra. A further argument against basing the quality of the present calibration runs on spectra, is that for the purpose of dike design considered here, the relevant parameters are in fact the integral quantities of significant wave height ($H_{m0}$), wave period (e.g. $T_{m-1,0}$, $T_p$) and mean direction $\bar{\theta}$. (The parameter $T_{m-1,0}$ is a direct measure for the momentum in the wave field.) It is therefore proposed that the quality of calibration runs of the Wadden Sea field situation should be based on these integral quantities. For the generic calibration sets (e.g. deep water balance), however, it is desirable to additionally consider a few characteristics of the spectrum, as presented in Table 2. The evaluation of these criteria could be automated, and checked against user-defined maximum tolerance for acceptance.

Given that the quality of the Wadden Sea calibration runs is to be evaluated using integral quantities derived from the spectra, a set of appropriate evaluation statistics should be selected. It is proposed to use at least the following statistical parameters for this purpose:

- The RMS error, as a measure of the absolute error over the period considered;
- The bias, as measure of systematic error;
- The scatter index, as measure of the relative error;
- The correlation between simulation results and observations.

In the Wadden Sea field application, these statistical parameters should be minimized. In the generic tests (deep water and shallow water balances) maximum allowable values of these statistical parameters should be set, to make explicit the minimum quality of representation of these processes that is needed for Wadden Sea applications.

(In the Delft Hydraulics validation project H1224 (Van Vledder, 1993) it was concluded that model evaluation and validation against independent data should always be based on a representative set of well-chosen and selective statistical parameters characterising the (mis)fit in combination with a set of graphical displays of the data, e.g. time series (also the difference), scatter plots and error histograms.)
5.3 Calibration guidelines

Using the parameter classification and measures of calibration quality discussed above, a system of calibration requirements is set out below. The basic concept of this system is the application of a hierarchy of calibration requirements:

1. The generic model requirements and constraints, as listed in Table 2, are set a priori.
2. Using these constraints, the basic processes in (2A) deep water followed by those for (2B) shallow water are calibrated first, yielding optimum parameter values plus ranges of acceptable settings of the lesser known parameters.
3. Finally the resulting parameter ranges are applied in the calibration of the model for complex field applications such as the Wadden Sea region.
4. In the latter, the calibrated deep water and shallow water parameter settings are allowed to vary within the calibrated acceptable ranges only (so we do not apply a strict hierarchy of calibration but allow reassessment of steps earlier in the calibration hierarchy. Such reassessment can only lead to restricted adjustments – within the pre-established acceptable ranges).

1) The first stage of the calibration process is the calibration of the action balance (1) in deep water. Here a number of generic constraints pertaining to the results of the deep water balance have been established, as listed in Table 2. These ensure that the relative magnitudes of the source terms are in proportion, and that the spectrum and quadruplet interaction do not attain non-physical values. In addition, the minimum required number of iterations is set to a value that ensures convergence in the results for the whole range of relevant physical processes.

2A) For initial calibration of the deep water processes, the assumption is made that deep water processes and shallow water processes can be separated. With the generic criteria set, the deep water balance itself can be calibrated. At this stage, an optimum value and a range of tolerance is determined for each parameter in the deep water balance. The parameter values of whitecapping dissipation, the closing term of the deep water balance, are found by considering the balance of all three deep water source terms. For this purpose, model results of deep water fetch-limited growth curves are compared against observations. Limits of acceptability of growth curve results should be set, for which a maximum bias in total energy and peak frequency of 10% appears reasonable. The optimum parameter value set is defined as that combination yielding the smallest bias in these parameters.

2B) Having established an acceptable parameter space for the deep water source terms, the second stage of the calibration can be entered, namely the action balance Equation (1) in shallow water. Here the sub-systems of triad interaction and depth-induced breaking may be isolated and calibrated first, using the data mentioned in Appendix B.3. Once the acceptable parameter ranges for triad interaction and depth-induced breaking have been found, the parameter for bottom friction (the closure term in shallow water) is calibrated. This is done by considering the balance of all deep and shallow water source terms, and using depth-limited growth curves, with the same limits of applicability as for the fetch-limited growth curves, as generic measure. The result is an eleven-dimensional parameter space containing parameter value combinations that produce acceptable results for generic situations in deep and shallow water.
3) Having calibrated all parameters to the selected generic situations, with the resulting parameter value space, the calibration to the Wadden Sea field case is considered. As discussed above, a number of complex wave evolution processes take place in the Wadden Sea. When performing a manual calibration, it would be possible to follow the wave evolution process from offshore to the foot of the dike, sequentially optimizing the processes in each region. For example, one may require a particular parameter setting to produce satisfactory results in the breaker zone of the ebb (tidal) delta before proceeding towards the tidal flats, for which the calibration is re-considered. Such a process is impractical to automate. Moreover, for the Wadden Sea, a single set of optimum parameter values plus ranges is aimed for. The system is therefore considered as a whole, choosing parameter values that yield the best average performance of the model for all processes balances found in the area under consideration. For such an evaluation, it is necessary to have adequate field observations in all the regions for which the parameter choices are to be optimized. For this purpose the before-mentioned tidal inlets, the shallow inlet sea and the shallow forelands near the dikes are relevant, and all should be well-instrumented (we note that issues of determining the optimum distribution and adequacy of observations for the Wadden Sea are not part of the present activity).

4) In the calibration to a shallow water situation such as the Wadden Sea, it is not desirable to move outside the parameter space established in the generic situations. Furthermore, as mentioned above, the optimal parameter settings of the deep water terms should only be changed within their established acceptable ranges. The parameter values of the shallow water terms may yet be optimized for the particular field situation, especially those in the ‘dust bin’ category of Table 2, such as the dissipation parameter $C_{ds,bot}$.

Calibrating a wave model consists of adjusting parameter settings until an optimal fit of computed wave parameters with measured wave parameters is found. In this process some parameter values may reach unrealistic values, i.e. values not within an accepted physical range. Moreover, the calibration process may yield unrealistic spectral shapes. Therefore, as stated above under 2A and 2B, the calibration tool should have facilities to deal with constraints in terms of acceptable ranges of the parameters, so-called “bound” optimisation techniques. Avoiding unrealistic spectra is much harder to achieve automatically. Probably, human inspection is required to judge possible outcomes of the calibration process (during the calibration procedure). In case unrealistic spectra are found, a new setup of a calibration run should be derived. Having an efficient calibration tool, allows the investigation of multiple settings.

Additional requirements for the calibration tool can be summarized as follows:

- Able to handle a non-linear model;
- Transparent and flexible definition of (least squares) error or Goodness-of-Fit (GoF) criterion, taking into account uncertainty information through weight factors;
- Determine accuracy of calibrated model;
- Determine a bandwidth around the calibrated parameters;
- Calibrate on integral wave parameters (and possibly quantiles of the spectrum);
- Allow for a limited number of SWAN runs; because of simulation time;
- The number of calibration parameters should be limited; because of simulation time.
6 Discussion

Developing a calibration tool for SWAN in the Wadden Sea is a challenging task. Both SWAN and the Wadden Sea contribute to this:

- SWAN has many source term formulations to choose from. For example, there are three different formulations for bottom friction. For the Wadden Sea application, a specific set of formulations should be selected beforehand;
- A SWAN computation in the Wadden Sea is time-consuming (this puts a practical constraint on the amount of computations that can be applied in the calibration process);
- SWAN is a non-linear model, mainly due to the inclusion of nonlinear quadruplet and triad interaction;
- Some processes put a constraint on some integral wave parameters (e.g. depth-limited wave height by breaking in shallow water);
- The accuracy of the numerical solution of SWAN depends on the number of iterations, the power of the imposed parametric spectral tail and on the spectral and spatial resolution.

For the Wadden Sea a number of reasons can be mentioned:

- The Wadden Sea contains various areas in which subsets of physical processes are dominant;
- The Wadden Sea has complex bottom topography, such that the wave field has many small scale variations. This makes it hard to obtain accurate data to compute an error function. This is especially true when wave measurements and model results are obtained near the edge of tidal channels;
- The wave conditions in the Wadden Sea are also determined by strongly nonstationary and inhomogeneous currents, and by a weakly varying wind field due to land-sea effects.

In this study the main model processes and their parameters were briefly described, an indication was given of the uncertainty associated with each and of the extent to which processes can be calibrated in isolation (summarised in Chapter 3, details in Appendix A). In Appendix B, a conventional manual calibration procedure was described, which shows how the calibration of the model starts from the primary deep water balance and proceeds to shallow water and eventually a particular shallow water field application. These elements were combined to form guidelines for an automated calibration procedure. The basic principle of the system of requirements presented here is that the parameter range used in the specific field application (i.e. Wadden Sea) is set by the requirement that the more generic processes (e.g. the deep water balance) should always be sufficiently reproduced, by ensuring that the earlier established acceptable parameter ranges are not violated. On the one hand this ensures the generality of the final set of calibration parameters, and on the other it limits the number of calibration runs required for the specific field application. However, even with such a methodology, the number and uncertainty of parameters in SWAN presents a large parameter range to test. If indeed all source term parameters are taken as uncertain (the most general case), and a range is allowed for each, the system of requirements presented above may still yield a very large number of
simulations. This number may be reduced by fixing the values of application-dependent parameters that are fairly well established (e.g. the wind input or DIA parameters). This reduces the total number of required simulations, at the cost of potentially reducing the number of valid parameter combinations. In case the computational effort of a SWAN run can not be reduced sufficiently (this is an ongoing process), massive parallel computing may have to be considered.
7 Requirements for the calibration tool

Based on the descriptions and discussions in the preceding chapters, the requirements and recommendations for the calibration tool can be categorised as follows:

Purpose of the calibration tool:
- The purpose of the calibration tool is to determine in an efficient and effective way the optimum parameter setting of the SWAN model to compute spectral wave transformation in tidal areas with complex bottom topography, notably the Wadden Sea.
- It should result in a single (optimum), physically realistic parameter setting for the Wadden Sea.
- The calibration tool should have facilities to deal with constraints in terms of acceptable parameter ranges.
- Due to the various sources of uncertainty the optimum parameter estimates are inherently uncertain. It is therefore recommended to quantify this in some way, e.g. by determining a band around the optimum, or, ideally, the probability density function for the parameters.
- With the calibrated model, the Hydraulic Boundary Conditions can be computed more reliably than with a non-calibrated model.

Description of the calibration tool:
- The calibration tool is a flexible software environment, allowing efficient defining, running and evaluating series of model simulations with the aim of efficient and effective assessment of the effects of variations in SWAN parameter settings. Key words are: (semi-)automated, quantified, objective and reproducible.
- The tool allows the flexible definition of explicit error measures or Goodness-of-Fit criteria (plus non-acceptance criteria) in terms of relevant measurable quantities, taking into account associated uncertainties.
- The tool should allow for formal application of penalties in the GoF or allow for checks on physics-based constraints.
- The above quantitative criteria should be accompanied by well-chosen postprocessing to present visualizations and key statistical quantities.

Calibration – the GoF:
- For each simulation the calibration tool will automatically produce one or more GoF’s, associated statistical and graphical presentations. Criteria for evaluation of the convergence will be necessary and will be implemented, to enable intermediate interruption of the automated calibration cycle when user evaluation is deemed appropriate, so avoiding continuation with unrealistic settings.
- The minimisation technique for the GoF criterion or criteria should be effective and numerically efficient.
- A critical a priori assessment of the quality of the calibration and validation data sets used for comparison is necessary, in terms of relevance for the process at hand, measurement accuracy and their spatial/temporal distribution and representativity for the Wadden Sea (or other domain) as a whole.
• This data assessment will be reflected in the appropriate weight factors in the GoF criterion.
• Based on general practice and availability of reliable data sets, the GoF will in principle be based on a formulation in terms of the integral parameters significant wave height ($H_{m0}$), peak period ($T_p$), wave period ($T_{m-1,0}$) and mean direction $\bar{\theta}$ (with weight terms), but could also provide information on the spectral form (tail). Information on the high end of the spectrum, relevant for various fail mechanisms, is represented by $T_{m02}$.
• As an example of a GoF or least squares criterion, we refer to Alkyon (2003). This formula could be adapted for the present case to read:

$$
GoF = \frac{\sum_{i=1}^{N_i} w_i \left( H^i_{s,obs} - H^i_{s,sim} \right)^2}{\sum_{i=1}^{N_i} w_i^2 \sigma^2_{H_{s,obs}}} + \frac{\sum_{i=1}^{N} w_{T^i_{m-1,obs}}^2 \sigma^2_{T^i_{m-1,obs}}}{\sum_{i=1}^{N} w_{T^i_{m-1,obs}}^2} + \frac{\sum_{i=1}^{N} w_{T^i_{p,obs}}^2 \sigma^2_{T^i_{p,obs}}}{\sum_{i=1}^{N} w_{T^i_{p,obs}}^2} + \frac{\sum_{i=1}^{N} w_{T^i_{m02,obs}}^2 \sigma^2_{T^i_{m02,obs}}}{\sum_{i=1}^{N} w_{T^i_{m02,obs}}^2} + \frac{\sum_{i=1}^{N} w_{\theta^i_{obs}}^2 \sigma^2_{\theta^i_{obs}}}{\sum_{i=1}^{N} w_{\theta^i_{obs}}^2},
$$

in which $N_i$ is the number of spatial calibration data points (possibly summed over a number of applications), $w^i_p$ is a weight function, and $\sigma^i_{\varphi_{obs}}$ the standard deviation of the observed parameter in the particular location, accounting for the uncertainty or quality of the respective observations. An appropriate directional measure would be the angle from the mean wave direction $\bar{\theta}$ (ensuring proper accounting for directional periodicity).

**Calibration – aspect of constraints and statistical quantities:**
• Required spectral and other behaviour will be checked in the form of constraints by defining appropriate checks which can be made in a semi-automated way.
• The following statistical measures should be calculated for each model simulation result: RMS error, bias, spread, scatter index, correlation index between simulation results and observations, see (Van Vledder, 1993).
• Similarly, the following graphical output should be provided for each model simulation result: time series plot, scatter diagram, error histogram, see (Van Vledder, 1993).

**Use of the calibration tool:**
• The calibration tool does not assume the existence of a rigid hierarchy or ranking of processes, as assumed in rigorous successive and separate generic calibration of key
processes and parameters, starting with numerical settings (iteration), deep water parameterisations, shallow water processes, and Wadden Sea application.

- Calibrated parameter settings for the deep water processes should only be adjusted within the earlier established acceptable ranges when calibrating shallow water process parameterisations.
- In line with Battjes and Stive (1985) and Ruessink et al. (2003), the parameter $a_{bj}$ in the depth-induced breaking formulation formulation is set to $a_{bj} = 1$, to avoid effects of interdependence as shown by Dingemans (1997, pp. 397-398).
- For the calibration material used for assessing the quadruplet and triad parameterisations benchmark simulations and flume experiment data will be used, respectively.

**Issues not addressed by the calibration tool:**

- The choice of model domain for an application is treated as fixed and well-founded at the start of the calibration – it cannot be subject of the calibration process.
- The same holds for the geographical model resolution; only in case of significant spatial redundancy in independent observations will calibration allow explicit conclusions about adequacy of the resolution.
- The optimum parameter setting obtained in the calibration process will not automatically be valid beyond the range of tested physics, i.e. for general extreme situations not represented in the calibration data sets used.
8 References


SWAN website: http://130.161.13.149/swan/


A Processes in SWAN; uncertain parameters

The model SWAN computes the evolution of wave action density $N(x,y,v,t)$ using the action balance equation (Booij et al. 1999):

$$\frac{\partial N}{\partial t} + \nabla_{s,y} \cdot \left[ \left( c_g + U \right) N \right] + \frac{\partial}{\partial \theta} \left( c_g N \right) + \frac{\partial}{\partial \sigma} \left( c_v N \right) = \frac{S_{tot}}{\sigma}$$

(1)

with

$$S_{tot} = S_{in} + S_{wc} + S_{nl4} + S_{bot} + S_{brk} + S_{nl3}$$

(2)

The terms on the left-hand side represent, respectively, the change of wave action in time, the propagation of wave action in geographical space (with $c_g$ the wave group velocity vector and $U$ the ambient current), diffraction and depth- and current-induced refraction (with propagation velocity $c_g$ in directional space $\theta$) and the shifting of the radian frequency $\sigma$ due to variations in mean current and depth (with the propagation velocity $c_v$). The right-hand side represents processes that generate, dissipate or redistribute wave energy. In deep water, three source terms are used: the transfer of energy from the wind to the waves, $S_{in}$; the dissipation of wave energy due to whitecapping, $S_{wc}$; and the nonlinear transfer of wave energy due to quadruplet (four-wave) interaction, $S_{nl4}$. In shallow water, dissipation due to bottom friction, $S_{bot}$, dissipation due to depth-induced breaking, $S_{brk}$, and nonlinear triad (three-wave) interaction, $S_{nl3}$, are additionally accounted for.

Equation (1) is implemented numerically with a second-order upwind, implicit four-sweep scheme for propagation in geographical space and a hybrid upwind-central scheme in the frequency and directional spaces. Because of the sweeping process in geographical space and the dependency of some source terms over more than one directional quadrant (i.e. over more than one sweep), Equation (1) must be solved iteratively until some convergence criteria are met.

From the above, it is seen that the processes in SWAN can be divided into three categories:

- propagation (including the influence of current),
- deep water processes and
- shallow water processes.

Additionally, the numerical implementation and settings influence model results, and one must be aware of this in a calibration procedure. The three process groups and numerical settings are described in more detail below, with specific attention to the uncertainty of the modelling of the various processes and the parameters to be calibrated. In this discussion the scope is limited to the default source terms of SWAN version 40.51.

A.1 Propagation of wave energy

The last three terms on the left-hand side of (1) represent the propagation of wave energy in geographical, directional and frequency space under the influence of topography and current. The expressions applied have been derived from first principles using linear wave
theory and the conservation of wave crests. As such, these expressions do not incorporate any parameters for calibration. Their performance therefore depends for a large part on the way in which they are implemented numerically (see below). Analytical expressions are available for the verification of these implementations. It is noted, however, that some of these expressions may still be inherently inaccurate, for example the modelling of wave-current interaction which does not take the actual current profile into account.

### A.2 Deep water processes

By deep water processes are meant the source terms of wind input, whitecapping dissipation and nonlinear four-wave interactions (quadruplet interaction) which, together with the propagation terms, form the primary spectral evolution balance in (1) in deep water. The processes of wind input and whitecapping are modelled using the expressions of Komen et al. (1984) and for quadruplet interaction the Discrete Interaction Approximation (DIA) of Hasselmann et al. (1985) is applied. Both the expressions for wind input and whitecapping dissipation are linear in the variance density. Quadruplet interaction, on the other hand, is a nonlinear function of the variance density, and tends to impress a frontal shape (in frequency space) onto the spectrum. Quadruplet interaction therefore has a dominant role in imposing a self-similarity onto the wave spectra during all stages of development.

Of these three, the wind input expression, based on Snyder et al. (1981), is the best-established experimentally - at least for light winds over fairly mature wind-sea. Quadruplet interaction, although difficult to measure experimentally, is well-established theoretically for homogeneous, random-phase wave fields. In operational applications, the DIA expression is used, which is an approximation of the complete set of quadruplet interactions described by Hasselmann (1962). The use of the DIA therefore introduces inaccuracies that are not insignificant, but the method is considerably faster than the full quadruplet calculation. In comparison to wind input and quadruplets, there is much uncertainty concerning the physical mechanism of whitecapping dissipation and hence the appropriate form for its source term. The expressions available for whitecapping are mostly speculative, and therefore whitecapping is customarily used as a closing term in the calibration process.

The wind input expression of Komen et al. (1984) incorporates one proportionality coefficient, \( \alpha_{in} \), the value of which is determined directly from measurements of momentum transfer from wind to the waves (e.g. Snyder et al., 1981). The complete calculation of quadruplet interaction is derived from first principles (apart from the application of a closure hypothesis) and does not contain any uncertain parameters. However, with the DIA approximation the parameters \( \lambda_{nl4} \) and \( C_{nl4} \) are introduced, which are chosen such as to yield a good general representation of the result of the full quadruplet calculation (e.g. Hasselmann et al., 1985). The whitecapping expression of Komen et al. (1984), being quite speculative, has three parameters, namely the exponents \( q \) and \( r \) and a proportionality coefficient \( C_{ds,wc} \). Since whitecapping dissipation is very difficult to measure in the field, very little direct measurement of this phenomenon is available. Therefore, the parameters of the whitecapping expression are calibrated to balance the expressions of wind input and quadruplet interaction in deep water.
A.3 Shallow water processes

In water of finite depth, the deep water processes discussed above are complemented by the processes of bottom friction dissipation, depth-induced breaking dissipation and nonlinear triad interaction. In shallower water the deep water terms remain important, but are increasingly dominated by the shallow water processes as the water depth decreases. Of the three shallow water processes, only nonlinear triad interaction has been described by expressions derived from first principles (e.g. Eldeberky, 1996 and Janssen, 2006). However, as is the case with quadruplet interaction, operational models use efficient parameterizations of the complete triad calculation. In SWAN, the Lumped Triad Approximation (LTA) of Eldeberky (1996) is used, which has a single proportionality coefficient \(D_{EB}\). As with quadruplet interaction, the value of \(D_{EB}\) is found by attempting to reproduce similar results as obtained with the full triad calculation.

The dissipation processes of bottom friction and depth-induced breaking are modelled using turbulence and hydraulic jump (bore) analogies respectively. As is the case with whitecapping, little is known about the mechanism of these dissipation processes, and the expressions are therefore speculative. Nonetheless, the source term for depth-induced breaking of Battjes and Janssen (1978) has proven robust in a wide range of applications. This expression has two parameters, namely \(\alpha_{BJ}\) and \(\gamma_{BJ}\). For bottom friction dissipation, the expression of Hasselmann et al. (1973) is used. This expression has a single parameter in the form of a proportionality coefficient \(C_{ds,bot}\).

The balance of source terms in water of finite depth is more complex and not as well studied as the balance in deep water mentioned above. In intermediate depths, the balance in (1) can be considered to be between propagation, the deep water source terms and bottom friction. The bottom friction expression may be considered as a closure term in this situation and its parameter calibrated accordingly. In very shallow water the source terms of triad interaction and depth-induced breaking dominate the right-hand side of (1). Advantage is taken of this fact to calibrate the parameters of the depth-induced breaking expression to observations of total spectral energy (e.g. Battjes and Stive, 1985).

A.4 Numerical procedure

The three main categories of physical processes in SWAN were discussed above. The numerical implementation of these processes is a given property of the SWAN 40.51 model, as are the parameterisations of its physical processes. They are the subject of the present calibration, as their adjustments will imply a new SWAN version, which needs a calibration as such. The SWAN 40.51 numerical settings need to be considered before calibration. As described above, equation (1) is numerically implemented with an implicit four-sweep scheme for geographical propagation, and as a result, is solved iteratively. Therefore, firstly, the number of iterations should be set. On the one hand, simulation time is proportional to the number of iterations applied and should be minimized, but, on the other hand, allowing too few can compromise the accuracy of results. In the second place, the resolution in geographical and spectral spaces and in time (for non-stationary simulations) need to be specified. The resolution and the number of iterations can be considered the primary numerical settings affecting both simulation time and the model accuracy. They need to be set before the actual calibration, preferably slightly conservatively, in order not to avoid
aliasing of inadequacies in these settings into the calibrated parameters. In addition to these, the schemes applied in the frequency and directional spaces have weighting factors by which upwind and central solution schemes are combined. These weighting factors are intended to provide the optimum between diffusive (first-order upwind) and oscillatory (second-order central) solutions. Model results are generally quite insensitive to these weighting factors, and they are not considered further here. Moreover, a small amount of (frequency-dependent under-relaxation may be required to obtain non-oscillating solutions. Based on prior experience, it is assumed that the under-relaxation and changes in the discretisation scheme weight factors do not affect the calibration. Preferably, for the Wadden Sea one single setting should be used.
B Conventional calibration procedure

As background to the compilation of a set of requirements for an automated calibration system, this section describes a conventional calibration procedure for SWAN. This procedure can be divided into the following steps:

1. Establishing the numerical settings;
2. Calibration of deep water processes;
3. Calibration of finite-depth processes and propagation;
4. Calibration for a specific field situation.

The discussion below is limited to the stationary mode of SWAN, since most generic calibration tests consider the time-independent model solution and also because this is the model mode that is of relevance for the Wadden Sea application area.

B.1 Numerical settings

The modelling step well before the calibration procedure is to define the geographical domain for the model, the spatial grid and its resolution and to establish the optimal numerical settings. The calibration can only explicitly reject the defined model domain as inadequate in the extreme case that the calibration does not lead to results that are consistently improving and are acceptable in physical sense. In that case the choice of model domain (and/or geographical resolution) needs to be revisited. Minor inadequacies in the model domain are implicitly absorbed in the parameter calibration (which therefore leads to formally non-optimal parameter estimates). For determining adequate resolution in geographical and spectral spaces, standard numerical techniques can be applied. The number of iterations required for convergence of a stationary simulation can vary per situation, and the default criteria for convergence may stop the simulation prematurely, compromising accuracy (Zijlema and Van der Westhuysen, 2005). To assure convergence, it is typically sufficient to allow between 30 and 50 iterations. For the Wadden Sea the appropriate number needs to be determined.

In activity 3.1 of the main SBW study “Gevoeligheidsanalyse numerieke aspecten” (WL, 2006, Chapter 9) the sensitivity of other numerical parameters to the wave conditions in the Wadden Sea is being investigated. These numerical parameters are the geographical resolution and the spectral resolution (in frequency space and directional space). Furthermore, the iteration behaviour has been investigated, resulting in a recommendation to use the newly developed convergence criterion of Zijlema and Van der Westhuysen (2005), based on the curvature of the relative error. Based on the latter, the iteration parameter needs to be set to an optimum value for the SWAN 40.51 Wadden Sea calibration, appropriate for all situations.

B.2 Deep water balance

The basic physical system calibrated is the balance expressed by Equation (1) in deep water, considering the balance between propagation and the source terms of wind input,
whitecapping dissipation and quadruplet interaction. The expressions for wind input and quadruplet interaction may be calibrated independently, and therefore this is considered first. The wind input expression is calibrated to measurements of momentum transfer from wind to the waves, using data of e.g. Snyder et al. (1981), Hsiao and Shemdin (1983) and Donelan et al. (2006). These observations are difficult to make and their scatter can be significant. As a result, the parameter value chosen is typically the mean of quite a large point cloud. Next, the parameters of the DIA expression for quadruplet interactions are found. These are obtained by optimising the source term results of the DIA expression with respect to those of the full calculation algorithm, for various spectra and parameter choices. Alternatively, the parameter values may be found by considering the entire deep water balance and optimizing the results of growth curves. The parameter values obtained by Hasselmann et al. (1985) are typically applied.

With the parameter values of wind input and quadruplet interaction set, the parameter values of whitecapping are determined. These are found by considering the balance between propagation and the three deep water source terms, with whitecapping taken as the closing term. This balance is expressed in the simulation results of (bulk energy and frequency) of deep water, fetch-limited growth curves, which are compared to observations. Measurements of fetch-limited growth curves are available from a number of sources, with those of Hasselmann et al. (1973), Donelan et al. (1985) and Kahma and Calkoen (1994) the most widely used. The statistical parameter used to evaluate the quality of these runs is typically the bias of the bulk parameters of energy and frequency. In addition to the optimization of these bulk parameters, some basic features of the spectra and spectral balance are also considered. These are, for example, the shape of the high-frequency tail, the general shape of the spectrum and the relative sizes and frequency distribution of the three source terms.

B.3 Shallow water balance and propagation

For shallow water application, the balance expressed by Equation (1) incorporates the processes of bottom friction, depth-induced breaking and triad interaction. Compared to the deep water balance, the shallow water balance is more complex and less generic. An additional complication is that, to date, little is known about the influence of finite depth on the processes of wind input and whitecapping. Nonetheless, as in the calibration of the deep water balance, some of the shallow water source terms may be calibrated individually. For triad interaction, cases may be isolated in which a wave field in shallow water, over which no wind is blowing, is highly nonlinear but not strongly breaking (e.g. Beji and Battjes, 1993 and Boers, 1996). Under such conditions the proportionality coefficient of the LTA approximation may be calibrated either to the results of a complete triad calculation, or simply to the observed spectra. Similarly, depth-induced breaking may be isolated and calibrated in the surf zone, where this process, together with triad interaction, dominates (e.g. Battjes and Stive, 1985 and Boers, 1996).

Having calibrated the expressions for triad interaction and depth-induced breaking independently, bottom friction may be calibrated to close the shallow water balance. For this purpose, the depth-limited growth relations by Young and Verhagen (1996) and Young and Babanin (2006) may be used, which provide observations of bulk energy and frequency as a function of dimensionless depth to which to calibrate. In these relations, the values at large
dimensionless depth resemble the deep water balance, whereas at intermediate depths the balance is between the deep water terms and bottom friction. Swell propagation over shelf seas and into estuaries is related to this latter case, in which the left hand side of (1) is balanced by quadruplet interaction, whitecapping and bottom friction.

**B.4 Specific field situation**

Having ensured, by the above process, that the parameter choices of the deep and shallow water source terms are sufficiently generic, these settings are applied to a specific field case of interest. In this discussion the Wadden Sea area will be considered. In general, the parameter values obtained in the generic tests could be optimized further for a particular field case. However, often a calibration hierarchy is assumed, which means that the calibrated parameter values of the deep water processes are not altered in a specific shallow water application, unless it can be motivated that such an alteration is due to finite-depth influence. If this is indeed required, it points to shortcomings (in shallow water application) in the expressions used.

In calibration for a shallow water field situation attention should therefore focus on the shallow water source terms. It is possible to separate the geographical area of the Wadden Sea into regions over which particular source term balances and processes are expected. Instead of making the common separation deep-shallow, a more regional separation can be made. We expect that the Wadden Sea can be divided into three sub-systems in which different sets of processes play a role. The first sub-system comprises of the tidal inlets through which long-period North Sea waves penetrate into the Wadden Sea. The second sub-system comprises of the shallow inlet sea in which wave (re)-generation takes places. The third sub-system consists of the shallow forelands near the dikes. The boundaries between these sub-systems cannot clearly be determined. In moderate to storm conditions these three sub-systems can probably be clearly identified, whereas in severe storm conditions the areas may overlap. This division into subsystems with different ranking of the key physical processes should not be interpreted as leading to more than one (1) set of optimum values for the calibration parameters.

The shallow water parameter values found previously from the generic calibration sets should be applied as a first estimate, and altered somewhat if required. However, again in the interest of generality, it is desirable that these newly calibrated values, once found, should be tested against the generic calibration sets. In this way, the calibration procedure has an iterative nature. As noted above, if the parameter values suited to the field case is found to be irreconcilable with the generic calibration sets, this might point either to shortcomings of the source term expressions used, or indeed of the quality and generality of the generic calibration data sets.