Storm surge duration and storm duration at Hoek van Holland

SBW-Belastingen

Deltares

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Storm duration, storm surge duration, Hydraulic Boundary Conditions, Hydra-B.

Summary
The probabilistic model Hydra-B is used to determine the design water levels ('toetspeilen') for assessing dikes in the Rhine-Meuse estuary. Storm surge duration and (wind) storm duration are two parameters that determine the design water level in Hydra-B. Both are set at 29 hours in the current version of Hydra-B, however without substantial scientific grounds.

This study determines both duration parameters from water level measurements (storm surge duration) and wind speed measurements (storm duration) at Hoek van Holland. Where possible, the same procedures were followed for both parameters. Relevant storm events were selected using a peaks over threshold procedure. The durations of surge and storm were determined for each selected storm, assuming a trapezoidal shape for the time evolution of both variables. The mean duration was then determined by averaging over all storm events.

For storm surge duration the mean duration was found to be 46 hours above a threshold of 0 m and 30 hours above a threshold of 0.5 m. The duration above a threshold level of 0.5 m was considered to be physically more meaningful. Therefore it is recommended to apply a trapezoidal shape with a duration of 30 hours above a surge level of 0.5 m for future usage in Hydra-B.

For storm duration, a mean value of 51 hours was found, using a trapezoidal time evolution with a peak duration of 1 hour. As an alternative, a trapezoidal shape as used in Hydra-VIJ, with a peak duration of 2 hours and a total duration of 48 hours, was also found to be an acceptable representation of the mean evolution of wind speed. For consistency with Hydra-VIJ, adopting this schematisation for wind speed in Hydra-B therefore merits consideration.

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Contents

1 Extended summary

1.1 General

The Dutch Water Defences Act requires the authorities to assess their primary water defences once every five years. Dike authorities sometimes have to contend with knowledge gaps when assessing water defences, because essential knowledge for carrying out the assessment process is not available. This may lead to an assessment of “no opinion”, which is socially and politically undesirable. It may also result in water defences being erroneously approved or rejected, outcomes which are equally undesirable. The SBW (Strength and Loads of Water Defences) programme aims to fill in the main knowledge gaps with respect to the assessment of primary water defences. SBW supplies knowledge and instruments for the WTI project (WTI = Legal Assessment Instruments; formerly HR/VTV). The SBW programme currently includes nine projects. The SBW Loads project looks at loads on the primary defences in all freshwater and saltwater systems in the Netherlands, and conducts studies for a more precise determination of the Hydraulic Boundary Conditions.

The probabilistic model Hydra-B is used to determine the design water levels for assessing dikes in the Rhine-Meuse estuary. Storm surge duration and storm duration are two parameters that determine the design water level in Hydra-B. The first refers to the water level increase compared to the astronomic tide, the second to the wind speed. Both are set at 29 hours in the current version of Hydra-B, but there would not appear to be sound reasons for this value. The provincial authority of South Holland, for one, considers it to be too short. This means that the design water levels determined for HR2001 and HR2006 may be too low. For instance, a storm surge duration of 40 hours rather than 29 hours will result in an increase in design water levels of some 25 cm at Haringvliet/Hollandsch Diep, where the effects are greatest [12].

1.2 Current modelling in Hydra-B

Hydra-B includes a database with computational results from the hydrodynamic model Sobek. Sobek was used to carry out simulations for various wind speeds, wind directions, sea levels, river discharges (from the Rhine and Meuse) and settings of sea defences (open/closed) to determine, throughout the Rhine-Meuse estuary, the maximum water level given those conditions. The evolution in time was also applied as a boundary condition in all simulations of both sea level and wind speed. The sea level is a combination of the astronomical tide and the surge resulting from high wind speeds ("storm surge"). An average situation is assumed for the astronomical tide. The assumed time evolution for storm surge and wind speed is schematized as follows:

- storm surge duration is defined as the length of time the storm surge exceeds 0 m;
- storm duration is defined as the length of time the wind speed exceeds 10 m/s;
- storm surge duration and storm duration are both 29 hours, independent of the peak values.
- an onset and aftermath of twelve hours each were added to the wind speed shape to describe the evolution between 0 m/s and 10 m/s;
- the wind speed has a peak plateau of 5 hours, while the surge has an almost flat peak of 4 hours;
- the storm surge peak occurs 4.5 hours prior to the astronomic tide peak.

The assumed evolution in time for storm surge is shown in Figure 6.1. The assumed evolution in time for wind speed is shown in Figure 11.1

1.3 Objectives

This study redetermines both duration parameters from water level measurements (surge duration) and wind measurements (storm duration) at Hoek van Holland for future usage in Hydra-B. A precondition is that Hydra-B will not be significantly modified. This implies that the duration of a representative storm with a single peak must be determined. The durations are also assumed independent of the peak value.

More complex time graphs (multiple peaks) and dependency between the peak value and duration have been explored to a limited extent in this study, with a view to possible future modifications to Hydra-B. It is important to realize that *design water levels* at the river side of the Maeslantkering are mainly determined by the *duration* of the closing of the barrier, rather than by the shape of the sea level hydrograph. The influence of storms with multiple peaks on this period is limited because, as a rule, it is possible to discharge between two storms.

1.4 Approach

Where possible, the same procedures were followed for the storm surge duration and the storm duration, but some exceptions were necessary. A major difference is that, to determine the surge duration, the storm surge first had to be derived from the water level measurements. This was done by subtracting the astronomical tide. A filter was then applied to the storm surge to remove residual tidal effects.

Relevant storm events were selected based on the criterion that the maximum value of either the surge or the wind speed had to exceed a defined threshold value. For each of the selected storms, the duration was then determined assuming a trapezoidal evolution of the wind speed in time. The mean duration for all selected storm events was then determined.

When quantifying the duration of an individual storm event, some decisions are required because of the use of a schematised evolution of the wind speed in time. After all, an actual storm does not follow a trapezoidal pattern. Indeed, storms with multiple peaks follow very different patterns. The question of how to determine the duration of such storms was submitted to a group of experts. In part given the recommendations of these experts, it was decided to exclude adjacent peaks as much as possible when determining the storm surge duration and storm duration. The main reasons are that [a] storms with multiple peaks are not consistent with the schematised shape used in Hydra-B and that [b] as a rule it will be possible to open the Maeslantkering between two successive peaks to discharge excess river water.

1.5 Conclusions and recommendations

The main conclusions from the study are as follows.

- For storm surge duration, a mean value was found of 46 hours above a threshold of 0 m and 30 hours above a threshold of 0.5 m. The results of this study better support the use of a threshold of 0.5 m as the basis for the schematised storm surge hydrograph for future computations with Hydra-B.
- For storm duration, a mean value was found of 51 hours above 0 m/s. The basic level of 10 m/s was abandoned.
- For storm duration, a comparison was made with an alternative schematisation, which is used in the Hydra-VIJ model for the IJssel and Vecht delta. This is a trapezium shape with a total duration of 48 hours. This shape also turned out to be a highly acceptable representation of the mean evolution of wind speed in time.

- For storm surge duration, the above value of 46 hours is a considerable increase compared to the current value of 29 hours. This is in line with earlier studies [13] suggesting that 29 hours is probably an underestimation.
- For storm duration, the current value of 29 hours refers to the length of time the wind speed is higher than a threshold value of 10 m/s with leading and trailing edges ending at 0 m/s. This corresponds to a period of 53 hours for a wind speed higher than 0 m/s. Consequently, the proposed new values of 48 or 51 hours are not major changes compared to the current schematisation.
- The current approach in Hydra-B, with a fixed surge duration, assumes that the surge duration is independent of the maximum surge. In the present study, no indications have been found that maximum surge level and surge duration are interdependent. This means the current assumption is acceptable.

The main recommendations from this study are the following:

Directly from this research

- We recommend adopting a mean storm surge duration of 30 hours above 0.5 m
- We recommend adopting a mean storm duration of 51 hours above 0 m/s. However, for consistency with Hydra-VIJ, adopting the schematisation from Hydra-VIJ in Hydra-B, together with the associated total storm duration of 48 hours, merits consideration.
- We also recommend making Hydra-B suitable in the future for more complex storm graphs, for instance with multiple peaks. For some applications, such as studies into storage of excess water, multiple peaks may be a highly relevant phenomenon.

Related to this research

- We recommend an analysis of the time difference between the maximum storm surge residual and the astronomical tide peak. Hydra-B currently assumes a time difference of 4.5 hours for all simulated storm events. A more realistic representation of this time difference seems appropriate and may significantly improve the estimates of design water levels. The proposed research should provide the necessary information for this adapted approach.
- We also advise improvements in the matching between Hydra-B and the strength models from the VTV. For instance, at present, the load duration is hardly incorporated, if at all, in the various models that describe the strength/resistance of flood defences.

2 Introduction

2.1 Background

Dutch Water Defences Act
The Dutch Water Defences Act requires water authorities to assess their primary water defences once every five years. The assessment must provide an insight into the current safety of the primary water defences and the results serve as a basis for initiating improvements. The Legal Assessment Instruments (WTI) prescribe the rules to be used. These instruments consist of the Safety Assessment Regulation (VTV), the Hydraulic Boundary Conditions (HR) and the underlying technical reports and guidelines. The Hydraulic Boundary Conditions are the numeric set of design hydraulic loads for all the locations of primary water defences. They must be determined every five years and adopted by the Secretary of State for Transport, Public Works and Water Management. The Safety Assessment Regulation prescribes how the assessment must be carried out and comprises a description of the assessment methods for the various failure mechanisms.

SBW loads project
Dike managers sometimes have to contend with knowledge gaps when assessing water defences, because essential knowledge for carrying out the assessment process is not available. The SBW (Strength and Loads Water Defences) programme aims to fill in the main knowledge gaps for assessing primary water defences. SBW supplies knowledge and instruments to the WTI project, not only for 2011, but also for subsequent assessment rounds. The SBW programme currently includes nine projects, with seven of them addressing the strength side and two the loads side (SBW Loads and SBW Wadden Sea). The study of storm surge duration and storm duration at Hoek van Holland, as described in the present document, is part of SBW Loads.

The objective of the SBW Belastingen (Loads) project is to demonstrate the quality of the models and methods, and to improve them where necessary. The idea is to present improved Hydraulic Boundary Conditions for the primary water defences in the Netherlands in 2016 and, where possible, in 2011.

Hydraulic boundary conditions for the lower rivers
For most water systems, hydraulic boundary conditions are derived with probabilistic methods. The probabilistic model Hydra-B is used to determine the design water levels for assessing the Rhine-Meuse estuary. A sensitivity analysis was conducted recently for a number of parameters in Hydra-B and the decisions made as Hydra-B was being set up [12]. One of the conclusions was that the required minimum dike crest height is sensitive to the values adopted for storm surge duration and storm duration.

2.2 Problem definition

The current storm surge duration and storm duration in the framework of HR2006 are set at 29 hours. However, the province of South Holland, for one, considers this to be too short. This means that the design water levels determined for HR2001 and HR2006 may be too low. For instance, a storm surge duration of 40 hours rather than 29 hours will cause an increase in design water levels of some 25 cm at Haringvliet/Hollandsch Diep, where the effects are greatest [12].

2.3 Objective

The aim of this study is to test the assumption for storm surge duration and storm duration of 29 hours in the Rhine-Meuse estuary against measurements at Hoek van Holland. If the study shows that the value of 29 hours needs to be adjusted, a recommendation will be issued to that effect.

2.4 Approach and scope

The following two questions are important with respect to storm surge duration for the Rhine-Meuse estuary and how it is used for WTI2011.

[a] Are there any reasons to deviate from the chosen duration of 29 hours?
[b] Are there any reasons to schematise the storm surge duration differently?

This report focuses on answering the first question. The obvious course of action is to leave the concept of Hydra-B and the associated Sobek calculations *for WTI2011* unchanged as far as possible. That is because the Hydra-B software and the control system for the Sobek calculations have to be completed by the end of 2009 in order to guarantee completion in time for WTI. It is not to be expected that major changes in both concepts can be implemented and accepted before then. Nevertheless, this report also looks at a number of considerations relating to different schematisations.

The study included the following:

- collecting multiple measurement series for wind speeds and water levels at Hoek van Holland;
- validating those measurement series;
- selecting suitable measurement series;
- deriving the surge from water level measurements and derived tide levels;
- the use of a filter to eliminate residual tidal effects.
- selecting relevant storm events;
- deriving surge durations and storm durations for each storm; and
- deriving the representative storm surge duration and storm duration;

Please note that the analysis of storm duration and storm surge duration *dependent of wind direction* is outside the scope of this study. The same applies to the analysis of the wind direction changes during storms.

2.5 Complementary analyses

In addition to determining the mean storm surge duration and storm duration, this report also discusses a number of additional analyses that may be relevant to practical application in the probabilistic model Hydra-B.

- Analysis of the relationship between storm surge duration and storm duration on one hand and maximum storm surge height and maximum wind speed on the other hand.
- Analysis of the probability distribution of the storm surge duration. This analysis was not made for storm duration. Section 11.4 explains why this was not done.

2.6 Project history: explanatory memorandum for main report and annex

During the course of the project, it was decided to produce an extra annex (in Dutch!) [9] in addition to the main report.
An explanation of the course of the project is required for a better understanding of the relation between the report and annex. This also explains the structure adopted for the report.

When deriving the duration of a storm event, it is important to decide whether or not to combine multiple peaks if they occur within a period of a couple of days. Moreover, a precise definition is required to state what exactly a secondary peak or an adjacent peak is. Various criteria can be chosen for this purpose and their inclusion or exclusion may have significant consequences for the eventual results. The possible criteria and their selection were discussed at length during an expert meeting on 26 March 2009. During the preceding months, an extensive sensitivity analysis was carried out of the implications of the selection of the criteria for the final results in order to feed this discussion.

The main conclusion of the meeting was that secondary should be excluded as much as possible. The experts' reasons were that [a] storms with multiple peaks are not consistent with the schematised shape used in Hydra-B and that [b] as a rule it is possible to open the Maeslantkering between two successive peaks to discharge excess river water. To enhance the readability of the main report, it was decided to include the sensitivity analysis for the expert meeting in a separate annex.

The annex describes only the sensitivity analysis for the storm surge duration. A similar analysis was not made for the storm duration since the initial aim of the project was solely to analyse storm surge duration. It was only at a later stage that it was concluded that the storm duration should also be derived, and separately. For reasons of consistency, we decided to adopt the same procedure for handling multiple peaks as for storm surge duration. This meant that a sensitivity analysis for storm duration no longer had any added value and so it was abandoned.

2.7 Report structure

This report describes the main results from the study. For the sake of readability (see previous section), we decided to include the more detailed analyses in an Annex [9].

Chapter 3 of this report describes the significance of storm surge duration in HR2006 and possible modifications for WTI2011. Chapter 4 describes a literature search for related past studies. Chapter 5 describes the analysis of the suitability of available measurement series for the study of storm surge duration. Chapter 6 describes the derivation of the storm surge duration. Chapter 7 describes the fitting of the probability distributions to the storm surge duration. Chapter 8 describes the correlation between storm surge duration and maximum surge height. Chapter 9 describes the effect on the derived storm surge duration of filtering to remove tidal effects from the surge. Chapter 10 describes an alternative way of deriving the storm surge duration. This alternative approach abandons the current Hydra-B modelling method. Chapter 11 describes the study of storm duration. It includes data analysis, the derivation of the storm duration and the correlation between wind speed and storm duration Chapter 12, finally, contains a summary and the preliminary conclusions of the study.

2.8 Review

Joost Beckers and Marcel van der Doef were responsible for the internal Deltares review of this report. Cees de Valk of BMT ARGOSS was responsible for the external review.

3 The role of storm surge duration and storm duration in HR2006 and WTI2011 for the lower rivers

3.1 Application of storm surge duration in HYDRA-B for HR2006

Design water levels in the Rhine-Meuse estuary are determined with the probabilistic model ‘Hydra-B’. Hydra-B includes a database with results from the hydrodynamic model Sobek. Sobek was used to carry out simulations for various conditions of wind speed, wind direction, seawater level, river discharge (Rhine and Meuse) and setting of sea defences (open/shut) to determine, throughout the Rhine-Meuse estuary, what the maximum water level will be under those conditions. A total of 6768 simulations were carried out with Sobek. For an extensive description of the Hydra-B model concept, we refer the interested reader to [7].

The seawater level is one of the random variables in Hydra-B. This means that
[a] a probability distribution for the seawater level is used to determine how probable these water levels are; and
[b] Sobek simulations were carried out for different seawater levels for the purpose of translation to local water levels in the river.

Probability distribution for seawater level

The random variable "seawater level" was defined as the maximum water level during a tidal period. The probability distribution describes the exceedance probability for possible maximum seawater levels. In addition, allowance is made for statistical dependence between seawater level and wind speed.

The probability distribution for the seawater level does not include information of storm surge duration.

Description of sea water level in Sobek simulations

Sobek simulations were carried out for six different maximum seawater levels: NAP+1.11 m, NAP+2m, NAP+3m, NAP+4m, NAP+5m and NAP+6m. The Sobek model of the Rhine-Meuse estuary has three downstream boundaries at the confluence with the sea where information on the water level is required: Maasmond, Haringvliet north and Haringvliet south. However, the water level at these three locations is so closely interrelated that it was decided to use only one random variable for the description. The sea water level at Maasmond was used as a random variable and the associated water level at two locations at Haringvliet was directly derived from it [7].

The seawater level as a parameter is defined as the maximum water level during a tidal period. However, in Sobek simulations, a water level evolution is also imposed upon the lower boundary, where the maximum corresponds to the parameter value of the seawater level.

The following characteristics determine the evolution of the seawater level in time:

[a] Astronomic tide, composed of:
- mean sea level
- the astronomic tide graph or amplitude (spring tide / mean tide / neap tide)

[b] Storm surge, composed of:
- maximum storm surge height
- **storm surge duration**
- the phase shift between the storm surge peak and the astronomic tide peak.

[ad **a**] In reality, the evolution in the astronomic tide in time varies gradually between the shape at spring tide and the shape at neap tide. However, in the schematisation, it was decided to keep the evolution in the astronomic tide in time constant during a single high water event. The simulations for easterly winds used the evolution in the astronomic tide in time according to spring tide; the simulation for westerly winds used the evolution in the astronomic tide in time according to mean tide.

[ad **b**] The general evolution of the storm surge is shown in Figure 3.1, where the maximum storm surge is described by variable S_{max} and the storm surge duration in hours by variable D. This is a trapezium shape in which a relatively constant increase/decrease of 0.05 m/hour is assumed during the period from 2 hours before the peak until 2 hours after the peak. During the periods before and after those 4 hours around the peak, the increase/decrease is steeper and they depend on both the maximum storm surge and the surge duration: $(S_{max}-0.1)/(0.5*D.-2)$ m/hour. In all Sobek simulations with HR2001 and HR2006, a surge duration D of 29 hours was applied irrespective of the value of the maximum storm surge, S_{max}.

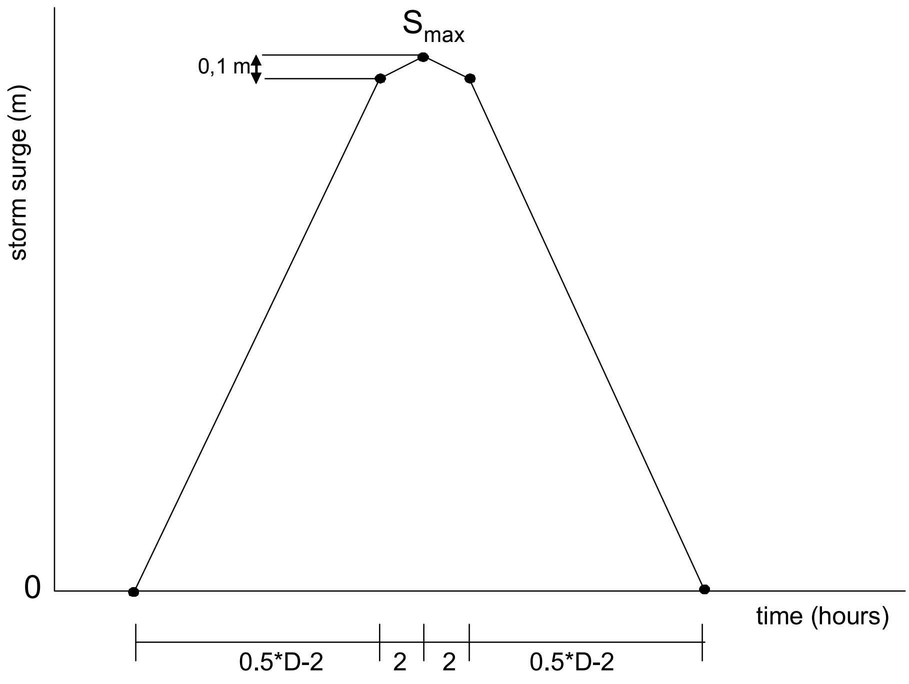


Figure 3.1 Storm surge hydrograph in Hydra-B Sobek simulations

A value of 4.5 hours was adopted for the phase shift F_s between the maximum values for storm surge and astronomic tide. In other words, the peak in the surge occurs 4.5 hours after the peak in the astronomic tide level (see Figure 3.2). At first sight, this assumption appears to result in *under*estimations of the water level compared to a phase shift of 0 hours. However, the opposite is true. The maximum storm surge level is selected so that, in combination with the tide, it results in a maximum seawater level that corresponds as closely as possible to the intended value of the random variable of seawater level in Hydra-B. To arrive at the same maximum water level given a phase shift of 4.5 hours, a higher maximum storm surge is needed than with a phase shift of 0 hours. The application of a relatively large phase shift keeps the seawater level closer to the maximum water level for a relatively long time (see Figure 3.2). So in this concept, a large phase shift is a conservative assumption which, incidentally, does not have major consequences according to [12].

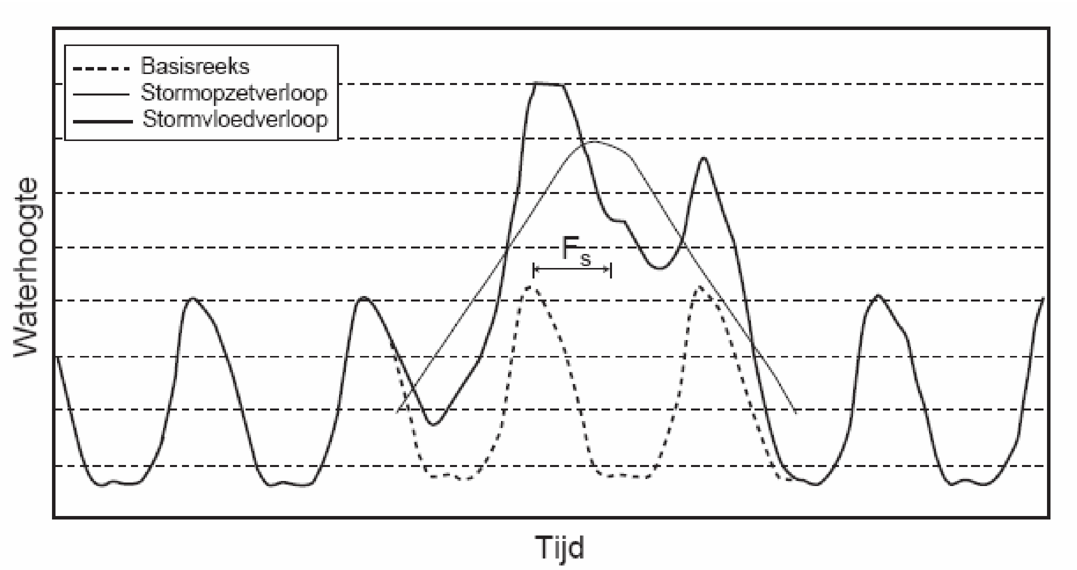


Figure 3.2 Storm surge hydrograph in combination with tide, as assumed in the Hydra-B Sobek simulations (figure copied from: [7])

3.2 Application of storm duration in Hydra-B for HR2006

The Sobek model needs information about the evolution of the wind speed in time to simulate a storm event for the Rhine-Meuse estuary. The wind speed is used in Sobek to determine local surge and waves, so statistical information about the wind speed over open water is required. However, measurements by KNMI and the derived statistics refer to the *potential* wind speed. Potential wind speed is a kind of normalised wind speed. It is an hourly mean for wind speed, supposedly measured at a given location 10 metres above the ground if the surrounding terrain is flat and open and with a roughness length of 0.03 m. This value corresponds to the roughness length of a grassy surface.

In the Hydra-B concept, the potential wind speed is extrapolated to produce a wind speed over open water using the "open-water transformation". This transformation is not necessary when deriving the statistical information for storm duration. That is because storm duration statistics are derived from the threshold values chosen *relative* to the peak value. In other words, the exceedance durations are derived for the threshold values of 95%, 90%, 80% etc. of the peak value. Correction factors for differences between potential wind speed and open water wind speed on the derived storm durations have no effect.

That is why the statistics for storm durations are derived directly from the KNMI measurement data without any correction for differences with the wind speed over open water.

The following assumptions were made for the Sobek calculations made for HR2001 and HR2006 [7]:

The general evolution of wind speed in time is shown in Figure 3.3, where the maximum wind speed is described by variable U_{max} and the storm duration by variable D_W (hours). The storm duration is defined as the length of time the wind speed is higher than 10 m/s. Above 10 m/s, the schematised time line is a trapezium shape, matching the maximum wind speed U_{max} for five hours. Before and after those 5 hours, the increase/decrease is steeper and depends on both the maximum wind speed and the storm duration: $(U_{max}-10)/(0.5*D-2.5)$ m/s/hour. Before and after the storm period with duration D_W a more gradual increase/decrease was assumed of 0.833 m/s/hour for a period of 12 hours. These “storm edges” connect the 10 m/s threshold to the zero level.

For HR2001 and HR2006, Sobek simulations were carried out for five different maximum wind speeds: 0, 10, 20, 30 and 42 m/s. In all simulations, the selected storm duration D_W was equal to the surge duration D: 29 hours. The value of 29 hours is independent of the maximum wind speed U_{max}.

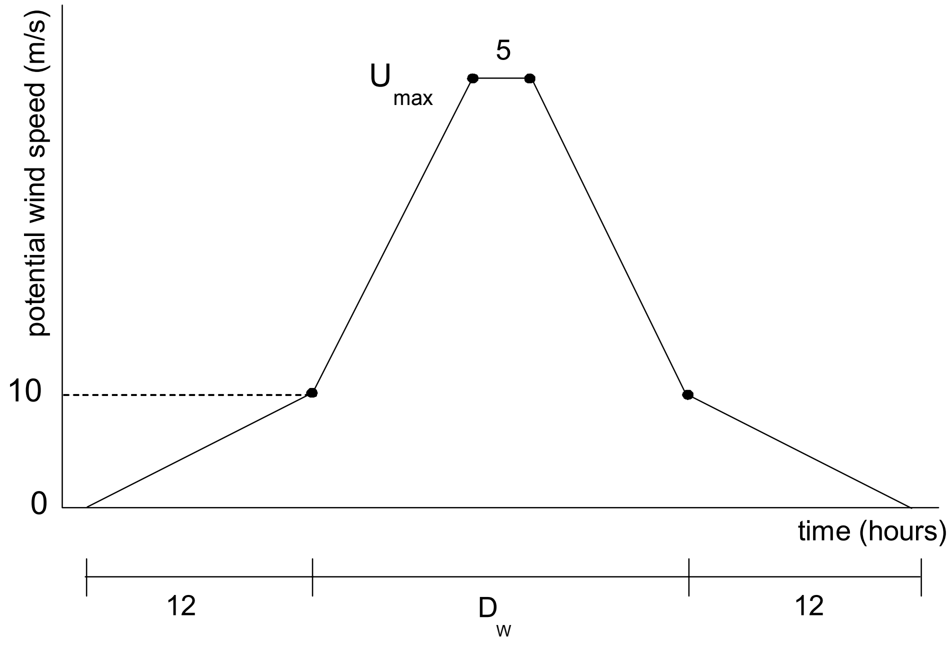


Figure 3.3 Evolution of wind speed in time, as assumed in the Hydra-B Sobek simulations (from: [7]).

The current study abandons the assumption that storm duration and storm surge duration are equal. Even though storm duration and storm surge duration are closely interrelated, they are definitely different quantities. That is why the analyses for storm surge duration and storm duration are made separately, even though the same procedures have been used where possible.

3.3 Considerations for the current study with a view to WTI 2011

The following two questions are important with respect to storm surge duration for the Rhine-Meuse estuary and how it is used for WTI2011.

[a] Are there any reasons to deviate from the chosen duration of 29 hours?
[b] Are there any reasons to schematise the storm surge duration differently?

This report focuses on solving the first question. The obvious course of action is to leave the concept of Hydra-B and the associated Sobek calculations *for WTI2011* unchanged as far as possible. That is because the Hydra-B software and the control system for the Sobek calculations have to be completed by the end of 2009 in order to guarantee completion in time for WTI. It is not to be expected that major changes in both concepts can be implemented and accepted before then. Nevertheless, this report also looks at a number of considerations relating to different schematisations with a view to possible improvements in the long run.

4 Literature study

4.1 Introduction

Various studies of storm surge duration have been carried out in the past. This chapter provides a summary of those studies and describes how they relate to the approach in the present study. Please refer to chapter 2 of the Annex for a more comprehensive literature study [9]. Note that we have unfortunately not been able to find any statistics or other grounds for the adoption of 29 hours for storm surge duration and storm duration, as in Hydra-B.

4.2 Concise review of literature study

We used the study by Van Weerden et al. [13] as a basis for the present study. The extrapolation method they used for deriving the storm surge duration at Hoek van Holland was also used in the present study.

The extrapolation method means that for each storm the surge duration at the 0.5 m level is determined, in other words the length of time the surge is higher than 0.5 m. Subsequently, the storm surge duration at the zero level is derived by extrapolating the surge duration at the 0.5 m level and the assumed evolution of the storm. The storm hydrograph is based on the trapezium shape and the cosine square shape. The normal and lognormal distributions are then used to derive the mean storm surge duration.

Using the extrapolation method, Van Weerden et al. found a storm surge duration of 35.6 hours for a trapezoidal surge and a storm surge duration of 40.7 hours for a surge with a cosine^2 shape. They propose the continuation of the provisional assumption of a trapezoidal surge with a lognormal distribution for the surge duration at the zero level with a mean duration of 35.6 hours. The latter value requires some explanation. Van Weerden et al. adopted the following parameters for the lognormal distribution in a trapezium shape: $\mu = \ln(33.2)$ hours; $\sigma = \ln(1.46)$. Based on a description of this kind, readers could conclude that the mean value for this distribution is 33.2 hours. However, this would only be the case if the value of σ is roughly equal to 0 ($\sigma \approx \ln[1]$). That is because the value of σ for the lognormal distribution affects the mean value: the higher the value of σ, the higher the mean of the associated lognormal distribution. An additional cause of the confusion may be the fact that, in recent years, exploratory studies have been carried out with Hydra-B in which the storm surge duration was set at 33 hours as an alternative to the standard value of 29 hours. That has given the value of 33 hours a certain “status” and it is conceivable that some people mistakenly believe that this value was proposed by Van Weerden et al. [13].

In addition to analysing the mean surge duration, Van Weerden et al. investigated the correlation between surge height and surge duration using the correlation coefficient *R*. They did not find a significant correlation. For this analysis, they used storms with a surge peak value higher than 1.5 m. However, De Valk and Steetzel [10] did find indications suggesting interdependence between surge height and surge duration. De Valk and Steetzel used quantile plots to demonstrate this interdependence (for a description of these plots, see section 8.2.2 of this report). However, the surge events they examined were of a very different nature from those of Van Weerden et al. De Valk and Steetzel examined surge events exceeding 0.5 m. The current study used both methods – the correlation coefficient and the quantile plots – to investigate any correlation between surge height and surge duration.

In addition to the extrapolation method, as used by Van Weerden et al., the present study also used the scaling method as described in [1] and [4] to derive the storm surge duration and the storm duration. This is a method involving the rescaling of all selected storms to a dimensionless peak value of 1. For each rescaled storm the exceedance duration is then determined at fixed percentages below the peak. Averaging these exceedance durations results in a mean storm hydrograph, also referred to as the standard shape. A random storm can now be obtained from this standard shape by vertically multiplying the standard shape by the required peak value. Geerse used this method for the evolution of the river discharge in time and storm durations (wind speed). The current study used the method for surge and wind speed.

5 Data analysis for storm surge duration

5.1 Introduction

The surge durations and related statistics have been derived from seawater level measurement series at Hoek van Holland. The measuring data was analysed before commencement.

This analysis is described in detail in Chapter 3 of the Annex [9]. Section 5.2 describes the main conclusions from this data analysis. At a later stage of the study, we decided to carry out the same analyses for a filtered measurement series. Tidal effects were filtered out to arrive at this filtered measurement series. The filter used is described in section 5.3.

Since it was only at a later stage of the study that we decided to use a filter, the results of the methods will first be discussed based on the unfiltered measurement series in chapter 6 - 8. The same analysis based on the filtered measurement series will then be discussed in chapter 9.

5.2 Findings and results

We decided to analyse the storm surge residual rather than the high water surge. High water surge is calculated as the difference between the maximum water level and the associated maximum height of the astronomic tide. Obviously, those peaks in water level and astronomic tide do not have to coincide in time. It is therefore difficult to link the moments at which they occur to the high water surge. That makes it an unsuitable quantity for deriving the statistics of the storm surge duration. This problem does not apply to the storm surge residual. The storm surge residual at a given moment is calculated as the difference between the water level and the astronomic tide at that moment. This makes the storm surge residual a quantity that can be expressed as a function of time. It was therefore decided to use the storm surge residual in this study for deriving the statistics for storm surge duration. This decision is, incidentally, in line with past approaches. So where this report uses the term "surge" from this point onwards, it is taken to mean storm surge residual, unless stated otherwise.

After removing some obvious errors in the available measurement series, the data was found to be reliable, while accepting some gaps in the data. The data do not have to be corrected for sea level rise since the subject of the study is surge.

Four types of data series are available with regard to time resolution.

- high and low tides (1887 – 2006)
- 3-hourly values (1939 – 1970)
- hourly values (1971 – 1986)
- 10-minute values (1987 – 2006)

The different time resolutions were compared. The high and low tide series is not considered to be practicable enough for the purposes of this study. Deriving a storm surge residual from the high and low tide series requires interpolation. The 6-hour time lapse between high and low tides was deemed too coarse for the derivation of a representative surge series using interpolation. The other series were considered to be practicable enough. Here, we must take into account minor anomalies in the surge peak for the time resolutions of 1 hour and 3 hours.

5.3 Filtering the measurement series for tidal effects

5.3.1 Introduction

In case of a positive surge, the propagation velocity of the tidal wave decreases. Reversely, in case of a negative surge, the propagation velocity of the tidal wave increases. This means the surge influences the timing of the peak of the tide, i.e. the peak can occur earlier or later then expected. By subtracting the level of the expected astronomical tide from the observed water level, the derived surge is influenced by this shift in timing. This causes fluctuations in the derived surge on the time scale of a tidal period. These fluctuations are not included in schematised shapes like trapeziums, but they may still influence the derived surge durations. Therefore, the initially derived surge series is filtered to remove these “residual tidal effects”.

Section 5.3.2 describes the filtering method. Section 5.3.3 provides a further motivation for applying this filter.

5.3.2 Method

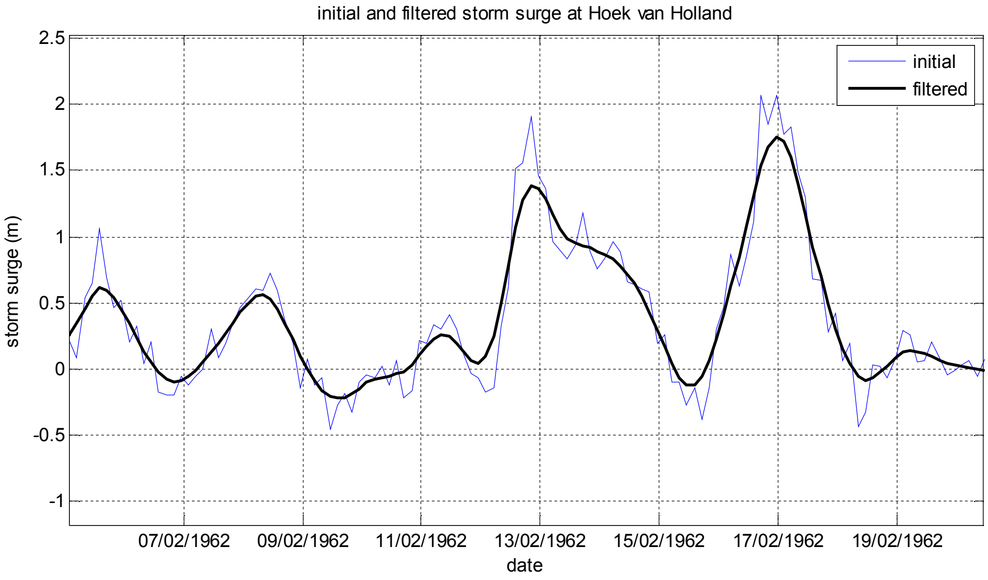
The study by De Valk [11] uses a filter with weightings [0.1; 0.2; 0.4; 0.2; 0.1] for the 3-hourly observations. In other words: after filtering, the surge at moment t is equal to 0.4 times its original value, plus 0.2 times the original values at t-1 and t+1 and 0.1 times the original values at t-2 and t+2. The same filter was used in the present study for the uniform measurement series at Hoek van Holland. Figure 5.1 shows that this filter preserves the general trend of the surge and removes most of the residual tidal effects. Figure 5.2 shows that the peak surge in storm events is reduced significantly when the filter is applied.

As discussed in the previous section, water level series at Hoek van Holland have been used with different time resolutions:

- 3-hourly values (1939 – 1970)
- hourly values (1986 – 1970)
- 10-minute values (1987 – 2006)

To be able to use the filter, the last two series are disaggregated into 3-hourly values to create a uniform series for the period 1939-2006 for time resolution. This uniform series was filtered.

The analyses for deriving the surge durations were carried out for the *unfiltered* surge series (Chapter 6 to 8) and for the *filtered* surge series (Chapter 9). The effect of filtering can be quantified by comparing the results of these two analyses.



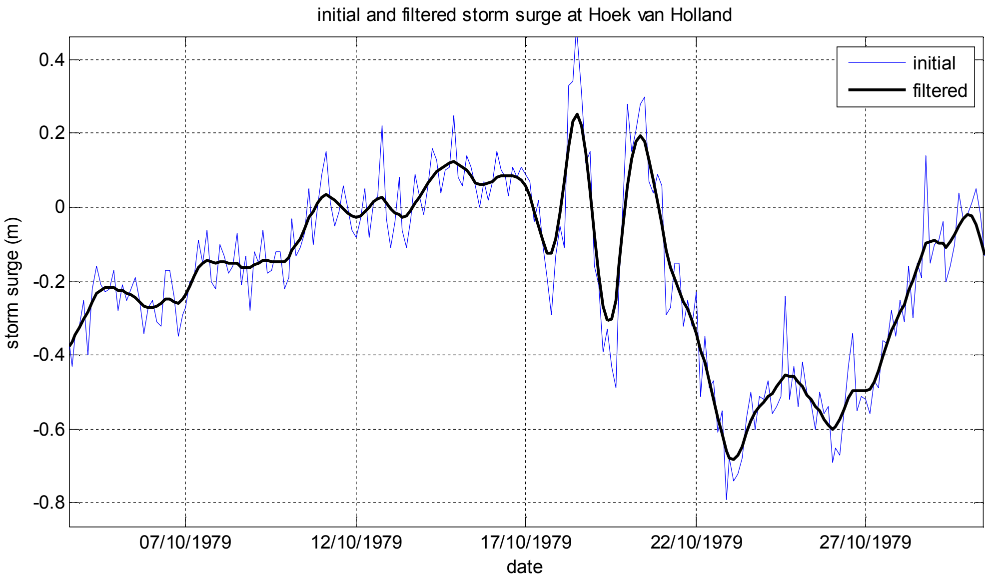


Figure 5.1 Filtering the measurement series

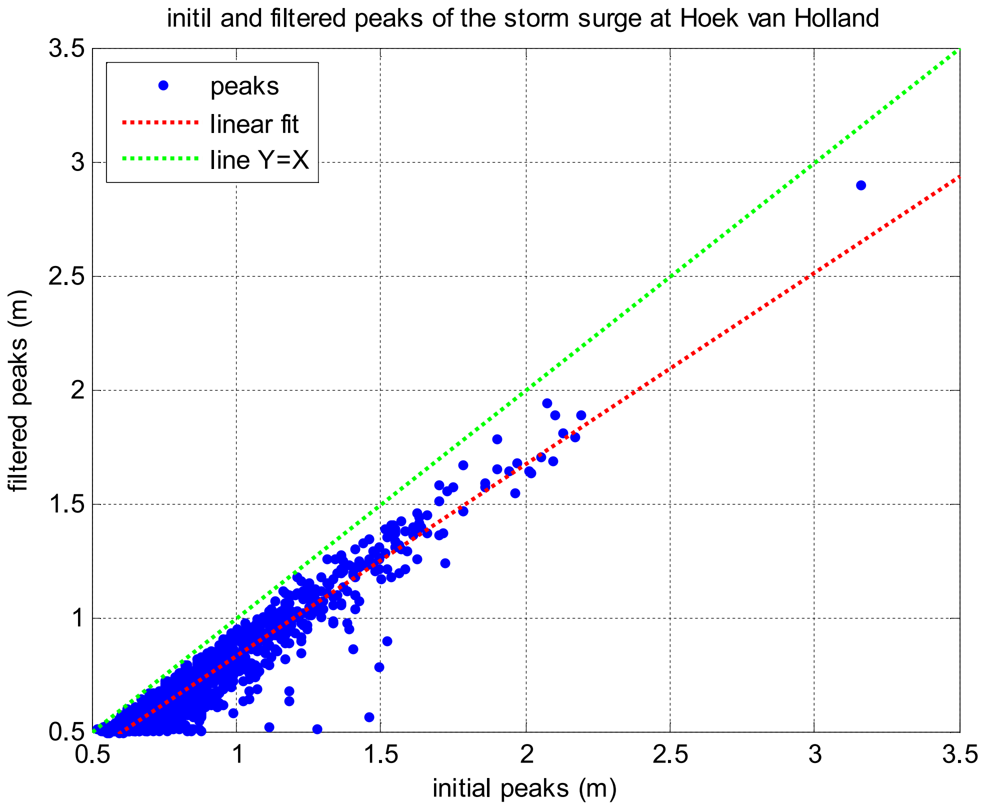


Figure 5.2 *Reduction of peaks as a result of the filtering process*

In the previous section it was shown that the filtering method reduces the peak of the initially derived storm surge hydrograph, which can potentially be considered a negative side-effect. In this section we demonstrate that this is not necessarily the case. For this purpose we have conducted 6 simulations of the 1953 storm with the Delft3D simulation model. In the first simulation the observed astronomical tide is combined with the observed storm pattern. In the other 5 simulations a time–shift of 2, 4, 6, 8 and 10 hours is applied to the storm pattern. Based on the simulation results, the storm surge hydrograph is subsequently derived in two ways: with and without filtering. Figure 5.3 shows the resulting filtered and unfiltered storm surges for the 6 simulated events.

The next step is to compare the 6 derived storm surges. In order to do so, the surges are shifted back in time. So, the derived surge hydrograph for the storm that was shifted e.g. 4 hours ahead in time, is shifted 4 hours back in time. Theoretically, this would lead to surge hydrographs that are exactly the same since the same storm event was applied on each simulation. Figure 5.4 shows that for the *filtered* series this is not exactly the case. However, differences are still small compared to Figure 5.5 where the surge hydrographs of the *unfiltered* series are shown. This clearly support the use of the filter.

The differences in peak values in Figure 5.5 (and similarly in Figure 5.4) show that the timing of the storm event with respect to the astronomical tide influences the derived peak of the storm surge hydrograph. This shows that the reducing effect of the filter on the peak surge is not per se unjust, since the peak of the unfiltered hydrograph is not necessarily the “real” peak. The value of the “real” peak surge is partly a matter of definition. The filtered series may slightly underestimate the “real” peak, but similarly the unfiltered series may slightly overestimate the “real” peak.

5.3.3 Discussion

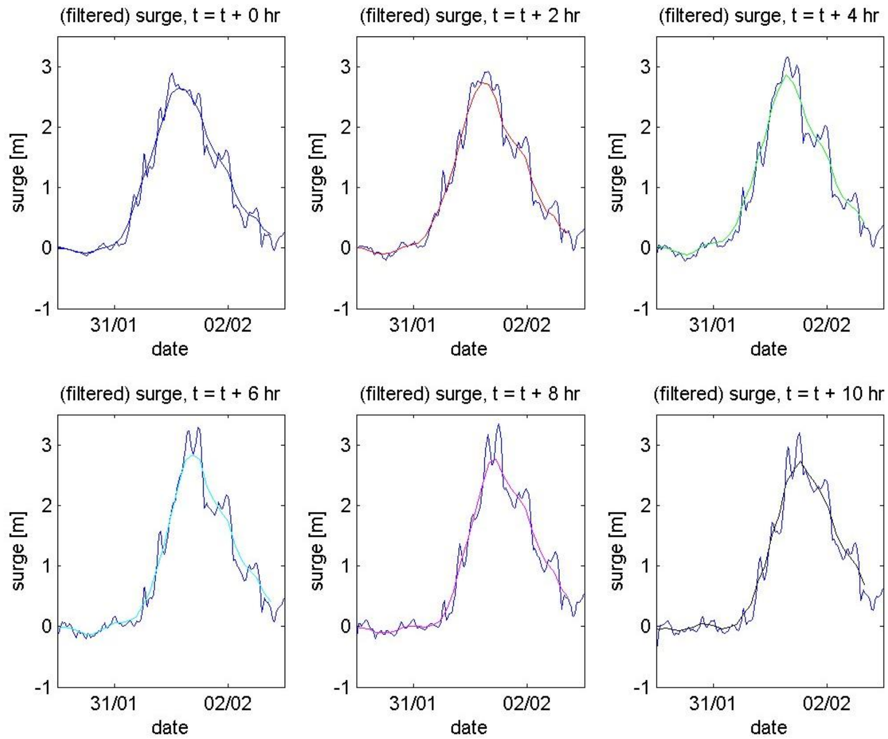


Figure 5.3 *Derived filtered and unfiltered surge hydrographs for the 6 simulated storm events.*

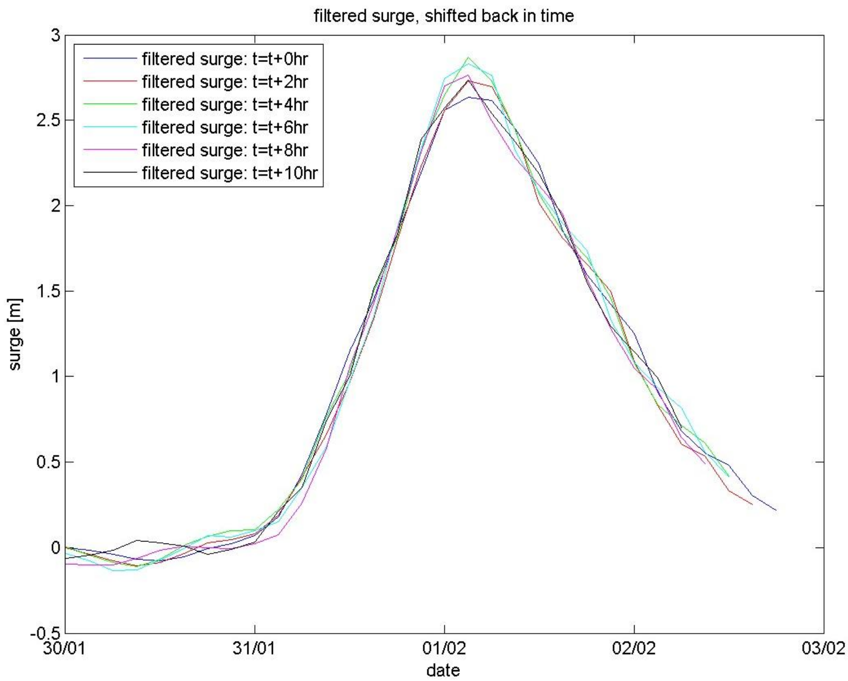


Figure 5.4 *Comparison of the filtered surge hydrographs for the 6 simulated storm events.*

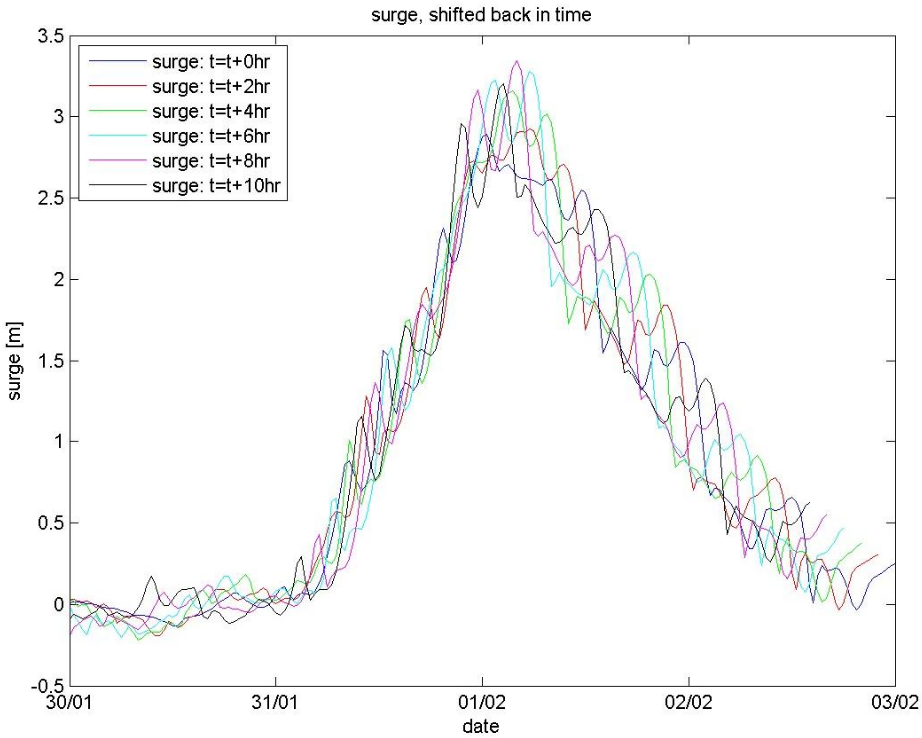


Figure 5.5 Comparison of the unfiltered surge hydrographs for the 6 simulated storm events.

6 Deriving storm surge duration for the unfiltered measurement series

6.1 Introduction

Storms are selected from the surge series of 1939-2006 using the Peak-Over-Threshold method (POT method) to derive the surge duration. This means that, first, all peaks above a certain threshold value are selected. Here, a peak is defined as a surge value higher than the surge in the preceding and subsequent time intervals. In addition to the threshold value, the POT method also requires a time window. This is the period of time, measured from the moment of the peak surge, in which the storm surge duration is derived. This time window is necessary to ensure that we do not select two successive events that in fact belong to the same storm.

In an earlier stage of this study, we analysed the sensitivity of the storm surge duration for the selected threshold value and time window. For this purpose, two standardized shapes were used for fitting observed hydrographs: a trapezium shape and a cosine^2 shape. These two shapes were adopted from Van Weerden et al [13]. Note that chapter 10 analyses whether these standardised shapes are actually supported by the data. The arithmetic mean for the trapezium shape varies between 37 and 78 hours, and between 42 and 86 hours for the cosine^2 shape. The large variation in the arithmetic mean is mainly caused by the inclusion or exclusion of adjacent and secondary peaks. The results of this sensitivity analysis are described in Chapter 4 of the Annex [9].

Eventually, it was decided to adopt a threshold value of 1.5 m and a one-day time window. There were two reasons to adopt a threshold value of 1.5 m. Firstly, it is in line with the threshold value chosen by Van Weerden et al [13]. Secondly, in this way, a series of roughly one storm a year is selected. This means that a sufficiently large population is selected to generate an image of the spread in storm surge duration. Furthermore, it ensures that the storm events are significant in all cases.

A one-day time window was adopted because storms regularly occur with large adjacent peaks. These events are also referred to as twin storms. During the stage of the study referred to above, in addition to the sensitivity analysis of threshold value and time window, we also looked at whether or not these adjacent peaks should be included. It emerged that describing these twin storms as a schematisation with a single peak is not advisable. The current Hydra-B and HR modelling systems do use a schematisation of this kind, namely the trapezium shape. We decided not to deviate from this approach for the next derivation of the HR (for WTI 2011). That is why we adopted a time window so small that adjacent peaks are selected as separate storm events. A one-day time window is considered suitable for that purpose. This decision was based in part on contributions by a group of experts to the expert meeting of 26 March 2009. The experts' reasons were that [a] storms with multiple peaks are not consistent with the schematised shape used in Hydra-B and that [b] as a rule it is possible to open the Maeslantkering between two successive peaks to discharge excess river water. The storm surge duration derived in this manner is suitable for the description of surge events with a single peak.

This chapter describes the methods for deriving the storm surge duration and the resulting storm surge durations assuming an unfiltered measurement series, a threshold value of 1.5 m and a one-day time window; the extrapolation method and the scaling method. The

extrapolation method starts by deriving the peak value and the duration above a surge height of 0.5 m. Based on a schematised shape for evolution in time (trapezoidal or cosine^2), the storm surge duration at the 0 m level is then determined.
In the scaling method, the surge hydrograph is divided by the peak value to normalise all storms. After this transformation, each storm has a peak value of 1, so the storms can be directly compared with each other. The mean exceedance duration is determined at various levels (0.95, 0.9, 0.8 etc) and a schematised shape (trapezium) is derived, based on these mean values.

In addition, this chapter briefly describes the results of the sensitivity analysis for time window, threshold value and adjacent/secondary peaks. Chapter 9 discusses the results of the extrapolation method applied to a *filtered* measurement series.

6.2 Method 1: extrapolation method

6.2.1 Storm selection

As mentioned earlier, storms are selected from the surge series for 1939-2006 using the Peak-Over-Threshold method (POT method). It was decided to adopt a threshold value of 1.5 m and a one-day time window. When peaks higher than 1.5 m are more than one day apart, these adjacent peaks belong to different storms. This POT method with a threshold surge value of 1.5 m and a one-day time window results in a series of 69 storms during the period 1939-2006. If, within one day before or after a peak higher than 1.5 m, one or more other peaks occur with a surge exceeding 1.5 m, the lower peaks are not selected as a separate storm. These lower peaks belonging to the same storm event are referred to as "secondary peaks". Section 6.2.3 describes how the secondary peaks are included in the derivation of the storm surge duration.

6.2.2 Deriving storm surge duration with schematic storm hydrographs

Ultimately, the intention is to derive the statistics for the surge duration at the zero level. This surge duration can be calculated directly from the data for each storm. However, at the level of 0 m surge, there is a lot of "noise" that cannot be attributed directly to the storm. For some storm events the surge will "hover" above the zero level for days. If that part of the event is included, the storm surge duration increases considerably while, in fact, that part of the storm is not relevant. Calculating the surge duration at zero level directly from the data will therefore lead to the overestimation of surge duration. So it was decided to derive the surge duration at zero level by extrapolation from the surge duration at higher levels. For this extrapolation, the surge duration at the 0.5 m level, the maximum surge during the storm and an assumed storm hydrograph were used. In line with Van der Weerden et al. [12], the storm hydrograph is based on the trapezium shape (see equation (6.1) and Figure 6.1) and the cosine^2 shape (see equation (6.2) and Figure 6.2):

$$D_0 = \frac{D_h\left(S_{\max} - \Delta h\right) - 2h\Delta t}{S_{\max} - \Delta h - h} \tag{6.1}$$

$$D_0 = \frac{\pi \frac{D_h}{2}}{\arccos\left(\sqrt{\frac{h}{S_{\max}}}\right)} \tag{6.2}$$

where:

D_0 = surge duration above the 0 m level (hr)

D_h = surge duration above the *h* m level (hr)

S_{max} = maximum surge during the storm (m)

Δt = half the duration of the triangular “cap” of the trapezium (= 2 hr)

Δh = height of the triangular “cap” of the trapezium (= 0.1 m)

Substituting h=0.5 results, for the trapezium shape and the cosine^2 shape respectively, in:

$$D_0 = \frac{D_{0.5}\left(S_{\max} - \Delta h\right) - \Delta t}{S_{\max} - \Delta h - 0.5} \tag{6.3}$$

$$D_0 = \frac{\pi \dfrac{D_{0.5}}{2}}{\arccos\left(\sqrt{\dfrac{0.5}{S_{\max}}}\right)} \tag{6.4}$$

For each storm event, the maximum surge and the surge duration at the 0.5 m level are derived from the measurements. Then, for each storm event, the surge duration at zero level can be calculated using equations (6.3) and (6.4).

The storm of December 1990 (Figure 6.3) will be used as an example to explain how surge duration at zero level and the associated trapezium shape are derived. This surge event was selected because the storm surge exceeds the 1.5 m threshold value: S_{max} = 2.05 m. The surge duration at the 0.5 m level was then determined from the data (red line in Figure 6.3): $D_{0.5}$ = 24.8 hours. Subsequently, using S_{max}, $D_{0.5}$ and equation (6.3), the duration at zero level was determined (pink line in Figure 6.3): D_0 = 32.0 hours. At this point, we know the surge duration at zero level and the trapezium shape can be drawn in the surge event.

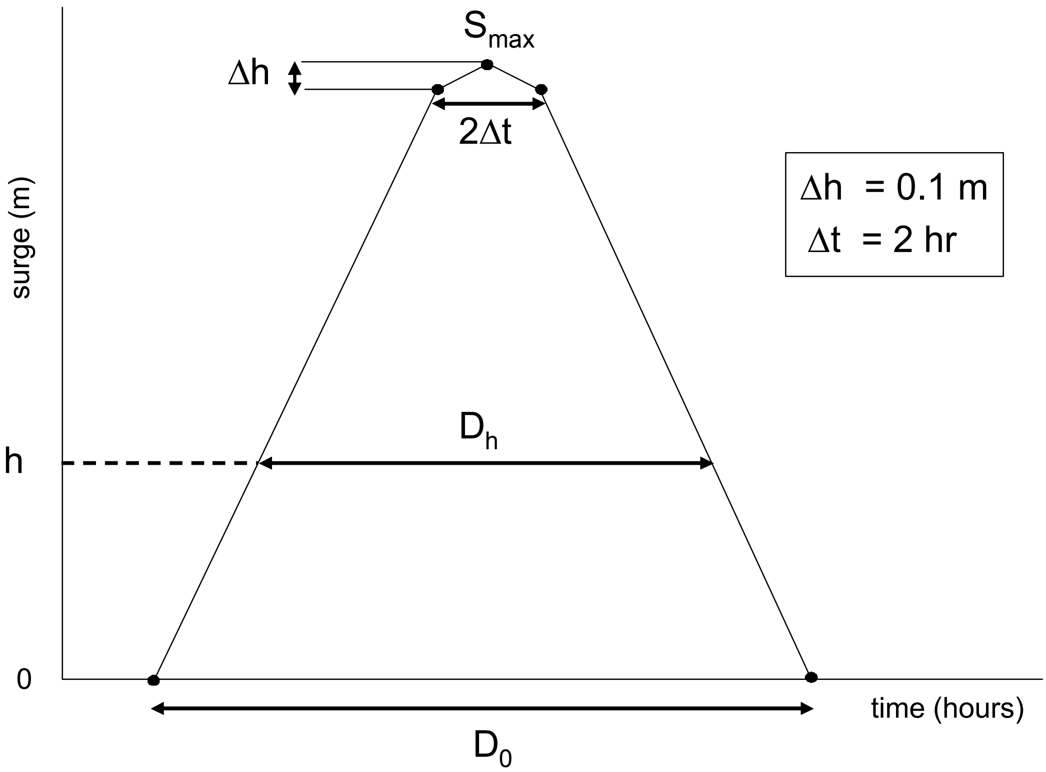


Figure 6.1 *Trapezium shape*

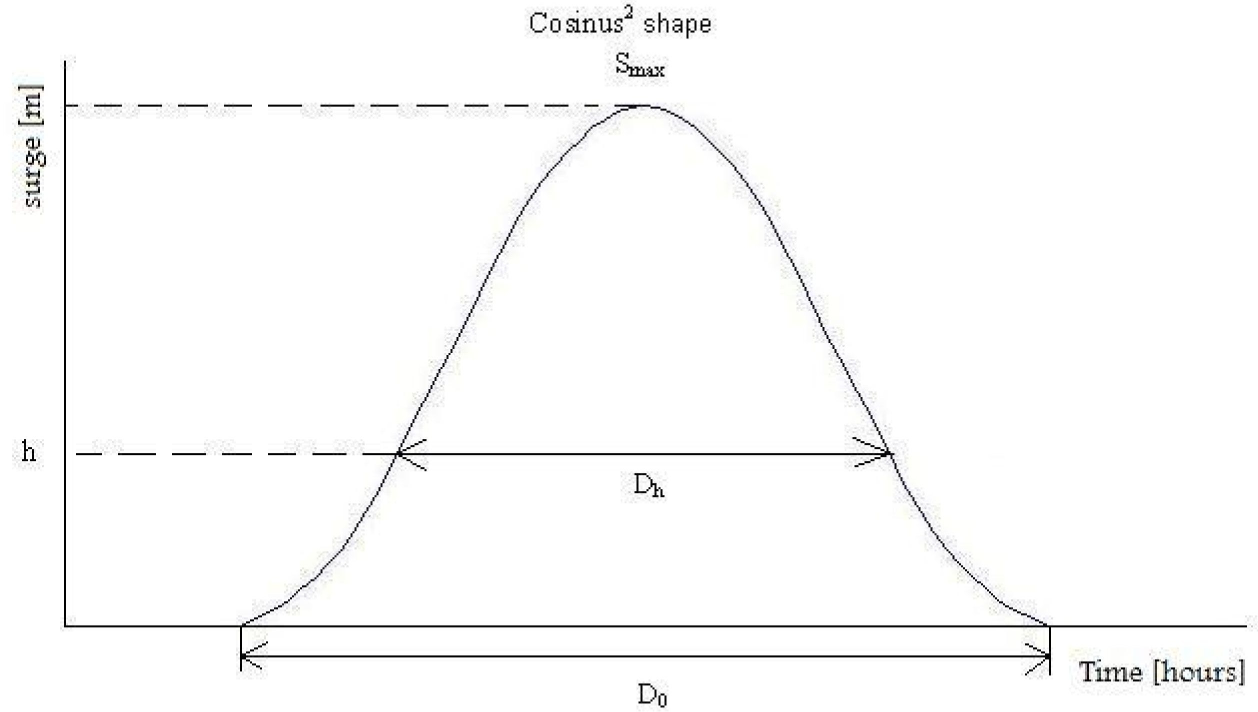


Figure 6.2 *Cosine² shape*

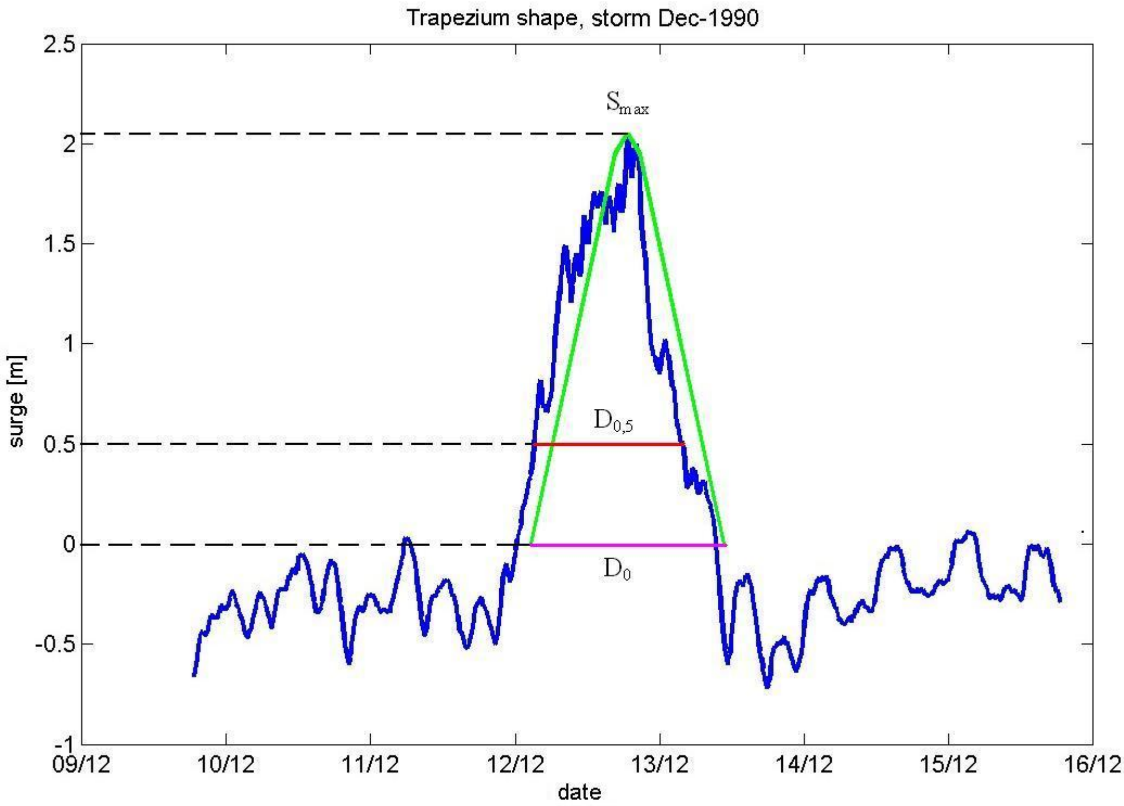


Figure 6.3 *Example of deriving surge duration at zero level and associated trapezium shape.*

In Figure 6.3 it is clear to see that the trapezium shape is a schematisation of the relevant surge event. The trapezium shape is symmetrical and it cannot therefore approximate skew in a surge event accurately. Hence, the shift in the trapezium shape relative to the surge event in Figure 6.3. Exactly the same reasoning applies to the cosine^2 shape, except that in this case equation (6.4) is used. In the case of adjacent or secondary peaks also, the trapezium shape and cosine^2 shape are not good approximations.

Finally, it should be noted that for each storm with a peak value higher than 1.5 m the duration at zero level derived using the cosine^2 shape results in a higher value than the value for D_0 derived with the trapezium shape.

6.2.3 Secondary peaks

When peaks higher than 1.5 m are more than one day apart, these peaks belong to different storms (as briefly explained in the introduction). If, within one day before or after a peak higher than 1.5 m, one or more other peaks occur with a surge exceeding 1.5 m, the peaks are considered to be part of the same storm event. The decision to adopt a one-day time window was primarily based on whether or not we want to include adjacent peaks. With time windows longer than 1 day, an increasing number of storms will be selected with major secondary peaks next to the main peak, see e.g. Figure 6.4. These secondary peaks can be included in deriving storm surge durations by merging the main and secondary peaks. If the secondary peaks are included, the durations at 0.5 m level of the main peak and any secondary peaks are totalized, otherwise only the duration of the main peak is taken into account.

It is clear that criteria are required to decide whether secondary peaks within a single storm event are included in the derivation of storm surge durations. At an earlier stage of this study a sensitivity analysis was carried out on the effect of different criteria for deciding whether or not to include secondary peaks in the analysis. This sensitivity analysis is described in more detail in Chapter 4 of the Annex [9] .

Including major secondary peaks leads to wider trapezium shapes that do not do justice to the physics of the system, see Figure 6.5. It was therefore eventually decided not to include major secondary peaks when determining the storm surge duration. By adopting a one-day time window, we divide storms with a main peak and a major secondary peak into two separate storms. The subsequent selection of very strict criteria for rejecting secondary peaks ensures that no major secondary peaks are included in the analysis. Secondary peaks will only be included if the surge level between the main peak and secondary peak is not below the 0.3 m level for longer than 0.25 day and if the secondary peak is at least 1.35 m high. In practice this means that hardly any secondary peak will contribute to the derived surge duration.

It is important to realise that a storm surge duration derived using a schematisation with a single peak can only be used for a physically realistic description of surge events with a *single* peak. Of course, it is advisable to investigate whether the secondary peaks occur frequently at a specific distance from the main peak. If that is the case, this could be included in the model, for instance by modelling a second comparable peak at a given time after the main peak in a certain percentage of the events. However, this analysis is outside the scope of this study.

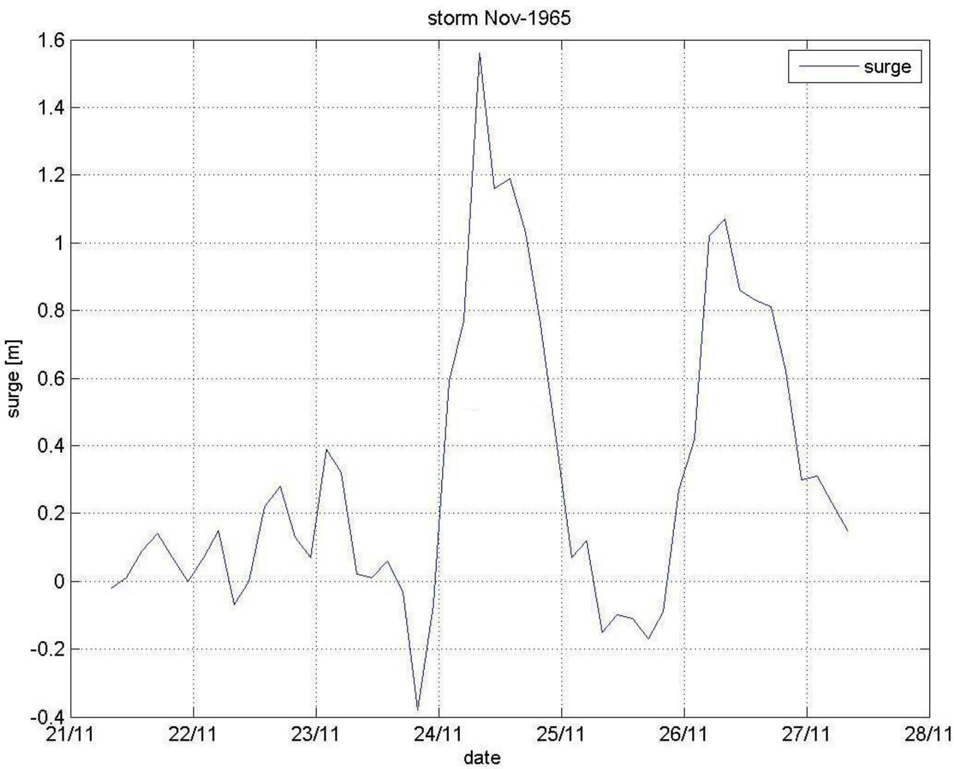


Figure 6.4 Example of two adjacent peaks

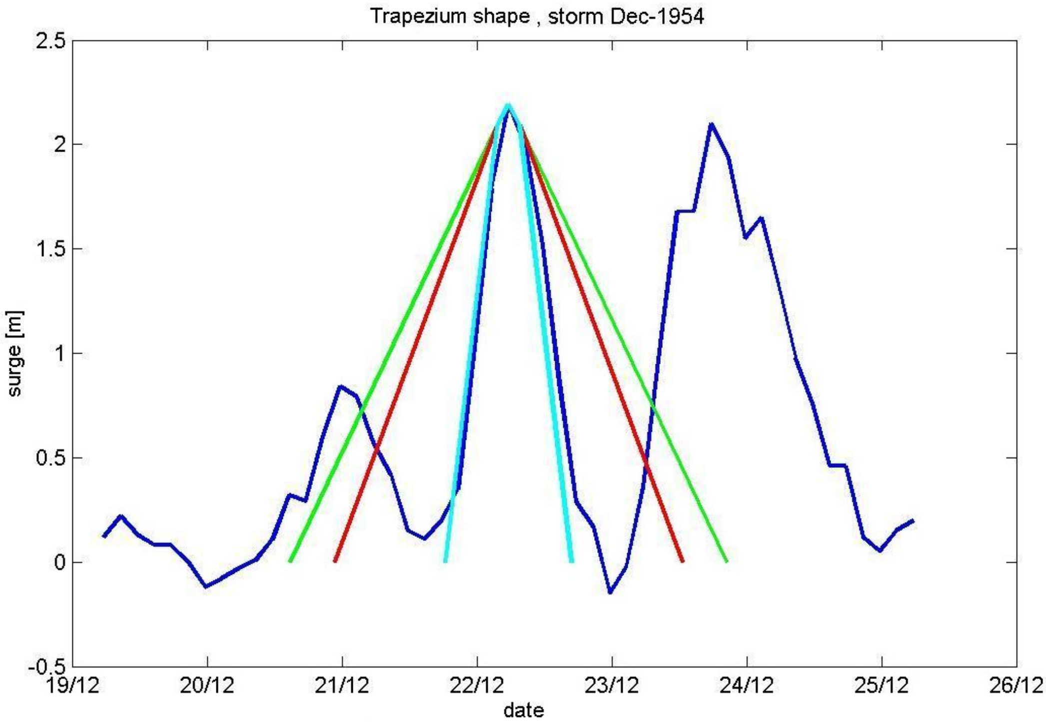


Figure 6.5 *The storm of 1954 is an example of a selected storm in which the inclusion or exclusion of secondary peaks results in different storm surge durations/trapeziums. Including secondary peaks results in a broader trapezium shape. Please refer to chapter 4 of the Annex for a more detailed explanation.[9]*

6.3 Method 2: scaling method

A second method used to derive storm surge duration at zero level is the scaling method. This method was developed at RIZA by Vincent Beijk and Chris Geerse. A detailed description of the scaling method can be found in the reports "Opschaling van afvoergolven and stormen" by Beijk and Geerse [1] and "Hydraulische Randvoorwaarden 2006 Vecht- en IJsseldelta" by Geerse. [4]. This section provides only a brief description of the method and the way it was used for determining the storm surge duration.

As with the extrapolation method, the scaling method involves the selection of surge events using the POT method; with a one-day time window and a threshold value of 1.5 m. Subsequently, any secondary peaks are merged with the main peak for each of the storms. In other words: exceedance durations of main and secondary peaks are totalised. The secondary peaks here are small ones. Because of the one-day time window, no surge events with major secondary peaks are selected. After merging the secondary peaks with the main peak, all surge events are scaled to a peak value of 1. This is done by dividing all surge values by the peak value. This therefore results in a dimensionless storm surge event. The exceedance duration can now be determined for each scaled storm at each surge level between 0 and 1. Averaging these exceedance durations results in a mean storm hydrograph, also referred to as the standard shape.

As with the extrapolation method, there is "noise" in the lower surge regions. The consequence is that, roughly speaking, only the top half of the standard shape is reliable. Fortunately, that is also the most relevant part of the storm surge event. The storm surge duration at zero level is determined by extrapolation from the top half of the standard shape.

The durations at 50% and at 25% below the peak of the standard shape are derived from the measurements. Then, using equation (6.5), the duration at zero level can be calculated.

$$D_0 = 3D_{50\%} - 2D_{25\%} \tag{6.5}$$

where
D_0 = surge duration at zero level

$D_{50\%}$ = surge duration 50% below the peak of the standard shape

$D_{25\%}$ = surge duration 25% below the peak of the standard shape

Equation (6.5) follows from Figure 6.6 and congruence. This is based on a symmetrical triangular storm shape, which almost completely matches the also symmetrical trapezium shape described earlier. The surge duration at zero level can be found in a similar way for asymmetrical standard shapes. The scaling method is suitable for the investigation of asymmetry in surge duration. However, this is outside the scope of this study.

As with the extrapolation method, the scaling method can be used only if there is no significant correlation between surge duration and surge height. This assumption is assessed in Chapter 8.

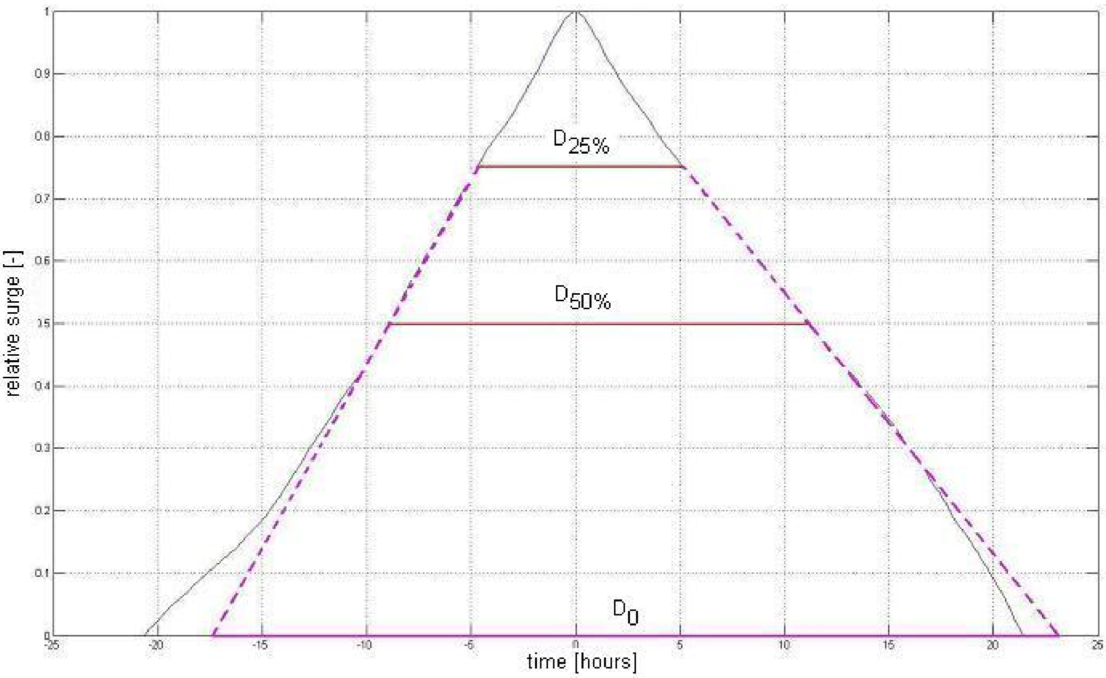


Figure 6.6 *Example of deriving surge duration at zero level*

6.4 Results

6.4.1 Statistical characteristics

6.4.1.1 Method 1: Extrapolation method

Durations at zero level were derived for each of the 69 selected storms. The storm surge duration is the arithmetic mean of these 69 storm surge durations at zero level. For both the trapezium shape and the cosine^2 shape the arithmetic mean and the associated standard deviation were calculated, see Table 6.1. Both the arithmetic mean and the standard deviation are a little higher for the cosine^2 shape than for the trapezium shape.

	Arithmetic mean	Standard deviation
Trapezium shape	40.1	12.2
Cosine^2 shape	45.3	13.1

Table 6.1Arithmetic mean and standard deviation of surge duration at zero level

The value of the time window is not as self-evident as it appears. As explained earlier, a one-day time window was chosen to split “twin storms”, like the one in December 1954 (Figure 6.5), into two separate storms. The reason for splitting twin storms is to prevent the surge from being described as a schematisation with a single peak that is too broad.

However, the storm of February 1990 was exceptionally long. As a result of the one-day time window, this exceptionally long storm was selected three times with an exceptionally long surge duration rather than once, see Figure 6.7. That erroneously extends the series of surge durations with two exceptionally long surge durations. We therefore decided to remove two of the three selected substorms from the series. Of the three storms, the one with the longest surge duration at zero level was retained; the other two were deleted. The results for the arithmetic mean and standard deviation of the new series surge durations are shown in Table 6.2.

As stated, the modification above of the multiple storm events of 1990 was made manually. Of course, criteria could have been incorporated in the software for the selection of storm events so that this event would have been identified immediately as a single storm. However, this was not done because the result would have been the same in the end.

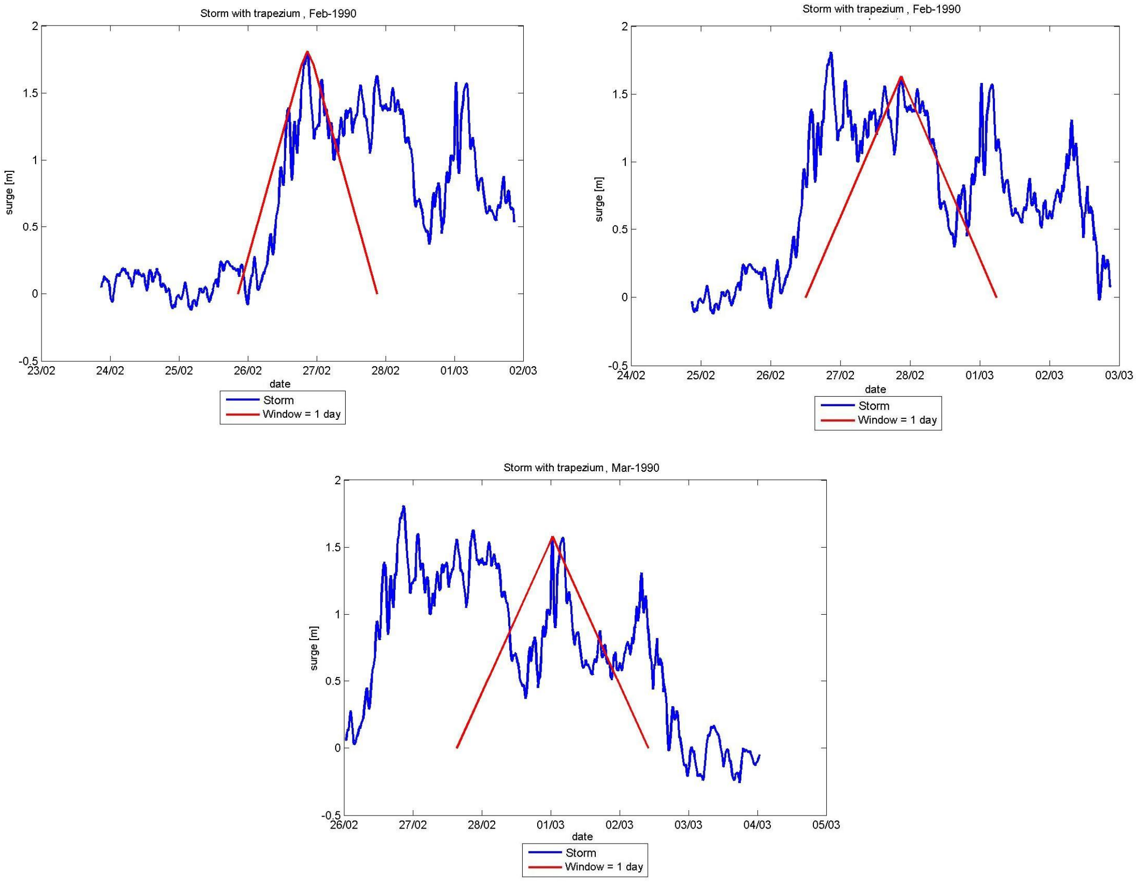


Figure 6.7 *As a result of the one-day time window, the storm of February 1990 with an exceptionally long duration is split up into three separate storms, each with a long surge duration.*

	Arithmetic mean	Standard deviation
Trapezium shape	39.6	11.9
Cosine^2 graph	44.8	12.8

Table 6.2 *Arithmetic mean and standard deviation of surge duration at zero level associated with the trapezium shape and the modified series of surge durations at the zero level*

The above explanation once more makes it clear that the evolution in time of some of the selected storm events is too complex to be described adequately using one standard shape. We therefore advise a follow-up study to investigate whether the surge should be modelled differently.

6.4.1.2 *Method 2: scaling method*

The scaling method does not derive surge duration at zero level for each separate storm, but the arithmetic mean values for surge durations at fixed percentages below the peak. The mean surge duration at zero level is then derived by linear extrapolation from the durations at 25% and 50% below the peak. The mean surge durations at 25% and 50% below the peak are 9.9 and 20.0 hours respectively. Then, using equation (6.5), a mean storm surge duration at zero level of 40.2 hours is found.

With the scaling method, we did not remove storms manually as was done with the extrapolation method for the multiple storm event in February 1990. This is because we used readily available Rijkswaterstaat software for this method and therefore it was considered unwise to intervene in the software. So this mean storm surge duration of 40.2 hours applies to the unmodified series of selected storms, which includes the storm of February 1990 three times. A comparison should therefore be made with the value for the mean storm surge duration from the extrapolation method before modifying this series of selected storms, where $D_{0,trapezium}$ = 40.1 hours or $D_{0,cosine}$ = 45.3. The scaling method produces a mean storm surge duration that is an excellent match with the mean storm surge duration for the trapezium shape from the extrapolation method. It matches the mean storm surge duration for the cosine^2 graph from the extrapolation method less closely. That is because both the scaling method and the extrapolation method with a trapezium shape use linear extrapolation to zero level, while the cosine^2 shape fans out more widely at zero level.

The scaling method confirms the surge duration at zero level as found by the extrapolation method. The scaling method also confirms the storm hydrograph. The scaling method produces a standard shape which is the mean of all storms normalised at 1. The top 50% of the standard shape is a proper description of the mean surge wave. Figure 6.8 - Figure 6.9 show that the trapezium shape used in the extrapolation method is a reasonable approximation of this standard shape. Only around the peak there are noticeable differences, which is inevitable because of the way these standardized shapes are defined. This is especially the case for hydrographs with relatively high peaks such as the one shown in Figure 6.9. The high peak causes the hydrographs to have a rather steep gradient. However, by definition the trapezium has a “cap” near the peak, which has a rather low gradient. This causes the trapezium to deviate from the triangular shape of the scaling method.

The scaling method increases the reliability and credibility of the extrapolation method. In current programming systems, the extrapolation method can handle more variations, such as the use of longer time windows and the manual removal of storms from the series of selected storms. We therefore eventually decided to continue with the results from the extrapolation method as described in section “6.2”.

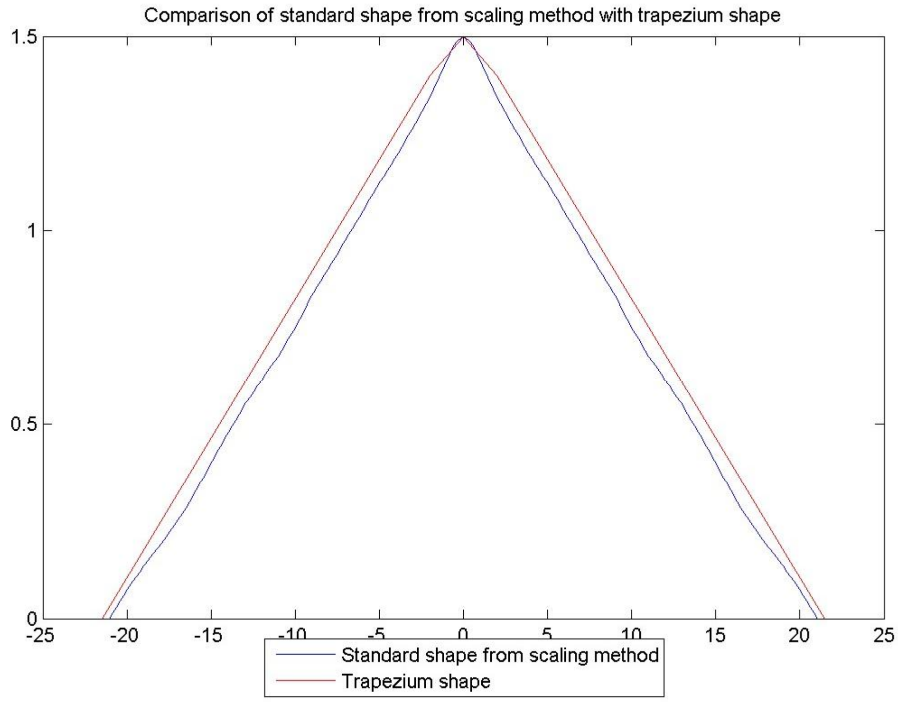


Figure 6.8 *Standard shape and trapezium shape with a peak value of 1.5 m*

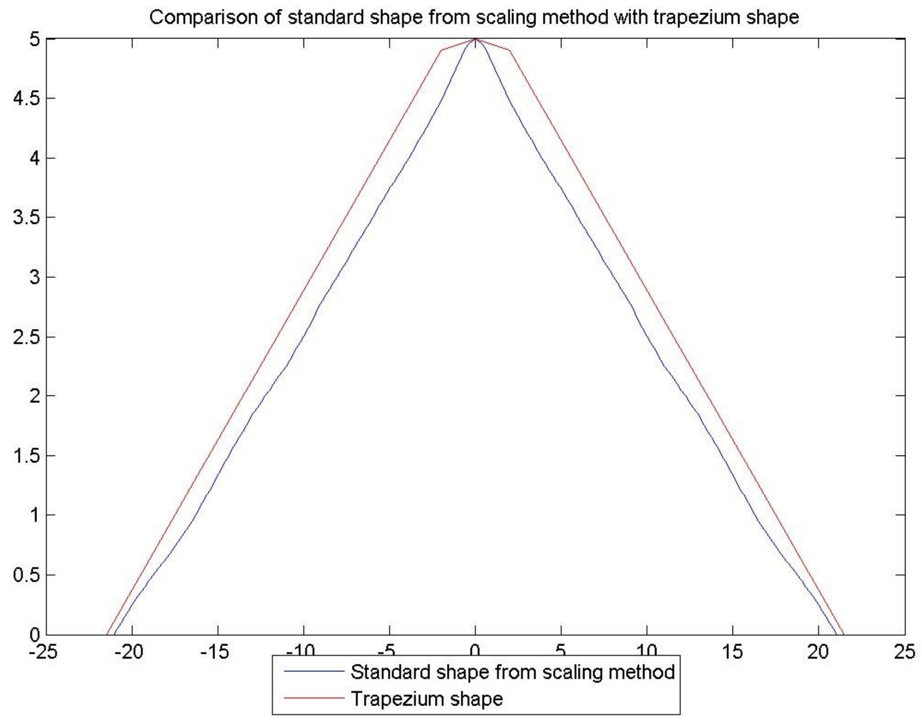


Figure 6.9 *Standard shape and trapezium shape with a peak value of 5 m*

6.4.2 Comparison with the results from the study by Van Weerden et al. [13]

The results from this study differ from the results in the study of Van Weerden et al. [13]. This difference in results was discussed at length earlier in the study [9]. We suspect that the study by Van Weerden et al. used different measurement data than those available for our study. This could be a different method for determining the astronomic tide, recalculations of measured water levels or the use of different interpolation methods. However, this can no longer be ascertained. Consultations with experts at the expert meeting of 26 March 2009 produced some plausible hypotheses for possible causes of the differences, but unfortunately no hard evidence. Chapter 4 of the Annex [9] documents the differences and possible causes. Helpdesk Water, which is responsible for supplying the series of measured water levels, told us the following (Koos Doekes, personal communication):

The astronomic water levels for earlier years used in the current study have been calculated some 10 years ago for the purpose of a calculation by the OSF department of RIKZ. The period 1971 to 1978 was hindcasted with an analysis of the data from 1973 to 1976, and the period 1979 to 1984 with an analysis of 1981 to 1984. This means the results in Van Weerden et al. [13] are definitely not based on the same surge data as in this study, and almost definitely not on the same water levels. This continues to be a question of speculation, but Van Weerden et al. probably used an earlier, manually collected, series of surges during storms. The starting year of 1898 could be an indication that the astronomic tide was based on the predictions in the old Tide Tables for the Netherlands – which listed Hoek van Holland from that year onwards – and the rest of the curve was adapted to it, possibly using standard curves and drawing templates. (The SVSD continued to do this until the 1980s.)

6.5 Sensitivity analysis for time window, threshold value and secondary peaks

As stated earlier, a sensitivity analysis of time window, threshold value and exclusion or inclusion of secondary peaks was carried out earlier during this study. Chapter 4 of the Annex [9] discusses the sensitivity analysis of the time window, threshold value and secondary peaks in more detail. It shows that the selected time window, threshold value and secondary peak criteria have a major impact on the resulting mean surge duration. Depending on the time window, threshold value and handling of secondary peaks, the arithmetic mean of the surge duration varies from 37 to 78 hours for the trapezium shape and from 42 to 86 hours for the cosine^2 shape. The large variation in arithmetic mean is mainly caused by the question of whether or not secondary peaks are included.

6.6 Conclusions

The main conclusions from this chapter, based on analyses using the unfiltered measurement series, are as follows.

- The arithmetic mean for the storm surge durations depends on the storm hydrograph selected (trapezium shape or cosine^2 shape). The cosine^2 shape results in a longer storm surge duration than the trapezium shape because the cosine^2 shape fans out more widely for surges < 0.5 m.
- For the trapezium shape, the extrapolation method results in a mean storm surge duration of 40 hours.
- For the cosine^2 graph the extrapolation method results in a mean storm surge duration of 45 hours.
- The extrapolation method with the trapezium shape and the scaling method both generate a mean storm surge duration in the range of 40 hours.
- The time window, threshold value and secondary peak criteria have a major impact on the resulting mean surge duration.

7 Probability distributions of storm surge duration

7.1 Introduction

Chapter 6 describes how the mean storm surge duration was derived from a series of selected storms. For application in the *current* Hydra-B approach, that value is, *in principle,* adequate. However, for many other applications, it is important to know the entire probability distribution in addition to the mean value. That information may also be relevant for Hydra-B if it is decided in the future to use the surge duration as a random variable, or to replace the mean value by the surge duration with the exceedance probability p (where p could be 25%, 10%, 5% or 1%). Another possibility is that the mean surge duration based on a fitted probability distribution deviates from the mean surge duration that has been derived directly from the available series.

This chapter describes how a probability distribution is derived for storm surge durations. Various functions are tested and compared with one another for that purpose. This chapter serves mainly to show the scope of the spread of storm surge durations and how it can be described with different probability distributions. This chapter will not test all possible probability distributions with the aim of selecting the best one. The analysis will be carried out based on the storm surge durations derived for the *trapezium shape*. All findings also apply to the cosine^2 graph. It is only the numbers that differ slightly.

7.2 Method

7.2.1 Selected probability distributions

The following four probability distributions have been fitted on the surge duration series

$$\text{normal distribution}: \quad F(x) = \frac{1}{2}\left\{1 + erf\left(\frac{x-u}{v\sqrt{2}}\right)\right\} \tag{7.1}$$

$$\text{lognormal distribution}: \quad F(x) = \frac{1}{2}\left\{1 + erf\left(\frac{\ln(x)-u}{v\sqrt{2}}\right)\right\} \tag{7.2}$$

$$\text{3-parameter Weibull distribution}: \quad F(x) = 1 - \exp\left(-\left(\frac{x-u}{v}\right)^k\right); \quad x \geq u \tag{7.3}$$

$$\text{Gumbel distribution}: \quad F(x) = \exp\left\{-\exp\left(-\frac{x-u}{v}\right)\right\} \tag{7.4}$$

where:

u = location parameter

v = scale parameter

K = shape or curve parameter

$$erf\left(x\right)=\frac{2}{\sqrt{\pi}}\int_0^x \exp\left(-t^2\right)dt \qquad (7.5)$$

Note: the fitted values of u, v and k differ for each distribution function

7.2.2 Fitting the distributions

The distributions are fitted using the "maximum likelihood method". In brief, this method selects the parameters of the probability distribution so that the joint probability density of the observations – surge durations – is at its maximum.

Figure 7.1 shows an example of a fit for the storm surge durations series. The histogram is the empirical estimate of the probability density function based on the series of, in this case, 67 selected storm surge durations. In this example, the fits of the Gumbel and the lognormal distribution match closely. The Weibull distribution deviates a little and the normal distribution clearly deviates from the other three. This final feature is mainly caused by the fact that the normal distribution is by definition symmetrical, while the other three functions are usually "skewed".

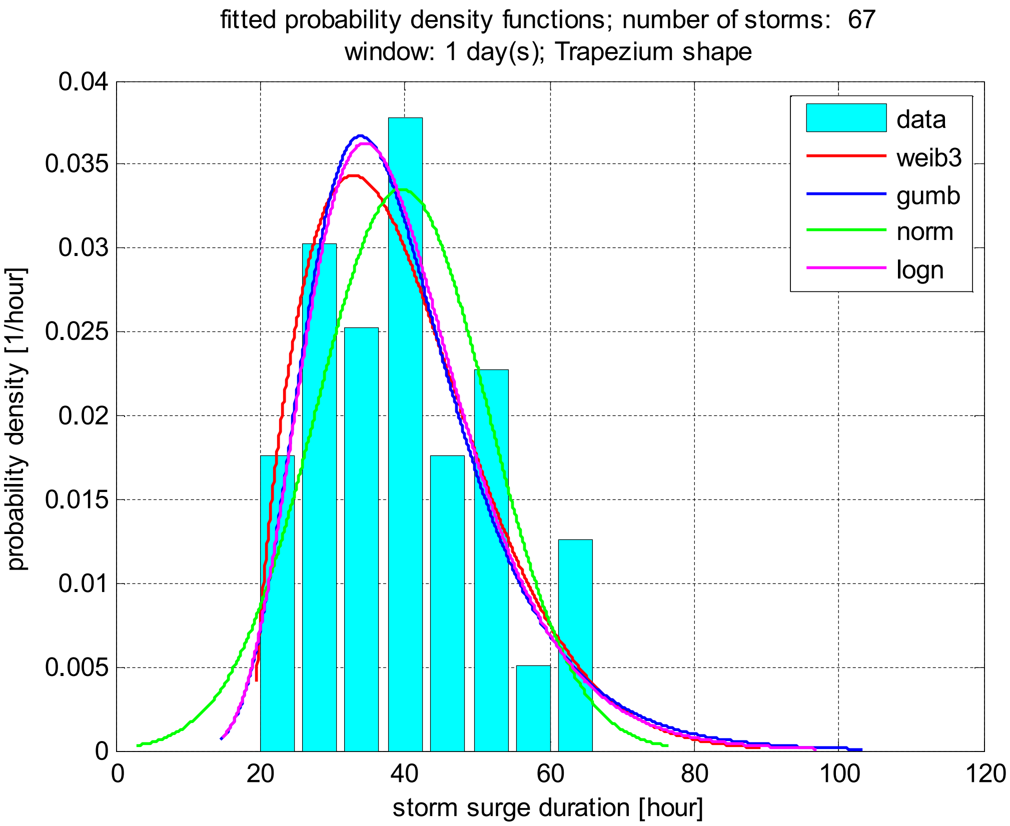


Figure 7.1 Histogram of storm surge durations and probability densities of fitted functions

The degree of skewness of a function is significant for the probability of the presence of extremes. In particular, the fits of the lognormal distribution and the Gumbel distribution in this example lead to a relatively high probability of extreme surge durations. Table 7.1 shows a number of quantiles for the four functions. The p-value in the top row shows the *non-*

exceedance probability of the quantile values listed in the relevant column. The last column, for instance, shows the values with a non-exceedance probability of 0.99, in other words an exceedance probability of 0.01. For the Gumbel and lognormal distribution this value is, respectively, approximately 13 and 10 hours longer than for the normal distribution. The mean values according to the function distributions are almost the same.

The skewness of the Weibull, Gumbel and lognormal distribution also emerges from the fact that the mode (surge duration with the highest probability density in Figure 7.1) and the median (p=0.5 in Table 7.1) are below the mean. In the case of the normal distribution, the mode, median and mean are all the same, in this case 39.6 hours. The standard deviation for the series of storm durations and most distribution functions is, after rounding off, 12 hours. The standard deviation according to the Gumbel distribution is a little higher (13 hours after rounding off) because of the considerable skewness in this distribution function.

distribution	mean	p=0.01	p=0.05	p=0.10	p=0.25	p=0.50	p=0.75	p=0.90	p=0.95	p=0.99
Weibull	39.5	20.6	23.2	25.3	30.2	37.6	46.8	56.2	62.3	74.6
Gumbel	39.7	18.7	23.0	25.6	30.7	37.6	46.4	56.5	63.7	80.1
normal	39.6	12.0	20.1	24.4	31.6	39.6	47.6	54.9	59.2	67.3
lognormal	39.7	18.7	23.0	25.6	30.8	37.9	46.5	55.9	62.4	76.8

Table 7.1 Mean and quantiles for the fitted functions from Figure 7.1

Figure 7.2 shows, for the sake of completeness, the exceedance probability based on of individual measurements – black dots – and based on of the four fitted distributions. The exceedance probability of the measurements was estimated as follows.

$$p_i = \frac{r_i - c}{N + 1 - 2c} \tag{7.6}$$

where:
p_i = exceedance probability of surge duration i
N = total number of storms (67)
r_i = ranking of the surge duration i (1 = longest, N = shortest)
c = (plot) constant

The value of c can be freely selected within a certain range. The values used in the literature are in the range from 0 (Weibull) to 0.44 (Gringorten). In this example, the value chosen for c was equal to 0. Note that the value of c does not influence the selected parameters of the distribution functions; the maximum likelihood method does not use the estimated probability value from equation (7.6). These values are only used to enable a visual comparison as in Figure 7.2.

Figure 7.2 shows that the data do not contain strange “outliers” and that the distribution functions are well within the vicinity of the measurements throughout the range.

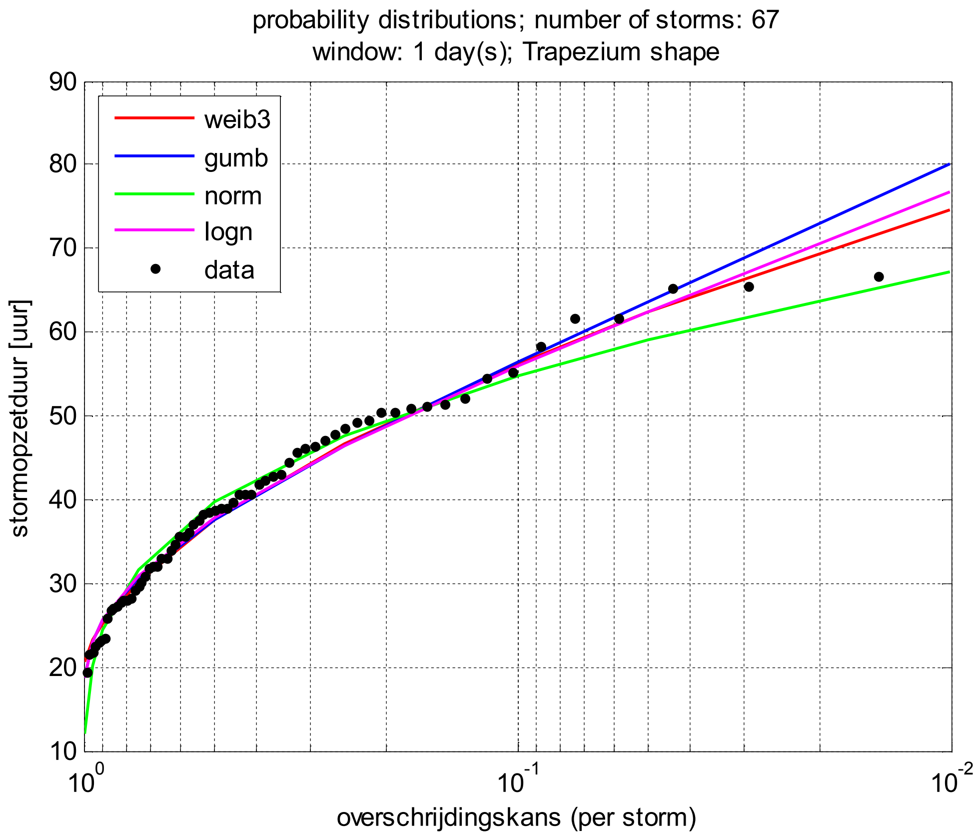


Figure 7.2 Estimated probabilities of exceedance for individual measurements – black dots – and based on the four fitted distributions.

7.2.3 Tests for "goodness of fit"

The previous section shows the importance of the selection of the distribution function used to fit the observations. This is particularly true for the extremes, where differences may be relatively large. For the mean value, which is mainly important for the present study, the choice of the distribution function is not so relevant, as emerges from Table 7.1.

The selection of the "best" distribution function can be made using statistical tests with a criterion for the "goodness of fit". The two most popular statistical tests are the Kolmogorov-Smirnov test (K-S test) and the Chi-square test. The K-S test determines the maximum difference between the empirical and the fitted probability distribution function. The Chi-square test determines the difference between the empirical probability histogram and the probability histogram for the fitted distribution. Of course, with both tests: the smaller the differences, the better the test result for the function. Both methods test what is known as the zero hypothesis:

H0: the tested distribution function is the actual distribution function.

Both tests quantify the difference between the empirical and the fitted probability distribution function, or probability density function. The following probability is then determined:

P(difference $\geq$ observed difference | H0)

This probability value is the level of significance. When there is a large difference between the empirical and fitted functions, the level of significance is low, and vice-versa. The function will be rejected as a possible fit if the significant level is below a predefined threshold P_s, for example 0.05 or 0.01. This threshold value represents the probability that the zero hypothesis will be falsely rejected.

Table 7.2 shows the level of significance for the fitted functions from Figure 7.1 for both tests. In all cases, the level of significance in the Chi-square test is considerably lower than the level of significance in the K-S test. This is a common phenomenon: the Chi-square test is a “stricter” test than the K-S test. According to the K-S test, the distributions result in comparable fits, but the normal distribution has the best fit according to the Chi-square test. This is because, in the storm surge durations series in this example, the level of “skewness” is relatively low. As a result, the normal distribution, which is symmetrical, results in a good fit with the data.

distribution	K-S	Chi^2
Weibull	0.96	0.05
Gumbel	0.94	0.06
Normal	0.92	0.32
lognormal	0.95	0.08

Table 7.2 Level of significance of specific functions from Figure 7.1 for the Kolmogorov-Smirnov test and the Chi-square test

7.3 Conclusions

The main conclusions from this chapter are the following.

- The selected distribution function is not significant when determining the average storm surge duration.
- The distribution function does have an impact on the determination of the probability of extreme surge durations. Selecting a symmetrical distribution such as the normal distribution may lead to a minor underestimation of extreme storm surge durations, while opting for a skewed distribution such as the lognormal distribution may lead to an overestimation.

8 Correlation between storm surge duration and maximum surge height

8.1 Introduction

Opting for a fixed value of 29 hours for the surge duration at zero level in the Sobek model, as done for HR2001 and HR2006, implies that the surge duration is assumed to be independent of the maximum surge. This chapter will investigate whether this assumption of independence is realistic. It will discuss the correlation coefficient, quantile plots and the correlation between surge height and surge duration at the 0.5 m level.

8.2 Method 1: extrapolation method

8.2.1 Correlation coefficient

Van Weerden et al. [13] and De Valk and Steetzel [10] investigated the correlation between surge height and surge duration with different results. Van Weerden et al. did not find any indications for a correlation between maximum surge height and surge duration at zero level. De Valk and Steetzel did find that surge height and surge duration are related. It should be noted that De Valk and Steetzel used a different method for selecting surge events. They defined a surge event as any surge above the 0.5 m level. Van Weerden et al. selected surge events in the same way as in the present report: with a threshold value of 1.5 m. In addition, they investigated surge duration at the level of 0.5 m and higher. In part because of the differences in results between the studies by Van Weerden et al. and by De Valk and Steetzel, the present study also examined the correlation between surge height and surge duration.

First, we looked at the correlation coefficient R, which expresses the correlation between maximum surge height and surge duration at zero level. R may vary between –1 and 1, and this corresponds to a variation from complete negative dependence to complete positive dependence. The value 0 means complete independence. The correlation coefficients R and R^2 are shown in Table 8.1.

	R	R^2
Trapezium shape	-0.13	0.016
Cosine^2 shape	-0.10	0.010

Table 8.1 Correlation coefficient R and R^2

A negative dependence between surge duration and maximum surge height was found. This dependence can be described as minor. The absolute value of R would have to be greater than 0.24 to conclude that the correlation deviates in a statistically significant way from 0, and that is not the case here. Remarkably, the correlation is actually negative, while instinctively it should be positive.

8.2.2 Quantile plots

De Valk en Steetzel [10] used an alternative method to quantify the correlation between surge height and surge duration. This method considers rankings of surge height and surge duration at zero level. Their method was also used for the surge durations in the present study.

A total of 67 storms were selected. This implies a series of 67 couples for surge height and surge duration. Both quantities were given a ranking. The highest surge duration or surge height was allocated a ranking of 1 and the lowest a ranking of 67. If the storm has a high ranking for the surge height, will that storm then also have a high ranking for surge duration? If that is true, there is a strong dependence between surge height and surge duration. For this would mean that a storm with a relatively high surge height can be expected to have a relatively high surge duration as well.

This degree of rank correlation can be illustrated with quantile plots. A quantile plot shows the rankings on the x-axis. The y-axis shows the following non-exceedance probability for each value of *x*:

$$P\left(\text{rank(surge duration)} \leq x \mid rank\text{(surge maximum)} \leq x\right)$$

When surge duration and surge height are completely interdependent, this probability equals 1, irrespective of the value of *x*. In the quantile plot, this corresponds to the line *y* = 1. When surge duration and surge height are completely independent, the probability increases as *x* increases since, if the ranking *x* is at its maximum and therefore equal to the length of the series (67 in this case), the above probability is equal to 1. Conversely, when considering the surge height with ranking *x = 1*, independence means that there is a low probability (1/67) that the surge duration of that same storm will also have a ranking of 1. Generally, in the case of a series with length *N*, when surge duration and surge height are completely independent, the above probability is equal to *x/N* for all values of *x*. Both on a regular scale and on a logarithmic scale, this is a 45 degree line. If the above probability is derived from the data and roughly follows a 45 degree line, this indicates independence. On the other hand, if the above probability derived from the data is close to the line *y = 1*, this indicates strong dependence.

The quantile plot is shown in Figure 8.1. The data for the higher rankings are on the 45° line. Noise can be seen for the lower rankings only (see the red circles). This noise is caused by the fact that these values are based on a relatively low number of storms: the storms with an extremely high surge. The small distance from the 45° line indicates that the two quantities are not significantly interdependent. Note that the surge durations with rankings 1- 10 to 15 (x-axis) are virtually all not visible in the plot. This is because the conditional probability estimated from the data (y-axis) for these rankings is equal to 0 and that value does not appear in a logarithmic plot.

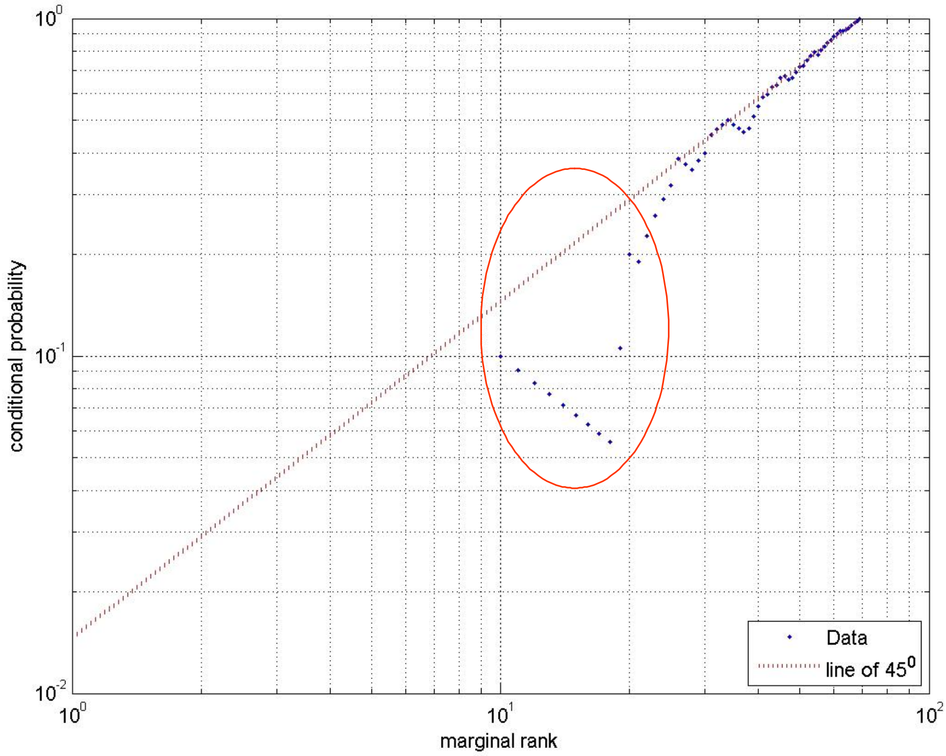


Figure 8.1 *Quantile plot for surge duration at zero level and maximum surge, with noise for storms with a low ranking. The lowest rankings represent the highest surge durations.*

8.3 Method 2: scaling method

To determine whether there is a correlation between surge height and surge duration, we can use the scaling method to look at the duration at a fixed percentage below the peak, for instance at 25% below the peak. When for the higher waves the duration at, for instance, 25% below the peak is different from the duration for the waves of lesser hight, we can conclude that there is a correlation between surge height and surge duration. This can easily be checked by calculating the mean surge duration at a fixed percentage below the peak for various threshold values. The duration at 50% and the duration at 25% below the top were derived for a number of threshold values. The results are in Table 8.2.

Threshold [m]	Duration at 50% below the peak [u]	Duration at 25% below the peak [u]	Ratio $D_{50\%}$ and $D_{25\%}$	Number of storms
0.5	17.9	7.8	2.29	1923
0.75	18.7	8.4	2.23	862
1	19.5	9.0	2.17	382
1.5	20.0	9.9	2.02	68
2	16.8	9.7	1.73	12

Table 8.2 *Surge duration at 50% and 25% below the peak*

Variation can be seen in the surge durations at 50% and 25% below the peak at various thresholds. However, this variation is small and does not suggest a major dependence between surge duration and surge height. A minor positive dependence can be observed for lower threshold values. There is a minor negative dependence at higher threshold values.

However, the ratio of the surge duration at 50% and 25% below the peak shows a negative dependence, in line with the negative dependence found in the extrapolation method. The higher the threshold, and therefore the higher the storm peak values, the smaller the ratio. This means that, in the case of storms with a higher peak, the duration at 50% below the peak is smaller with respect to the duration at 25% below the peak than for storms with lower peaks. This indicates that storms with a higher peak have, relatively speaking, a slightly broader peak than storms with a lower peak. Note that this dependence is only minor!

All in all, the correlation here is weak. Both methods produce comparable results. This supports the idea that both methods can be used.

8.4 Conclusions

Neither the quantile plot nor the correlation coefficient R constitute cause to question the independence of maximum surge height and surge duration at zero level. This assumption is backed up by the fact that there is also no correlation between the maximum surge height and the surge duration at the 0.5 m level [9].

9 Deriving the storm surge duration for the filtered measurement series

9.1 Introduction

As indicated in section 5.3 the initially derived surge series contain residual tidal effects, which may influence the surge durations to be derived. At low tide, the effect of wind surge is usually more prominent than at high tide. In his 2009 study, De Valk [11] used a filter to eliminate these residual tidal effects from the measurement series at location Vlissingen. That filter was used in the present study for the measurement series at Hoek van Holland. The results will be discussed in this chapter.

9.2 Method

After filtering, the general trend of the surge is preserved and residual tidal effects largely disappear, see Figure 5.1. Large adjacent peaks and twin storms are still found in the filtered measurement series. The arguments from the group of experts for the adoption of a one-day time window still apply to the filtered measurement series. Consequently, as with the unfiltered measurement series, a one-day time window was chosen for the POT methods for the filtered measurement series.

To chart the effects of the filter on the storm surge duration accurately, an identical threshold value for the POT method was initially chosen. So a threshold value of 1.5 m was used at first for the filtered measurement series. However, the use of a filter results in significantly lower peak surges, see Figure 5.2. As a consequence, at a 1.5 m threshold value, only 22 storms were selected for the filtered measurement series. That is significantly less than approximately one storm a year. That is why the storm surge duration was also derived using a 1.25 m threshold value for the filtered measurement series. This resulted in 67 storms a year. The following section will discuss the results for the filtered measurement series for both threshold values.

9.3 Results

9.3.1 Extrapolation method

A 1.5 m threshold value resulted in a storm surge duration of 42 hours, while the unfiltered series at the same threshold value led to a storm surge duration of 40 hours. This is therefore a relatively low increase of 2 hours. However, as indicated in the previous section, at a threshold value of 1.5 m, only 22 storms are selected for the filtered series and a threshold value of 1.25 m is a better value for the filtered series. Adopting this value pushes the storm surge duration up to 46 hours, which is a significant increase of 6 hours compared to the 40 hours of the unfiltered series.

	$D_{0.5}$	D_0
Without filter and threshold value = 1.5 m	29	40
With filter and threshold value = 1.5 m	30	42
With filter and threshold value = 1.25 m	30	46

Table 9.1 Mean surge duration at level 0.5 m and at zero level

Table 9.1 clearly shows that the effect of the filter on the surge duration at the 0.5 m surge level is relatively limited. $D_{0.5}$ only increases by 1 hour, irrespective of the threshold value. The effect on the surge duration at zero level (D_0) is considerably greater. This increase is mainly caused by the fact that the peaks of the filtered series are lower than those of the unfiltered series (see Figure 5.2). The surge duration at zero level cannot be derived directly from the data because of the noise. That is why the surge duration at zero level is derived from the surge duration at the 0.5 m surge level and the maximum surge using extrapolation. This extrapolation method is discussed in detail in Chapter 6. With this extrapolation and assuming the same duration at the 0.5 m level: the higher the peak value, the shorter the surge duration at zero level.

The extrapolation from 0.5 to 0 m is also the cause of the duration increase at zero level when the threshold value is lowered from 1.5 to 1.25 m (see Table 9.1). That is because lowering the threshold value causes additional storm events to be included, all with a relatively low peak surge. As a consequence, and because the duration at the 0.5 m level ($D_{0.5}$) does not change, the duration at zero level (D_0) increases. Assuming a standard trapezium shape with a constant value $D_{0.5}$: the lower the peak surge, the higher the value of D_0 (as a result of extrapolation). This is an argument in favour of adopting $D_{0.5}$ rather than D_0 as the “constant” for input into Hydra-B. However, section 10.4 sets out arguments in favour of adopting D_0 as the constant value. For a discussion of these apparently contradictory results, we refer to section 10.4. Conclusion: the storm surge duration increase from 40 hours (Chapter 6) to 46 hours (Chapter 9) is mainly caused by the fact that the filter lowers the peaks.

9.3.2 Scaling method

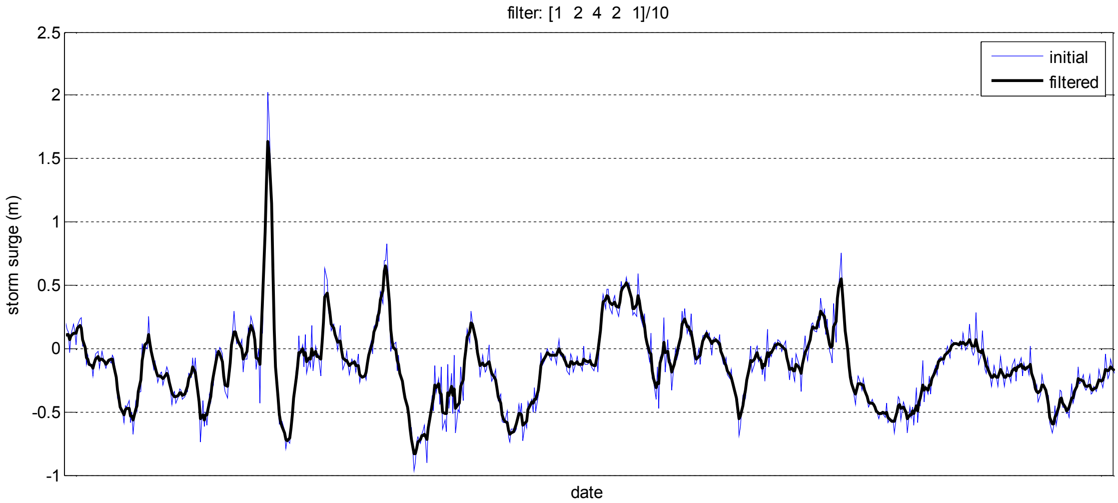
A similar comparison between filtered and unfiltered series has been made for the scaling method. In this case filtering caused an increase from 40 to 43 hours. The standard deviation for the surge duration at zero level is 13 hours. For the unfiltered measurement series this value is 12 hours. Filtering the surge therefore leads to a minor increase in the surge duration spread.

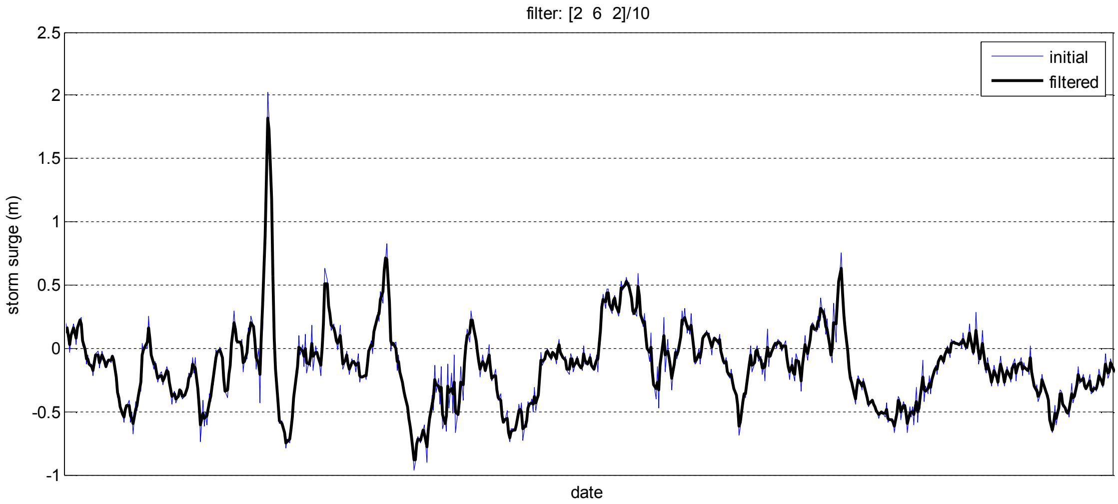
9.4 Discussion about the use of the filter

The major advantages of the filter have been discussed in chapter 5. A potential drawback is that the peaks may sometimes be reduced a little too drastically. The peaks are flattened and the shape becomes a little broader. The reduction of the peaks by the filter results in an increase in the derived duration above the zero level. The selection of the filter is a factor here. The stronger the filter, the more the peaks are flattened and the longer the ultimate surge duration becomes. Figure 9.1 shows an example of the application of three different filters. The filter in the upper plot is the filter used in earlier sections, the second filter is ”weaker” (improved preservation of the original graph) and the third filter is stronger (more flattening). In all three, the general surge hydrograph is preserved. A stronger filter removes residual tidal effects more efficiently, while a lighter filter preserves the original shape better. Table 9.2 shows that the duration at the 0.5 m surge level is hardly affected by the choice of the filter. On the other hand, the surge duration at zero level is sensitive to filter selection. The use of these three different filters results in storm surge durations of 46, 43 and 55 hours respectively. This is caused by the fact that durations at 0 m are based on extrapolation of derived durations at 0.5 m. Therefore, we propose to change the base level of 0 m in Hydra-B and start using 0.5 m as the base level, with a corresponding duration of 30 hours.

	$D_{0.5}$	D_0
Without filter and threshold value = 1.5 m	29	40
With weak filter and threshold value = 1.35 m	30	43
With average filter and threshold value = 1.25 m	30	46
With strong filter and threshold value = 1.1 m	33	55

Table 9.2 Mean surge duration at level 0.5 m and at zero level





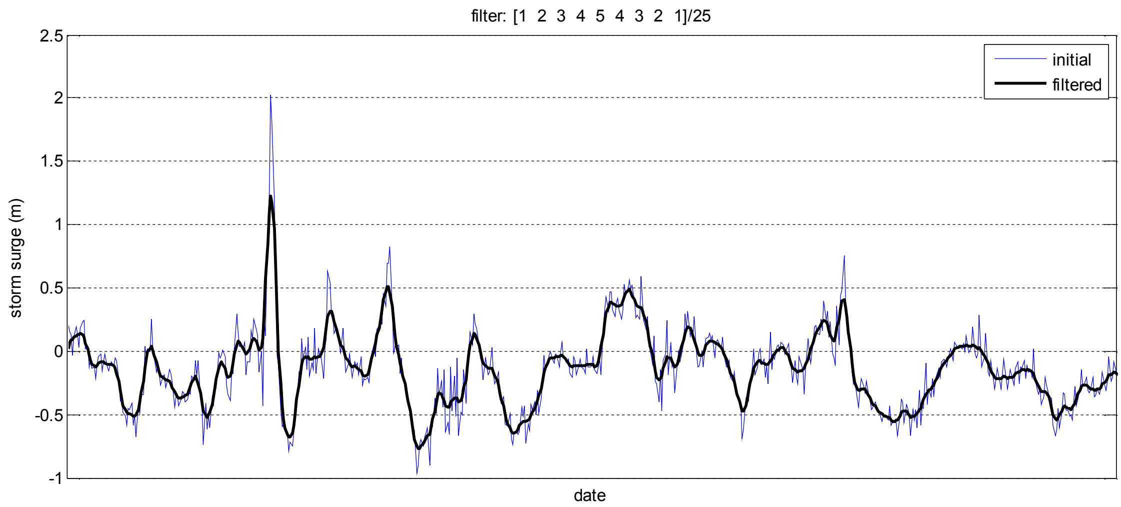


Figure 9.1 *Application of three different filters: average (top), weak and strong (bottom).*

Because of the benefits of removing the residual tidal effects, as disucussed in section 5.3, it is advisable to use a filter. We have adopted De Valk's filter selection [11], in other words the filter with factors [0.1; 0.2; 0.4; 0.2; 0.1].

9.5 Conclusions

The use of a filter for tidal effects on the surge has a significant impact on the storm surge duration. For now we opt for the filter used by De Valk [11]. This results in a storm surge duration at zero level of 46 hours above a level of 0 m. This is an increase of 6 hours in comparison with chapter 6, where no filtering was applied. This effect results mainly from the reduction of the peaks by the filter. The stronger the filter, the more the peaks are lowered and the longer the storm surge duration that ultimately results.

This sensitivity to filtering mainly applies to the duration above 0 m.. This is due to the fact that durations above 0 m are based on extrapolation of derived durations above 0.5 m. Different filters result in different peak values, and that causes differences in the derived (extrapolated) durations above the 0 m surge level. The duration above the 0.5 m level is fairly insensitive to the filter selection, because at this level no extrapolation is applied. Therefore we propose to change the base level of 0 m of the surge hydrograph of Hydra-B and start using 0.5 m as the base level, with a corresponding duration of 30 hours.

10 Deriving the storm surge duration with an alternative method

10.1 Introduction

In the previous chapters, storm surge duration was derived based on current Hydra-B modelling, focusing on schematisation with a single peak such as the trapezium shape. De Valk [11] demonstrates an alternative method based on measurements at Vlissingen. This alternative method differs from the earlier approach, mainly in the following areas:

Extrapolation method (Chapters 6 and 9)	De Valk method, 2009
• uses a threshold of 1.5 m (H6) and 1.25 m (H9) for selecting storms	• uses a 0.5 m threshold for selecting storms
• uses a time window for deriving the duration of exceedances of threshold values	• does not use a time window
• determines the storm surge duration based on a fitted trapezium shape	• does not use a predefined shape

Table 10.1 Differences between the two methods in terms of approach

This chapter demonstrates the alternative method of De Valk for Hoek van Holland and discusses the results. The main reasons for discussing this alternative method in the present report are:

1 The method substantiates the assumptions underlying the scaling method described earlier and the selection of a trapezium shape (or in fact triangular shape) as the schematised shape.
2 There are several methods for deriving the storm surge duration and we think it important for the reader to be informed about them.

At the end of this chapter we will discuss the pros and cons of each method.

10.2 De Valk Method

The De Valk method uses the filtered measurement series as discussed in Chapter 9. The following procedure is then used to derive the surge exceedance durations.

- Storm events are selected based on the exceedance of the 0.5 m threshold. The points at which this threshold is crossed (upwards and downwards) mark the beginning and the end of a storm event.
- The storms are divided into classes based on the surge maximum of each storm. The class limits are chosen in such a way that each class contains 50 storms.
- For each class, the average duration above a number of threshold values is determined. These threshold values are lower than the peaks.
- For each class the mean exceedance duration for each threshold value is derived for all 50 storms in the class.
- For each class, the exceedance level at zero level is derived from the relation between threshold value and exceedance duration. For this purpose, auxiliary straight lines that closely resemble the derived relation between threshold value and exceedance duration are extrapolated to the zero level.

10.3 Results

A total of 1222 storms were selected over the entire analysis period (1939-2006). That means roughly 18 storms a year. These 1222 storms were then classified according to peak surge value into 24 classes of 50 storms and 1 class of 22 storms. Figure 10.1 shows all peaks and the class limits. Particularly in the highest class, the spread is considerable.

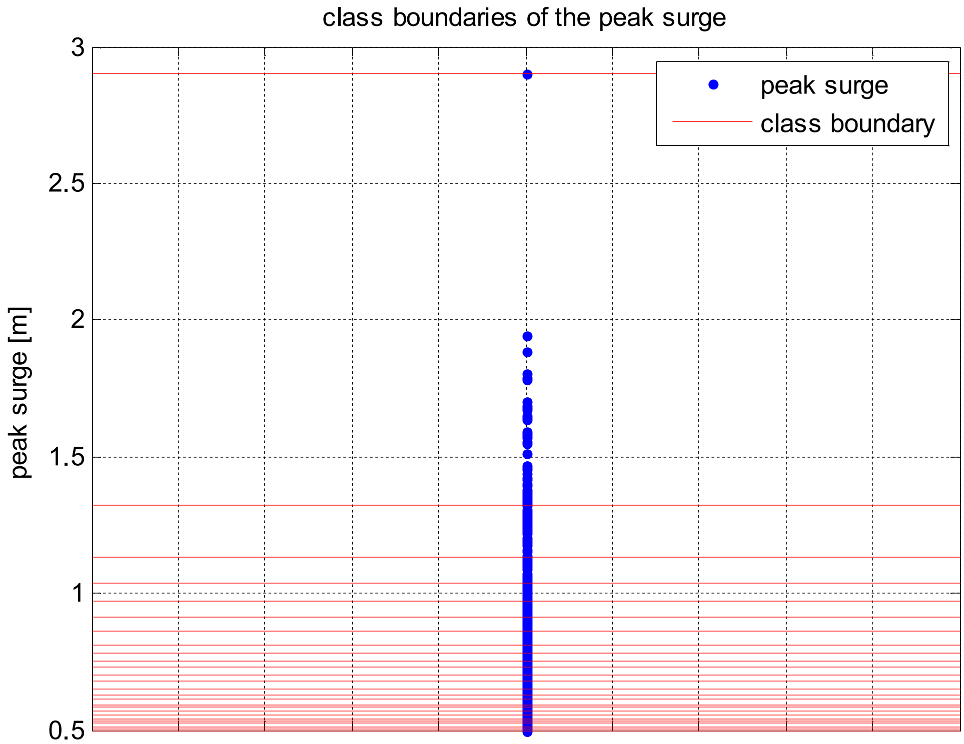


Figure 10.1 Peak surge (blue dots) and class limits (red lines) for every 50 peaks.

Figure 10.2 shows the exceedance durations for each threshold value for the classes of 50 storms classified according to the maximum surge height. Each coloured line represents a single class. The dotted black gridlines all end in the point (48 hours, 0 m). The following can be concluded from this figure.

- For each class the surge hydrograph is approximately a triangle because the coloured lines are approximately straight.
- Average duration at zero level determined by linear extrapolation appears to be independent of surge height and is roughly 48 hours.

Figure 10.3 to Figure 10.6 show the same coloured lines as Figure 10.2, but in combination with other gridlines for the purpose of extrapolation. Figure 10.2 sets the intersection with the x-axis at 48 hours; in Figure 10.3 to Figure 10.6 the selected values are 40, 45, 50 and 55 hours respectively. These figures show that 40 and 45 hours are too short as values for the basic duration, while 55 hours is too long. Both 48 hours and 50 hours seem to be suitable.

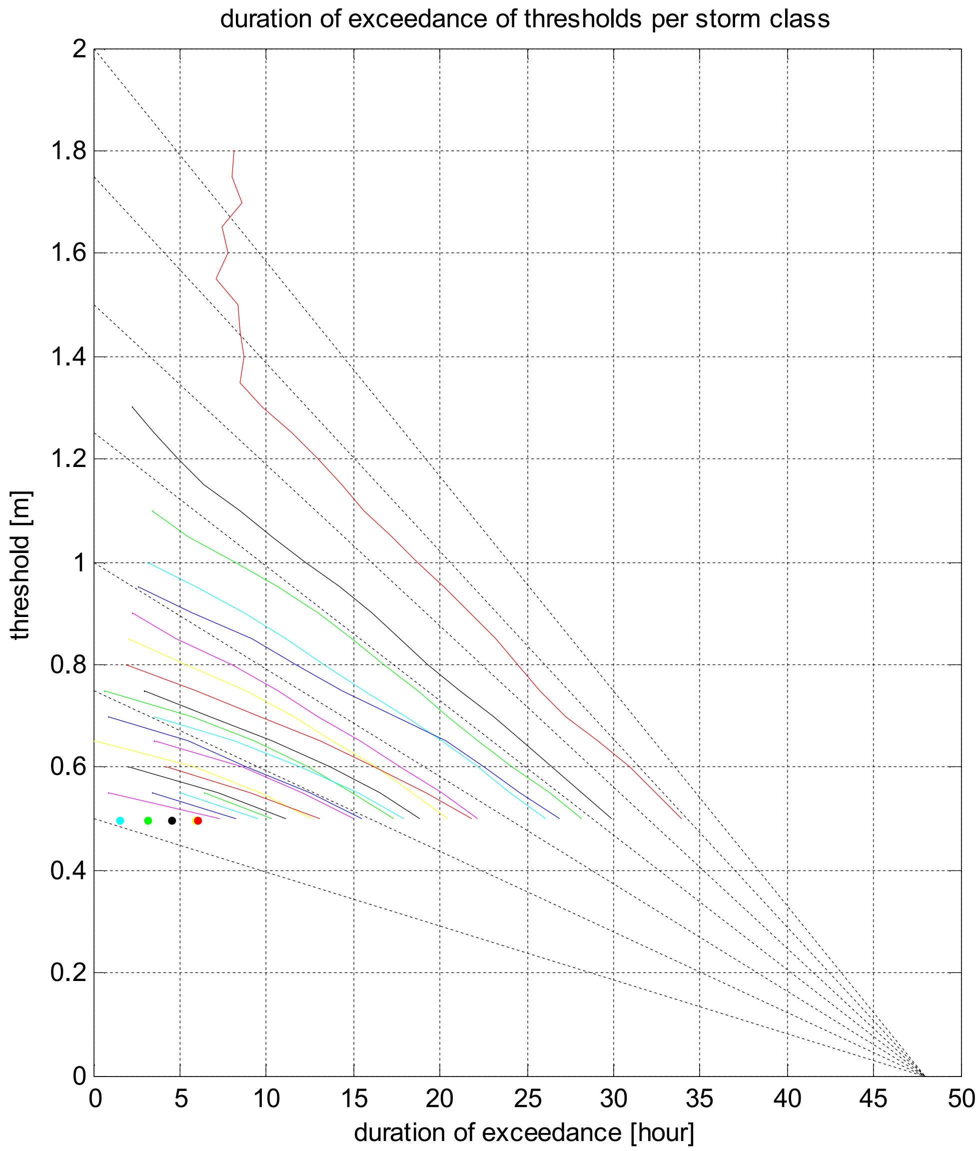


Figure 10.2 *Exceedance durations for each threshold value during storms, for classes of 50 storms classified according to maximum surge height (coloured curves). The dotted black gridlines go through the point (**48 hours, 0 m**).*

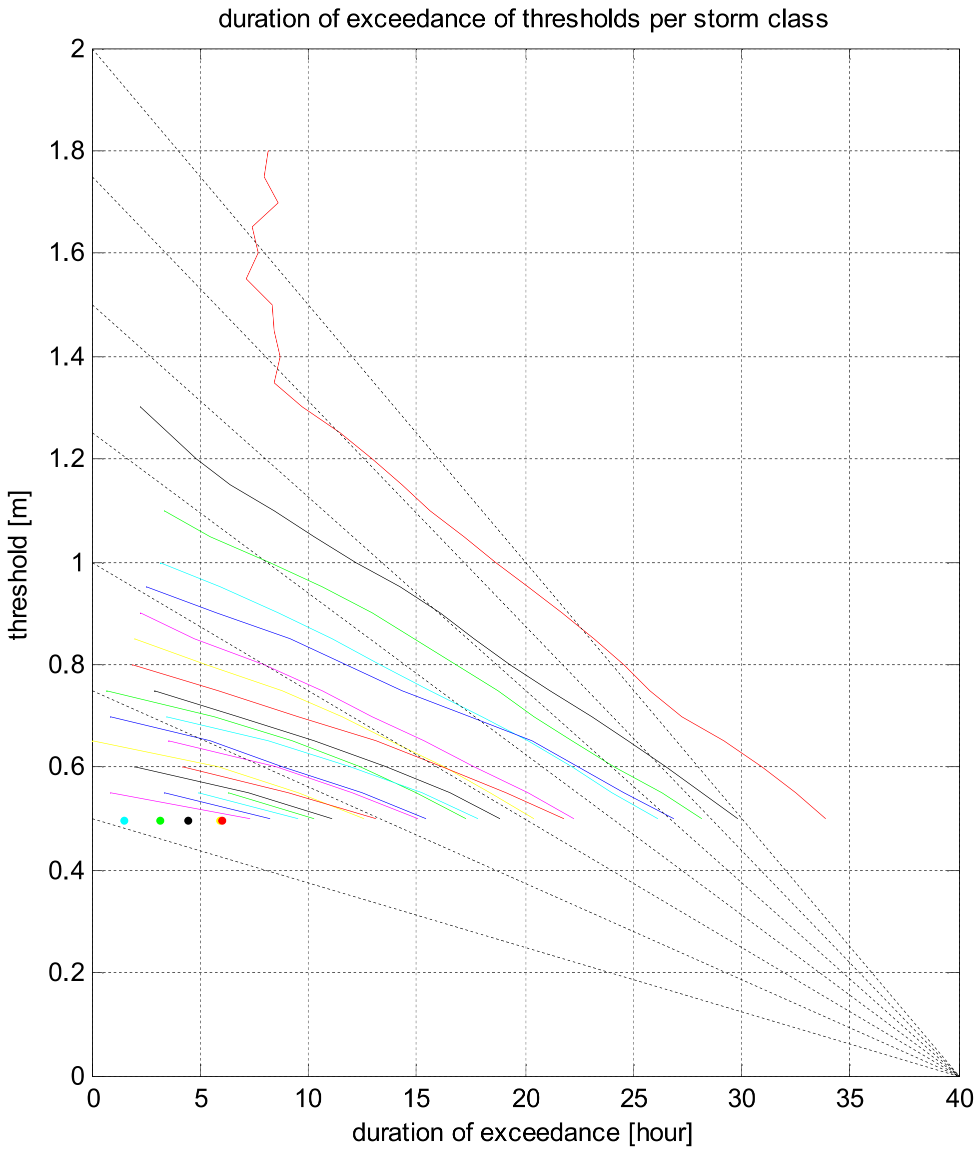


Figure 10.3 *Exceedance durations for each threshold value during storms, for classes of 50 storms classified according to maximum surge height (coloured curves). The dotted black gridlines go through the point (**40 hours, 0 m**).*

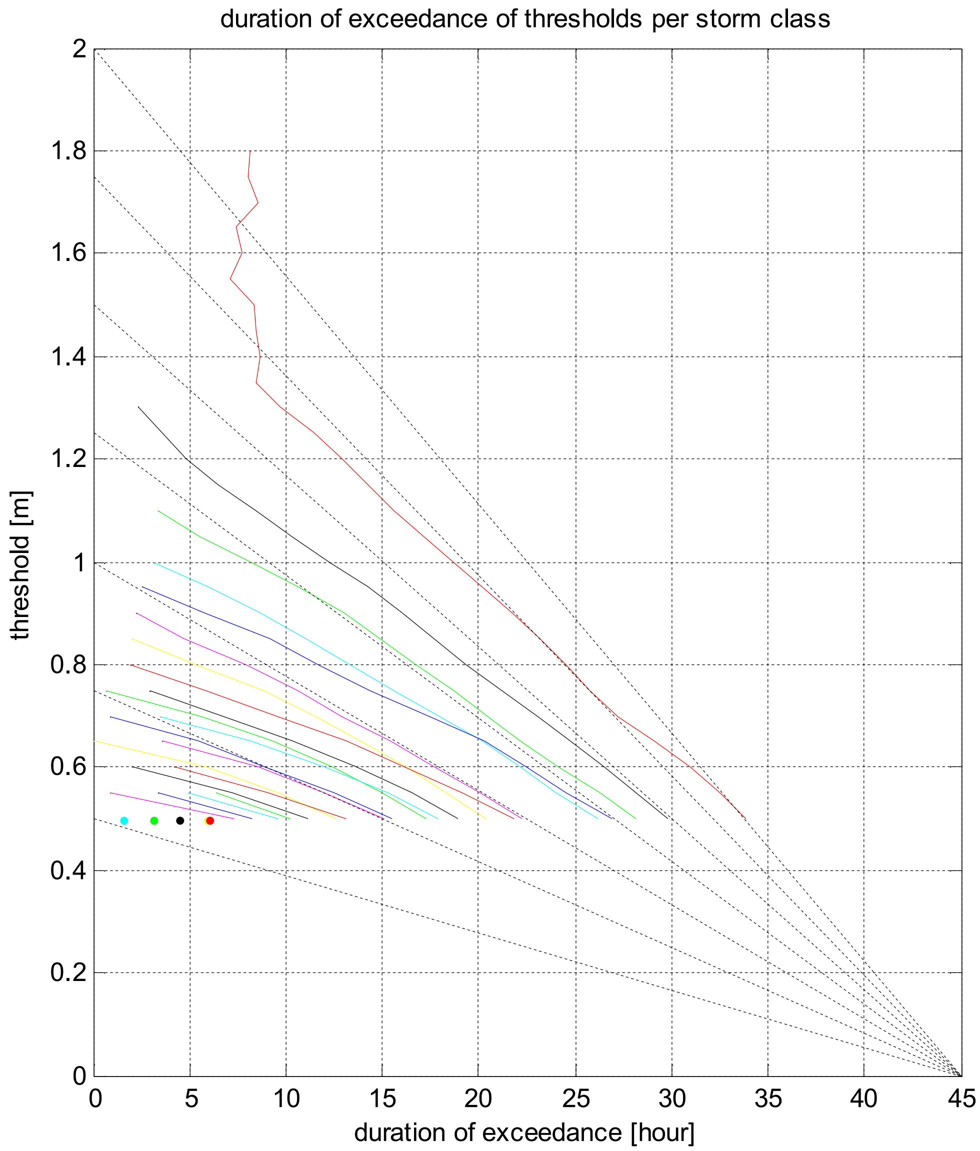


Figure 10.4 *Exceedance durations for each threshold value during storms, for classes of 50 storms classified according to maximum surge height (coloured curves). The dotted black gridlines go through the point (**45 hours, 0 m**).*

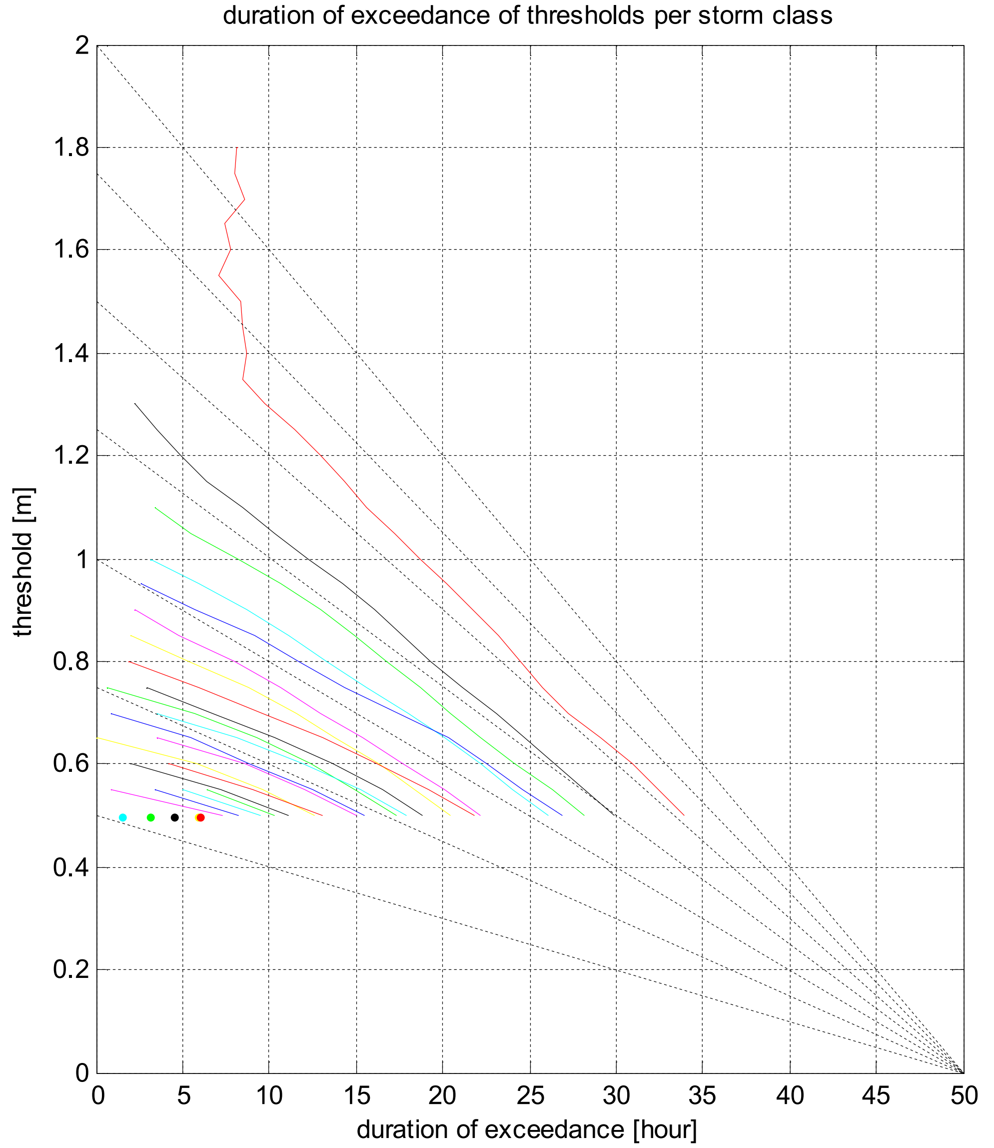


*Figure 10.5 Exceedance durations for each threshold value during storms, for classes of 50 storms classified according to maximum surge height (coloured curves). The dotted black gridlines go through the point (**50 hours, 0 m**).*

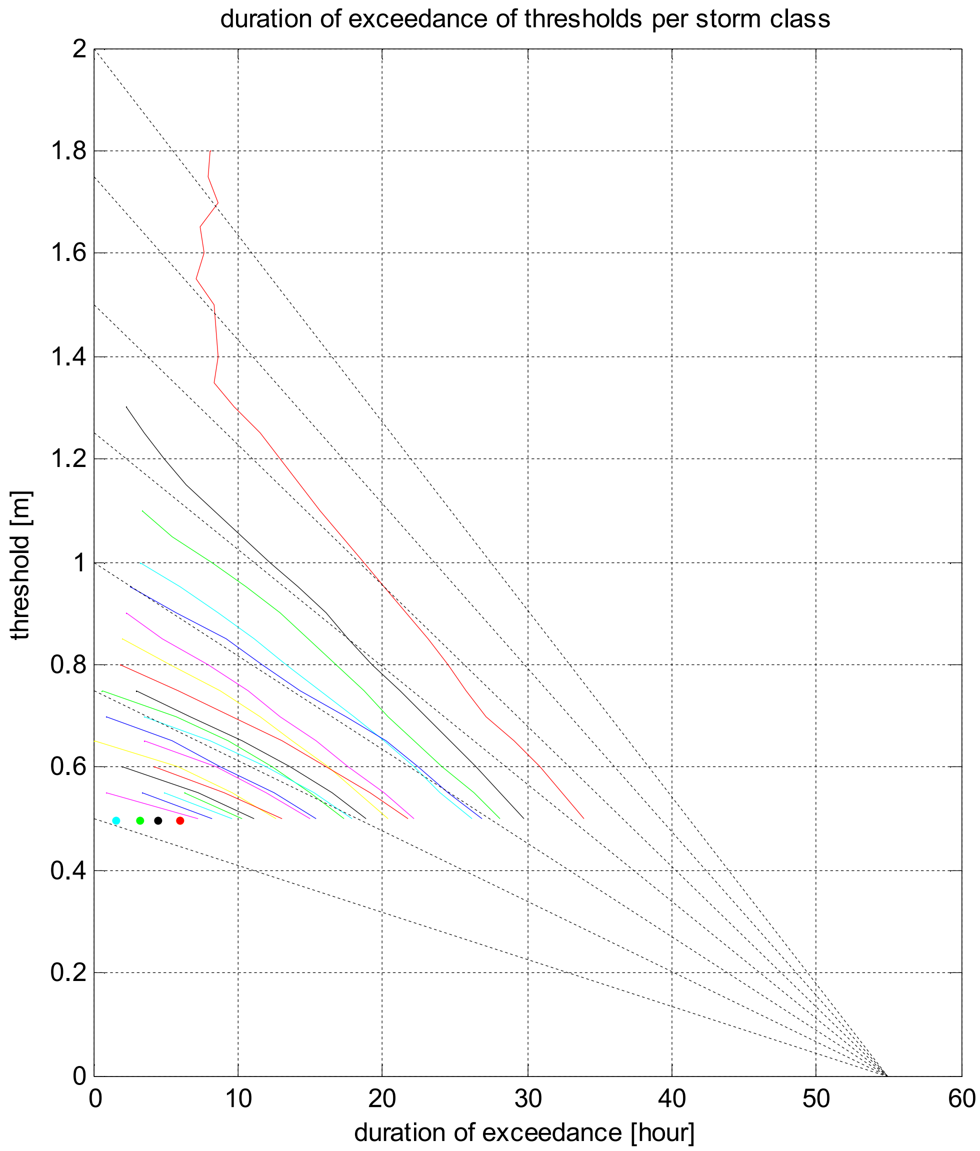


Figure 10.6 *Exceedance durations for each threshold value during storms, for classes of 50 storms classified according to maximum surge height (coloured curves). The dotted black gridlines go through the point (**55 hours, 0 m**).*

10.4 Points for discussion

10.4.1 Surge duration independent of the maximum storm surge

It emerged from the previous section that the average duration at zero level is independent of the surge height. However, this is not the case if no filter is used, as emerges from Figure 10.7. The coloured lines in Figure 10.7 do not all converge to the same surge duration, as was the case for instance in Figure 10.2. This is in line with the findings of ref [11]. So the characteristic of independence, a major assumption of Hydra-B, only applies for the filtered surge duration.

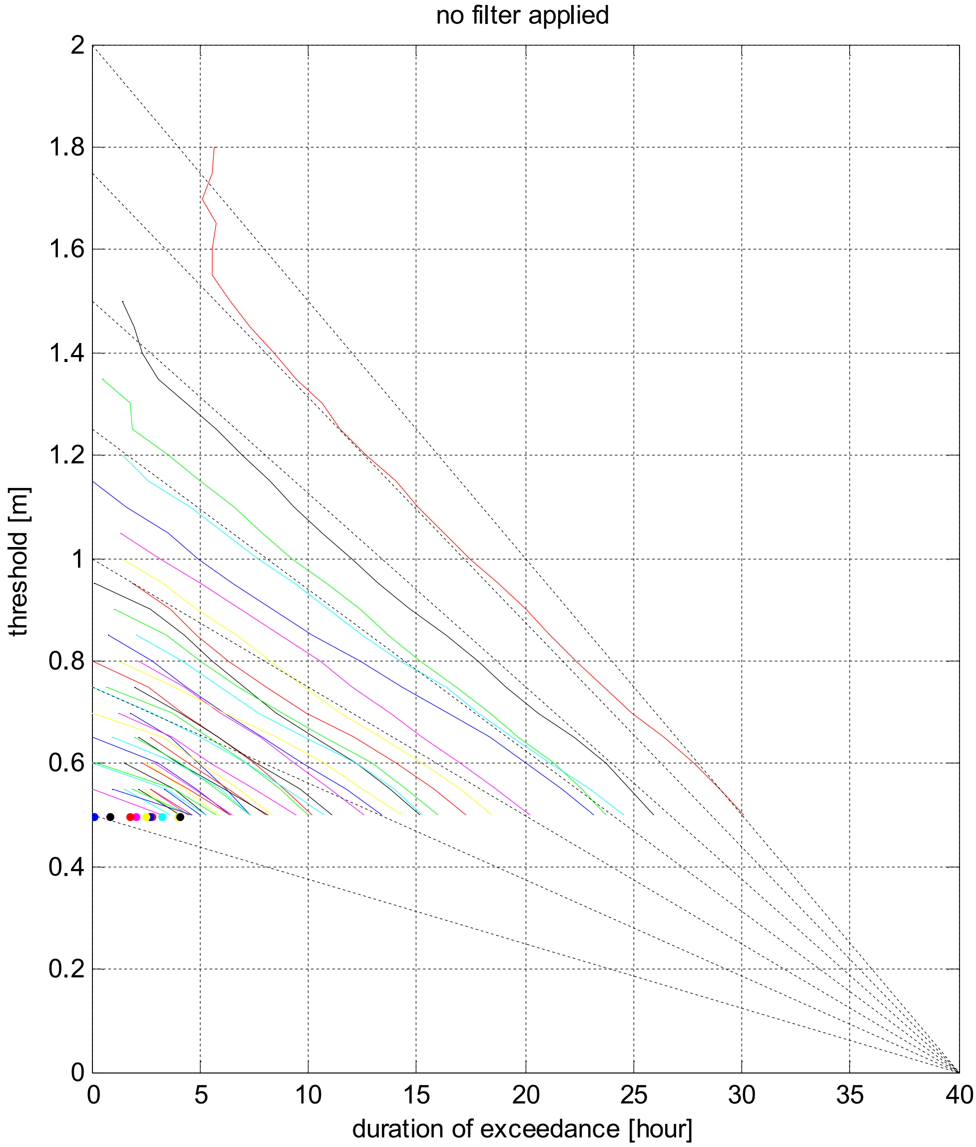


Figure 10.7 *Exceedance durations for each threshold value during storms, for classes of 50 storms classified according to maximum surge height (coloured curves). The dotted black gridlines go through the point (**40 hours, 0 m**). In this example, **no filter** was used*

10.4.2 Filter selection

As discussed in Chapter 9, the use of the filter has a significant effect on the storm surge duration to be derived. Figure 9.1 shows three different filters characterised as "average" (top), "weak" (middle) and "strong" (bottom). In section 10.3 the average filter was used. In Figure 10.8 to Figure 10.10 the three different filters were used. It emerges that, when these three different filters are used, the resulting exceedance durations at zero level are 50, 45 and 60 hours respectively.

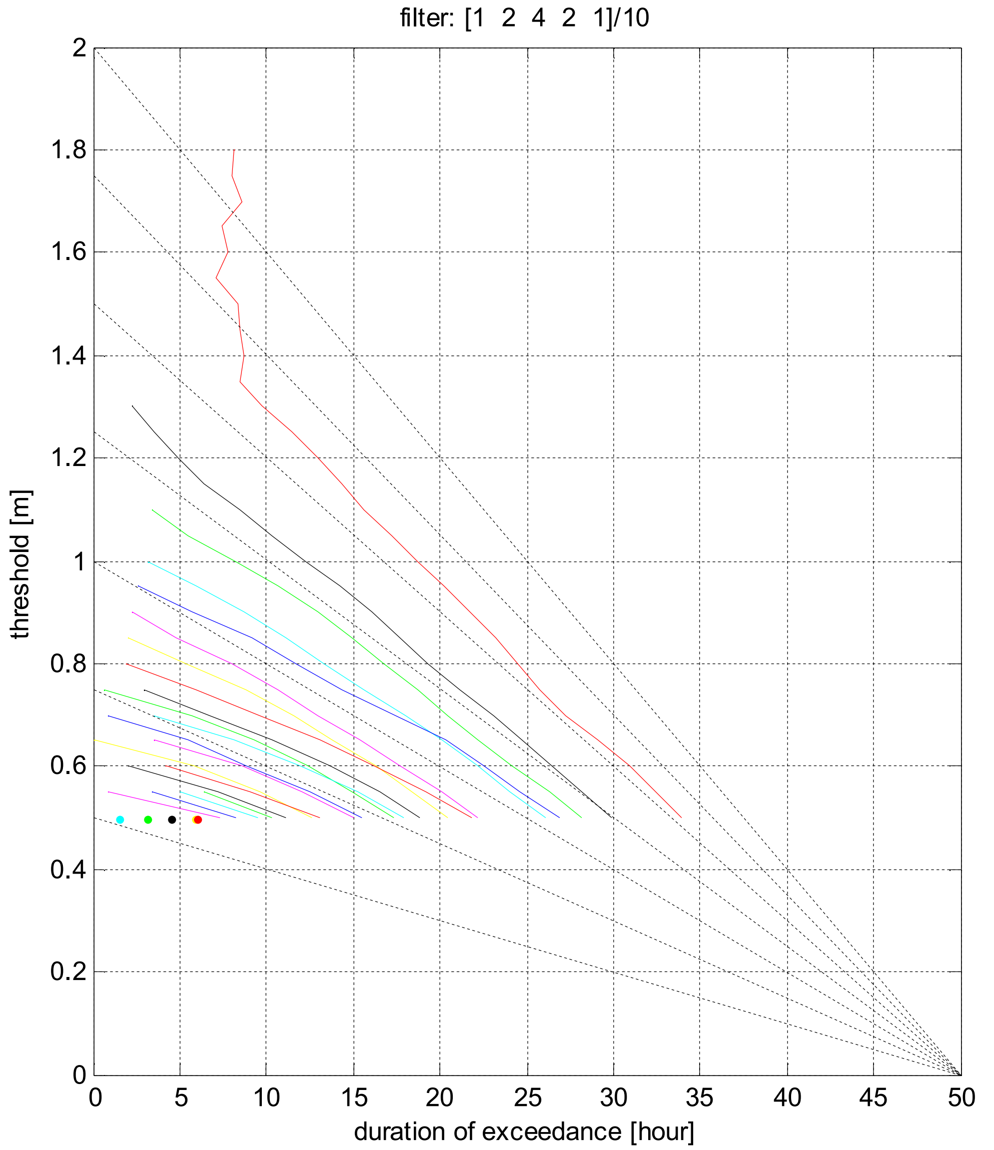


Figure 10.8 Exceedance duration of 0 m surge (50 hours) after using the "average" filter [1 2 4 2 1]/10

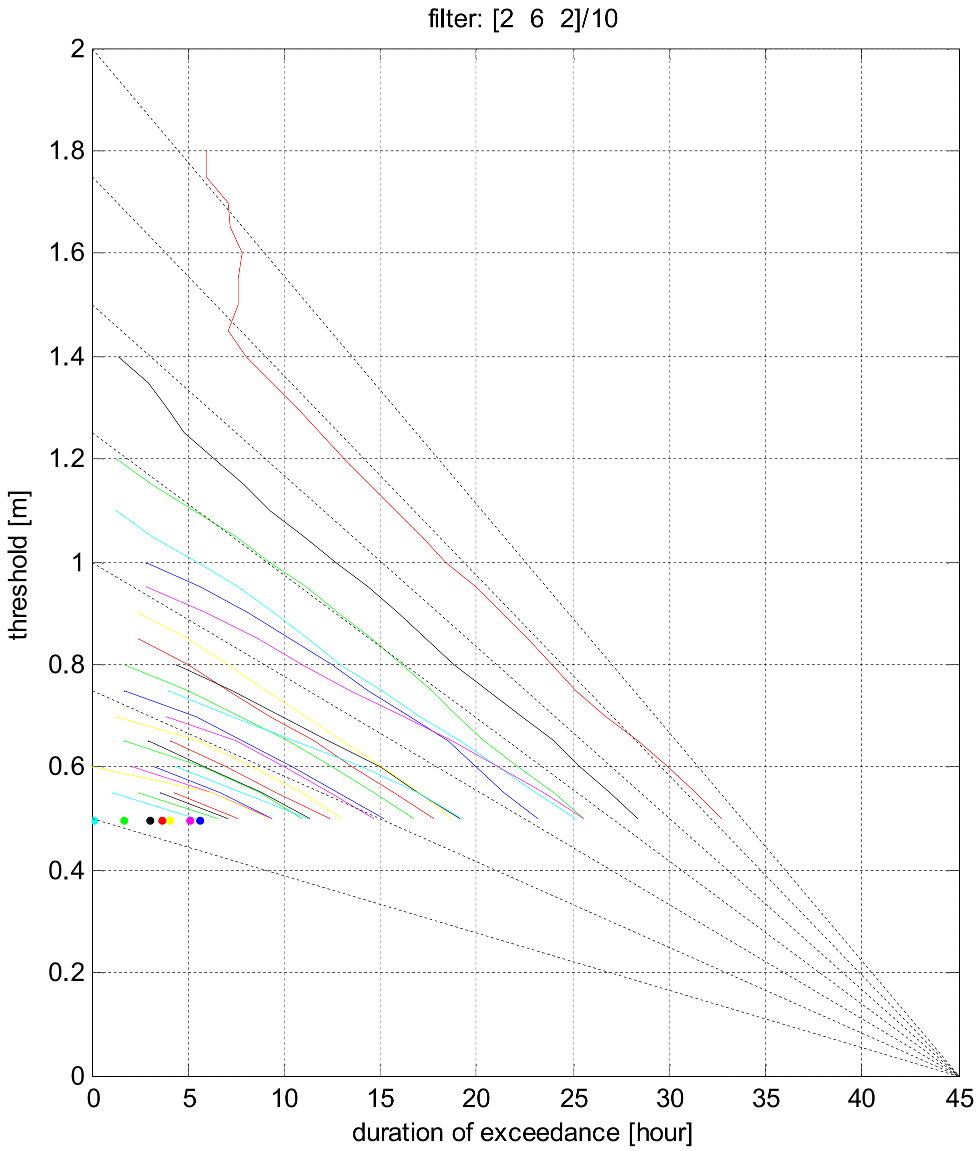


Figure 10.9 Exceedance duration of 0 m surge (45 hours) after using the "weak" filter [2 6 2]/10

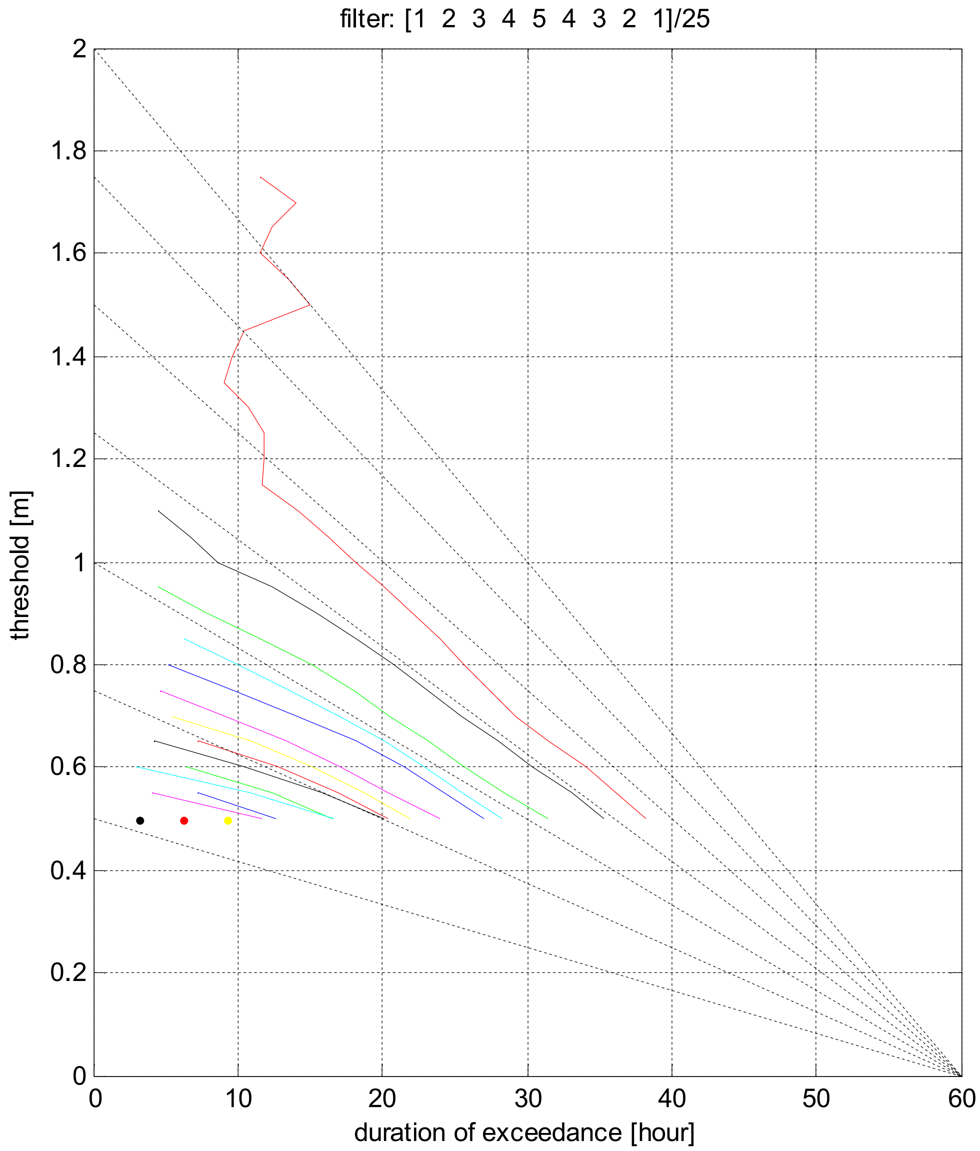


Figure 10.10 Exceedance duration of 0 m surge (60 hours) after using the "strong" filter [1 2 3 4 5 4 3 2 1]/25

10.4.3 Handling multiple peaks

When using the extrapolation method (Chapters 6 and 9) various criteria were used to remove adjacent peaks from the storm graph. Criteria of this kind were not used in the De Valk method. The criterion that was used was that all observations in between an intersection with the 0.5 m threshold in the upward and downward direction belong to the same storm. This means, in the case of the period from 26 February to 3 March 1990 for example, that several peaks are considered to be part of the same storm event (see Figure 10.11). This contradicts the consensus of the expert meeting. That is why, in the present study, we propose maintaining the criteria for storm selection and the derivation of the storm surge duration as used for the extrapolation method (see Chapter 9).

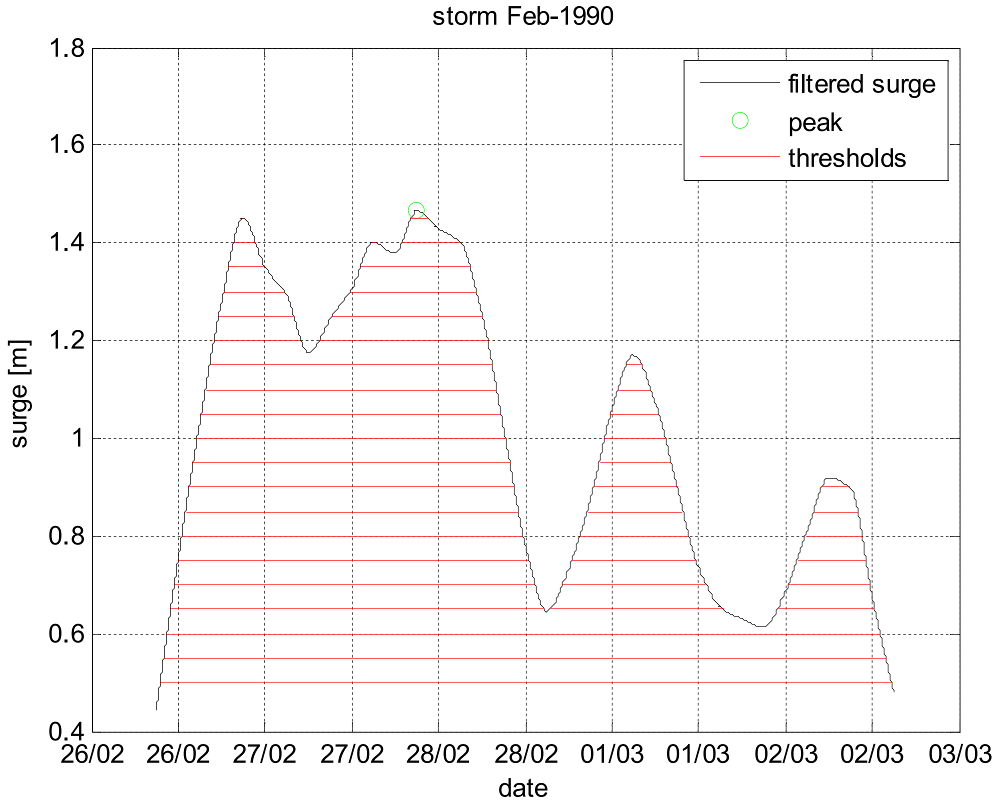


Figure 10.11 *Filtered surge hydrograph for the multiple storm event in February 1990 (black) and durations for the exceedance of threshold levels (red lines).*

10.4.4 Surge duration at level h = 0.5 m

In section 9.4 it was concluded that the duration of the exceedance of the 0.5 m level is rather insensitive to the selected threshold value for selecting the peaks, while the duration of exceedance at the 0 m level is very sensitive. This indicates that the duration at level 0.5 m hardly depends on the peak values, if at all. However, if an analysis similar to the one in the present chapter is made for the threshold value of 0.5 m, it emerges that this is not quite true. Figure 10.12 and Figure 10.13 show examples of converging lines (black dotted lines) to a duration above the 0.5 m threshold value of 30 hours (Figure 10.12) and 33 hours respectively (Figure 10.13). The exceedance durations derived from the data, which are represented in the figures by the coloured lines, do not follow these converging lines sufficiently to justify describing this as a constant exceedance duration at 0.5 m. In particular, the class of the highest peak surges (top red line in Figure 10.12 and Figure 10.13) deviates from the other lines. On the basis of this class of highest surges, a value of 32 to 33 hours above a 0.5 m threshold seems justified. The other lines would rather seem to indicate a value of 30 hours.

This result seems to contradict section 9.4, partly because of the difference in the method followed to derive storm durations (see the discussion in the previous section 10.4.3, about including or excluding adjacent peaks). On the other hand, the results are not so very contradictory: the range referred to above of 30–32 or 33 hours does not indicate a very broad spread in the exceedance duration above a 0.5 m threshold. As stated in chapter 9, we therefore advocate to adopt a value for the duration at 0.5 m as a basis for Hydra-B. The proposed duration of 30 hours is supported by the analysis of the current chapter.

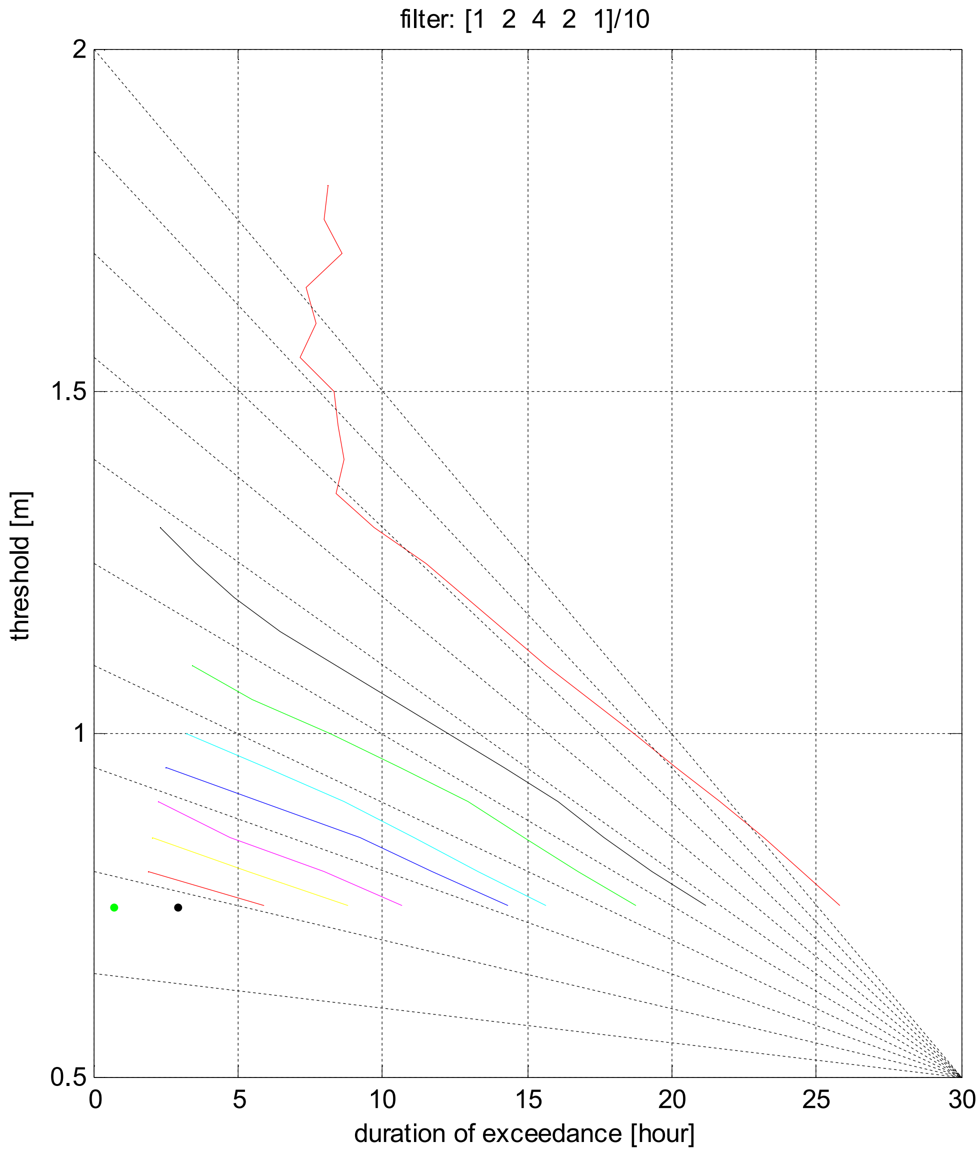


Figure 10.12 *Exceedance durations for each threshold value during storms, for classes of 50 storms classified according to maximum surge height (coloured curves). The dotted black gridlines go through the point (**30 hours; 0.5 m**)*

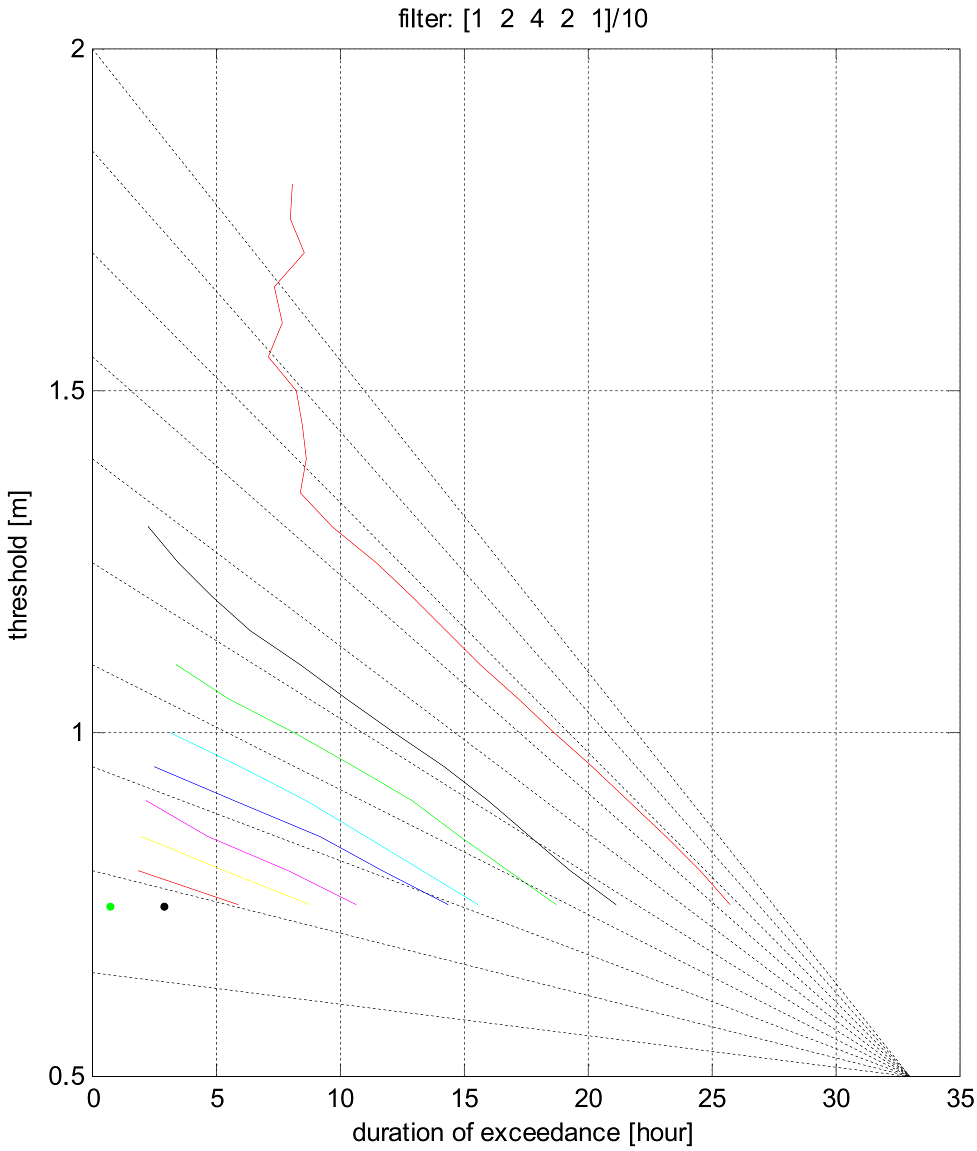


Figure 10.13 *Exceedance durations for each threshold value during storms, for classes of 50 storms classified according to maximum surge height (coloured curves). The dotted black gridlines go through the point (**33 hours; 0.5 m**)*

10.5 Conclusion

The “alternative” method for deriving the storm surge duration as presented in this chapter supports the idea that the mean storm follows a triangular pattern. This is in line with the standard trapezoidal storm surge hydrographs because these are almost the same as the triangular shape.

The first step in the method is to filter the time series for the storm surge duration to remove residual tidal effects from the derived surge. After filtering as recommended in [11], the resulting surge duration at zero level is 48 hours. The extrapolation method for the similarly filtered surge series gives a result of 46 hours (see Chapter 9). For the duration above 0 m surge, the value of 46 hours is better in line with the scope of this study, since with this choice adjacent peaks are not combined. However, we recommend not to use a threshold level of 0 m surge as the basis for the schematised hydrograph for future computations with Hydra-B. Instead, a threshold value of 0.5 m is recommended with a corresponding duration of 30 hours. This duration was already proposed in chapter 9 and further supported by the analysis of the current chapter.

11 Storm duration

11.1 Introduction

The preceding chapters have shown that the present study indicates that a storm *surge* duration in the order of magnitude of 46 hours is more realistic than the value of 29 hours applied so far in Hydra-B and the HR. For storm duration (evolution of wind speed in time), the value of 29 hours has also been used until now for a wind speed of 10 m/s. Even though storm duration and storm surge duration are interrelated variables, they are not exactly the same in physical terms. Therefore, in this report the proposed value for the storm surge duration is not automatically chosen as the storm duration. Instead it has been investigated which value is realistic for storm duration.

Since many of the choices made and the methods used are the same as those for determining storm surge duration, the derivation of storm duration will be discussed in a single chapter. Section 11.2 discusses the data analysis. Section 11.3 discusses the derivation of storm duration. Section 11.5 describes the correlation between peak wind speed and storm duration.

11.2 Data analysis

Storm duration was derived from a measurement series of potential wind speeds at Hoek van Holland. The measurements are available for the period from 1 January 1962 to 1 January 2006. They are potential hourly average wind speeds from the Dutch meteorological institute KNMI. These are the wind speeds after correction of the measurements to make them representative for a height of 10 m over open ground with a roughness length of 0.03 m [4]. This value corresponds to the roughness length of a grassy surface.

After removing some obvious errors in the available measurement series, the data was found to be reliable, while accepting some minor gaps in the data.

11.3 Derivation of the storm duration

First, storms are selected using a POT method with a threshold value of 20 m/s and a one-day time window (similar to storm surge duration). As with storm surge duration, we chose a threshold value that results in approximately one storm a year. This means that the selected population is large enough to provide an impression of the spread in storm duration. Furthermore, it also means that significant storm events are included. The choice of a threshold value of 20 m/s and a one-day time window results in 53 selected storms.

Two methods were used to derive the storm *surge* duration, the extrapolation method and the scaling method. Both methods have been described in detail in Chapter 6 and are therefore assumed to be known to the reader here. We investigated whether both methods are suitable for deriving storm duration.

11.3.1 Extrapolation method

Hydra-B uses a different schematisation for the evolution of wind speed in time than for the surge hydrograph. The evolution of wind speed in time as modelled in Hydra-B is shown in Figure 11.1. By contrast with storm *surge* duration, in the current Hydra-B modelling approach, storm duration is not the duration at zero level, but the duration at 10 m/s.

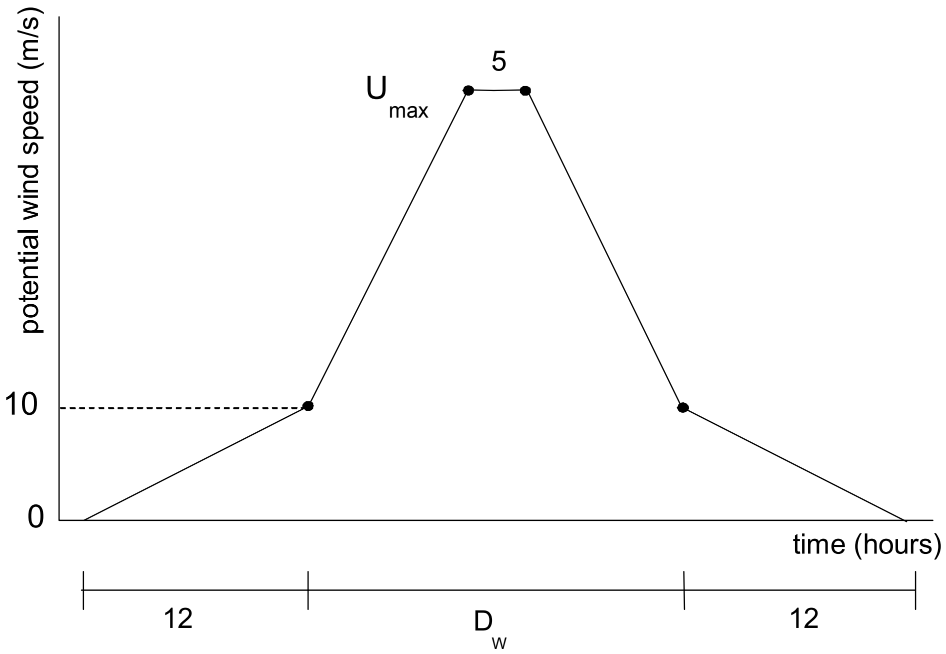


Figure 11.1 *The evolution of wind speed in time as modelled in Hydra-B where D_w = 29 hours. Note that storm duration (D_w) is the duration at the level of 10 m/s.*

For applications in "dike safety assessment", the higher wind speeds are particularly relevant. The trapezium used to model wind speed must therefore be particularly accurate for the highest part of a storm, say the top 30% [4]. The extrapolation method is used to determine the duration at the 10 m/s level by extrapolation (see Section 6.2 for a detailed description of the extrapolation method). It emerges from Figure 11.2 that the extrapolation method for storm duration is sensitive to the selection of the exceedance level used for extrapolation. This sensitivity is caused by the fact that most storms fan out for lower wind speeds. An example of a storm that fans out at lower wind speeds is shown in Figure 11.3. The sensitivity to the selected exceedance level led to the decision to reject the extrapolation method for deriving storm duration.

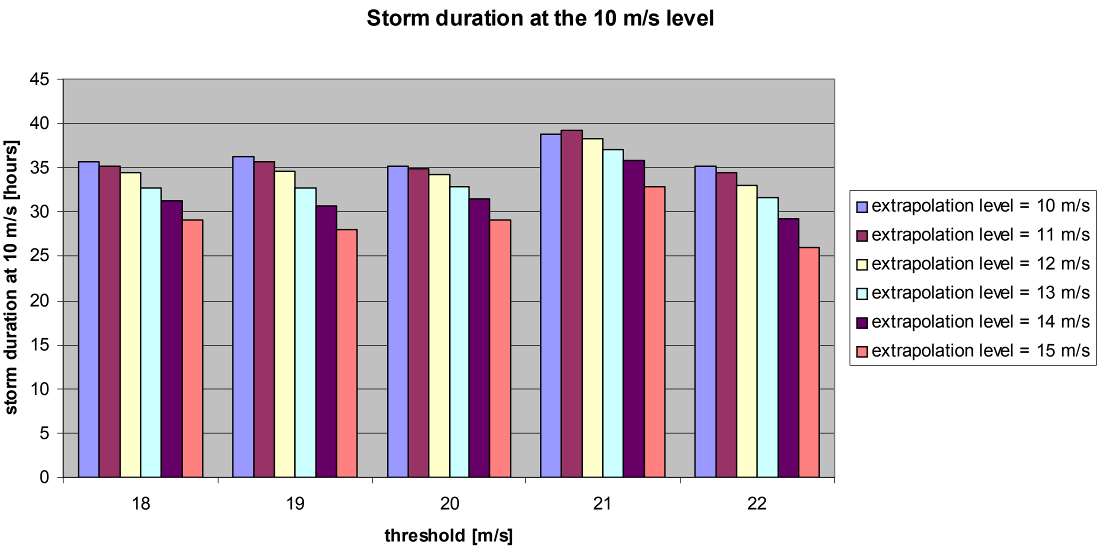


Figure 11.2 *Sensitivity analysis for the selection of the POT method and the exceedance level for extrapolation to 10 m/s*

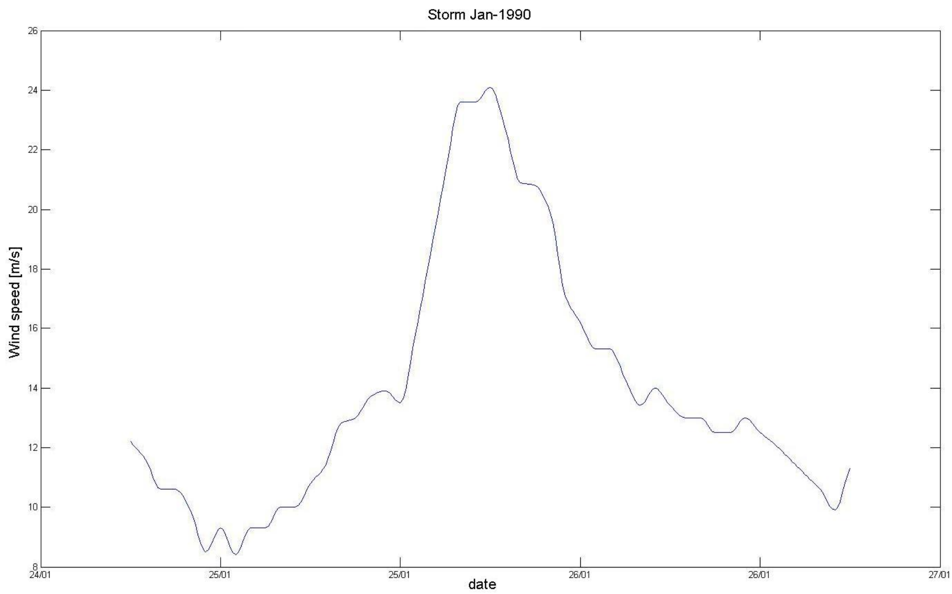


Figure 11.3 *Storm of January 1990*

11.3.2 Scaling method

11.3.2.1 Method

The scaling method rescales each storm to a dimensionless peak wind speed of 1. That makes it inconvenient to derive the mean storm duration at the 10 m/s level, since for each storm, the 10 m/s level is at a different percentage below the peak. An alternative would of course be to consider the level of 10 m/s as the “0% level” in the scaling method. However, for convenience it was decided not to do so. This means it was decided not to use the standard shape as currently used in Hydra-B (see Figure 11.1). A new schematisation therefore has to be selected.

Currently, Hydra-VIJ uses a different schematisation than Hydra-B, see Figure 11.4. The origin of the schematisation used in Hydra-VIJ is documented in the report "Hydraulic Boundary Conditions 2006 Vecht and IJssel delta" [4]. The main difference between the schematizations of Hydra-VIJ (Figure 11.4) and Hydra-B (Figure 11.1) is the fact that the latter has a change in gradient at 10 m/s. The other noticeable difference is that the schematization of Hydra-VIJ has a peak duration of 2 hours, whereas the schematization of Hydra-B has a peak duration of 5 hours.

For reasons of consistency, it was decided to also consider the shape of Hydra-VIJ as the proposed shape for Hydra-B. The following sections show a comparison of this standardized shape with the shape that was derived from the data. In order to make a choice for the peak duration and the base duration of the standardized shape, these values will be varied.

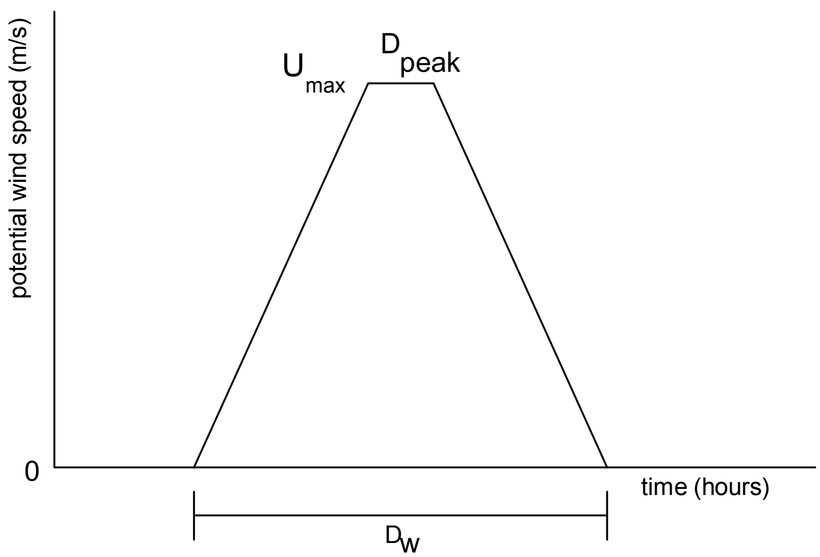


Figure 11.4 *The evolution of wind speed in time used in Hydra-VIJ, where D_{peak} = 2 hours and D_w = 48 hours. Note that the storm duration (D_w) is at zero level.*

11.3.2.2 *Results for a peak duration of 1 hour*

The scaling method does not derive storm duration at zero level for each separate storm, but the arithmetic mean values for storm durations at fixed percentages below the peak. The storm duration at zero level can then be derived by linear extrapolation from the fixed percentages under the peak. For storm *surge* duration, it was decided to extrapolate linearly from the durations at 25% and 50% below the peak. That was also done for storm duration. The mean storm durations at 25% and 50% below the peak are 13.8 and 32.8 hours respectively. This approach results in a mean storm duration at zero level of 71 hours.

However Figure 11.5 and Figure 11.6 show that a trapezium shape with a basic duration [1] of 71 hours results in a bad fit to the evolution of wind speed in time (the standard shape[2] from the scaling method). This can be explained based on of Figure 11.7.

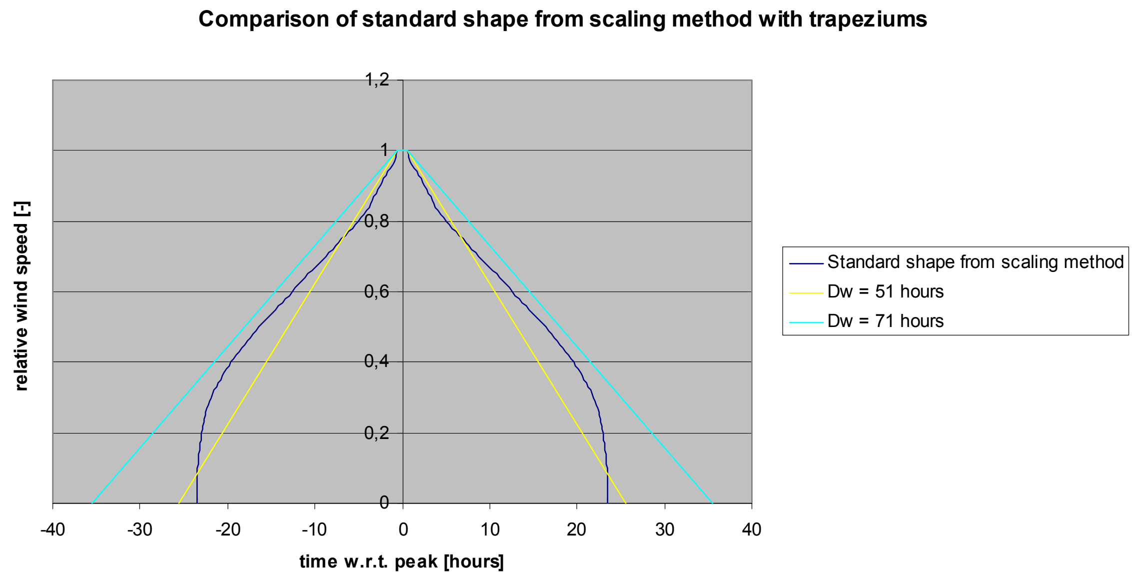


Figure 11.5 *Standard shape from the scaling method for storm duration with two different trapezium shapes where D_{peak} = 1 hour and D_w = 51 and 71 hours.*

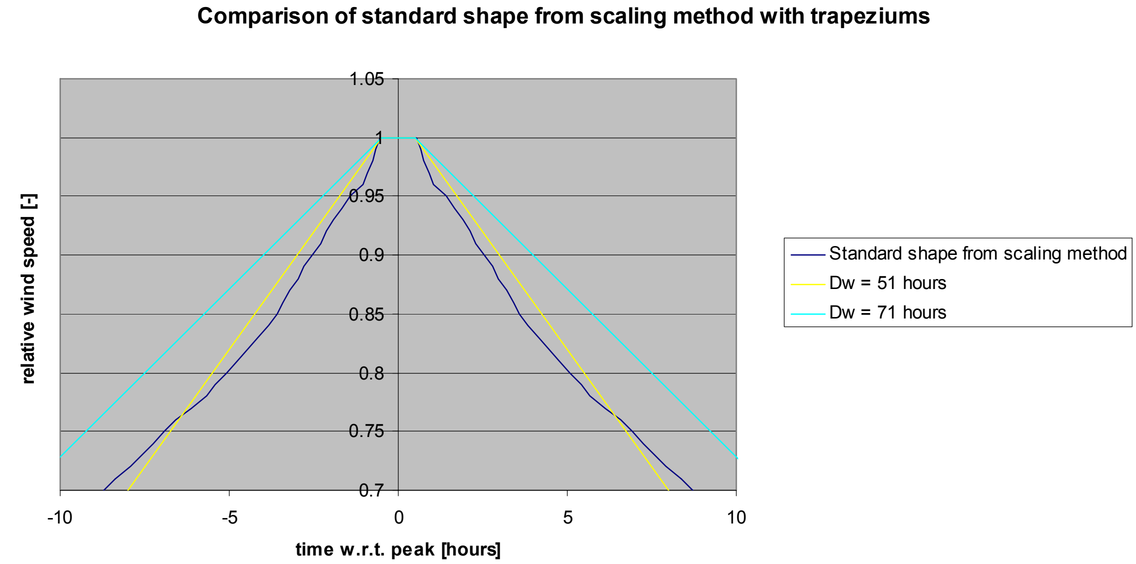


Figure 11.6 *Standard shape from the scaling method for storm duration with two different trapezium shapes where D_{peak} = 1 hour and D_w = 51 and 71 hours. (zoomed version of Figure 11.6)*

1. *Basic duration is the duration at zero level.*
2. *The scaling method calculates the mean exceedance durations for fixed percentages below the peak. That results in a mean evolution of wind speed in time. This average evolution of wind speed in time is also referred to as the standard form. See section 6.3.*

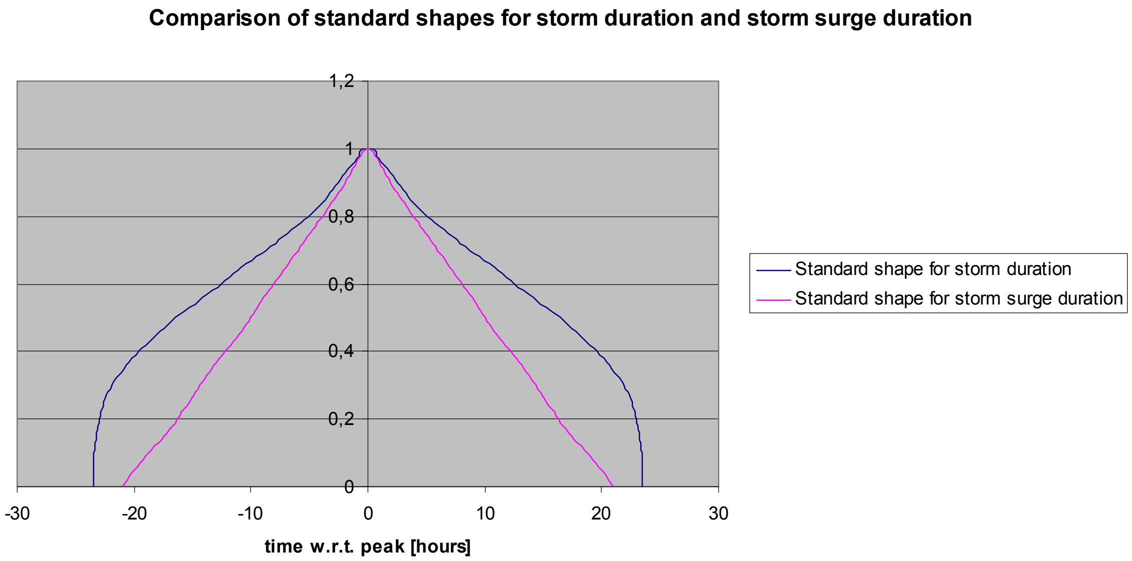


Figure 11.7 Standard shape from scaling method for storm duration and storm surge duration

The figure shows that the mean shape for lower wind speeds fans out widely[3]. This fanning out is the reason the slope of the evolution of wind speed in time between the levels of 25% and 50% below the peak is not representative for the slope of the line in the peak. Fanning out starts at about 20% below the peak (see Figure 11.7). That is why we decided to use the storm durations at 10% and 20% below the peak for extrapolation to zero level. The following formula is used

$$D_0 = 9D_{20\%} - 8D_{10\%} \tag{11.1}$$

The mean storm durations at 10% and 20% below the peak are 5.1 and 10.2 hours respectively. Using equation (11.1) a mean storm duration at zero level is found of 51 hours. The trapezium shape with a basic duration of 51 hours clearly produces a better fit at the peak of the mean wind speed shape than a trapezium shape with a basic duration of 71 hours, see Figure 11.5 and Figure 11.6.

The trapezium shape with a basic duration of 51 hours results in a slight overestimation of the mean duration near the peak. Figure 11.8 shows that a trapezium shape with a basic duration of 42 hours produces a better fit to this top part of the peak. However, a basic duration of 42 hours already results in a considerable underestimation of the duration at 30% below the peak. Wind speeds are still relevant at 30% below the peak. We therefore consider an underestimation of this kind of duration at 30% below the peak to be undesirable. When the complete peak down to 30% below the peak is considered, the trapezium shape with a basic duration of 51 hours produces a better fit than the trapezium shape with a basic duration of 42 hours.

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3. *The downward slope for really low wind speeds is an edge effect caused by the one-day time window used in the analysis.*

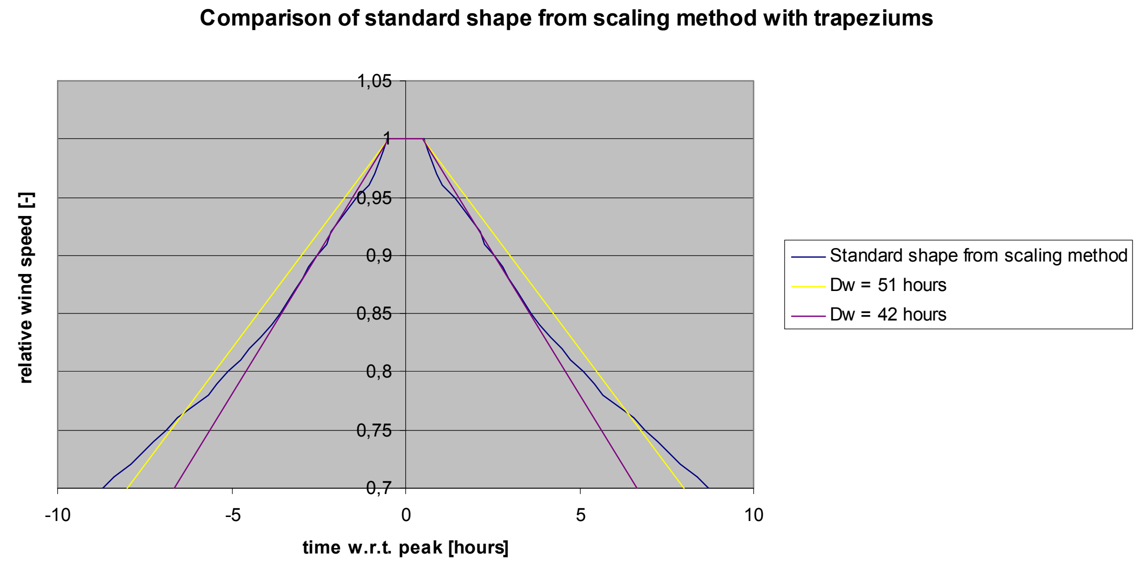

Figure 11.8 *Standard shape from the scaling method for storm duration with two different trapezium forms where D_{peak} = 1 hour and D_w = 42 and 51 hours.*

11.3.2.3 *Results for a peak duration of 2 hours*

Figure 11.9 and Figure 11.10 show that the Hydra-VIJ version with a peak duration of 2 hours and a basic duration of 48 hours also produces a reasonable fit at the peak of the mean wind speed shape for Hoek van Holland. The peak duration of 2 hours does result in a slightly higher overestimation of the duration in the top part of the peak. However, for the sake of consistency between Hydra-B and Hydra-VIJ it may be decided to accept this somewhat higher overestimation and to adopt the Hydra-VIJ version in Hydra-B.

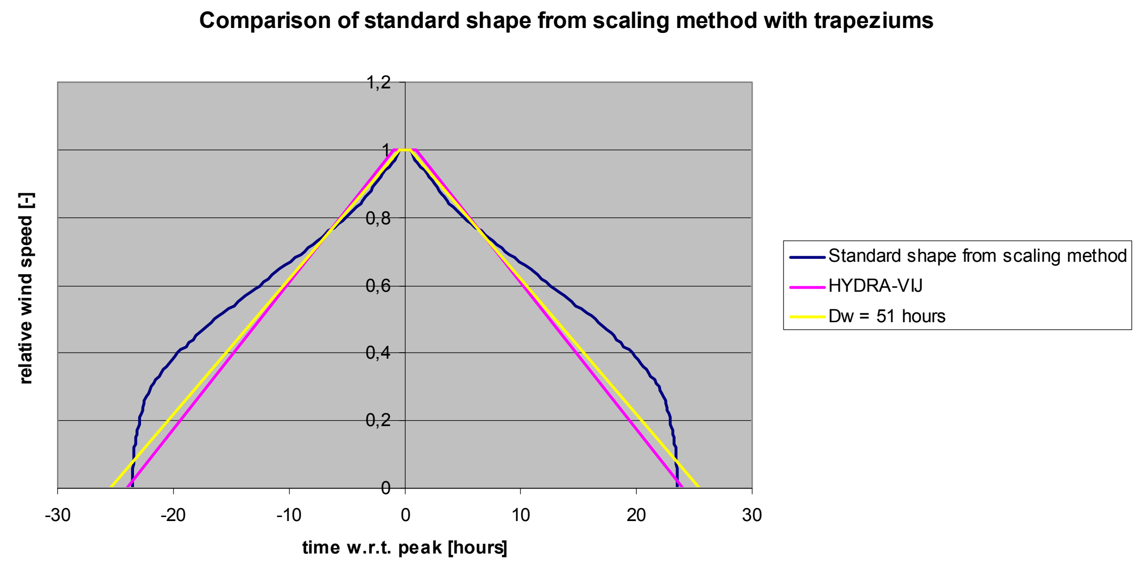

Figure 11.9 *Standard shape from the scaling method for storm duration with two different trapezium shapes where D_{peak} = 1 hour, D_w = 51 hours and D_{peak} = 2 hours, D_w = 48 hours (Hydra-VIJ version).*

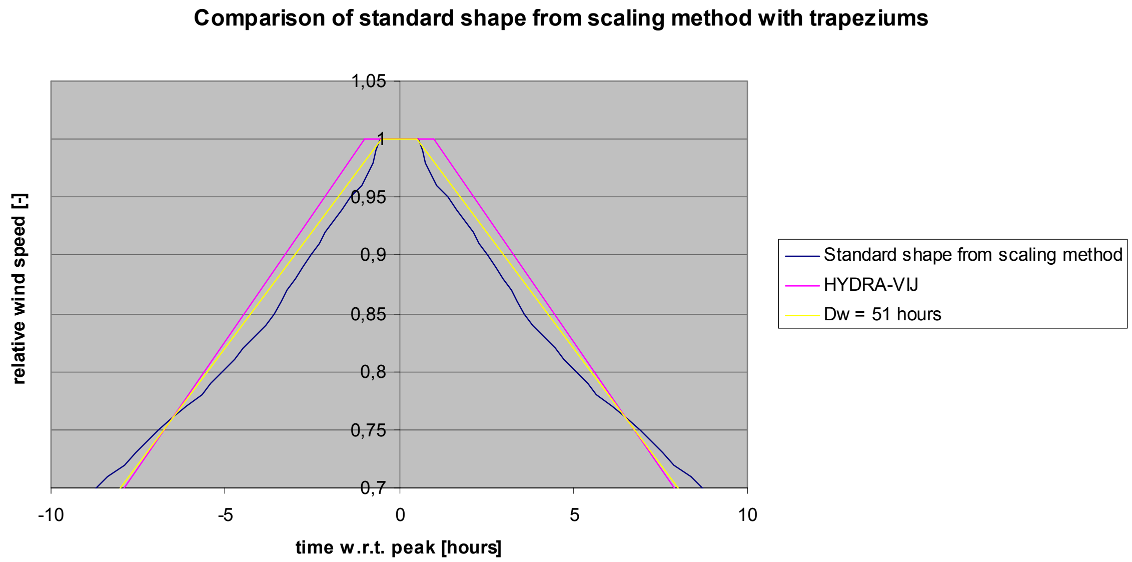

Figure 11.10 *Standard shape from the scaling method for storm duration with two different trapezium shapes where D_{peak} = 1 hour, D_w = 51 hours and D_{peak} = 2 hours, D_w = 48 hours (Hydra-VIJ version).*

11.4 Probability distribution for storm duration

For the storm *surge* duration, probability distributions have been fitted to series of surge durations associated with selected storms, see Chapter 7. That was possible because, for storm *surge* duration with the extrapolation method, a surge duration at zero level was derived for each individual storm. These series were subsequently used for the analysis of the probability distributions.

The extrapolation method was considered unsuitable for storm duration. So only the scaling method was used to derive the storm duration. However, the scaling method calculates only a mean surge duration at zero level. So, with this method, no probability distribution is derived for the zero level. Figure 11.11 and Figure 11.12 do show the histogram of the exceedance durations for the levels 80% and 90% of the peak value, as determined on the basis of the 53 storms. It emerges from these figures that the distribution of exceedance durations is “skewed”. This means that the probability of “major” exceedance of the mean is higher than the probability of “major” non-exceedance. Of course, this is largely a consequence of the fact that the exceedance duration is limited from below.

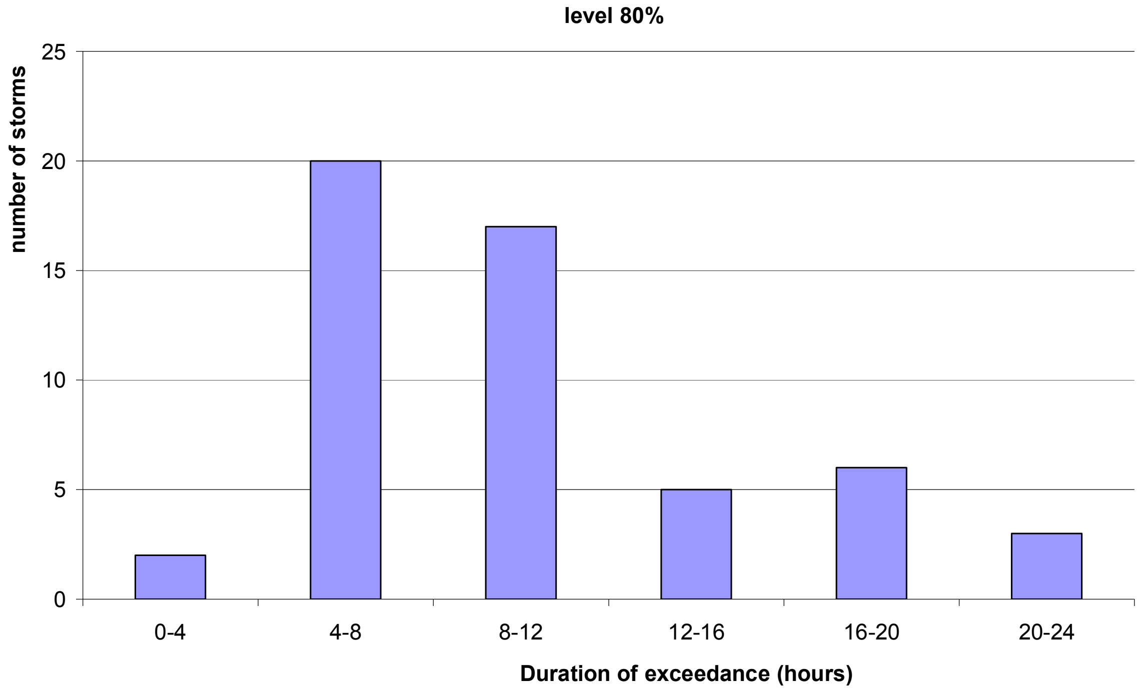

Figure 11.11 *Histogram showing exceedance durations at the level of 80% of the maximum surge.*

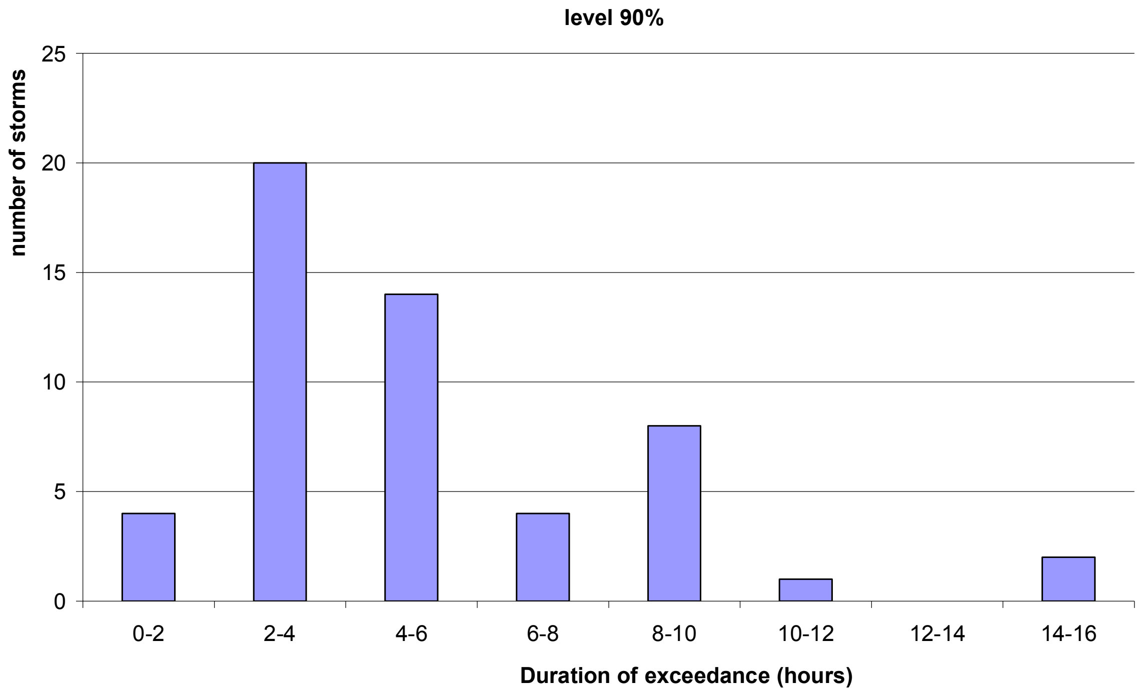

Figure 11.12 *Histogram showing exceedance durations at the level of 90% of the maximum surge.*

11.5 Correlation between peak wind speed and storm duration

As with storm *surge* duration – see Chapter 8 – the correlation between storm duration and peak wind speed was also investigated. This can easily be checked by calculating the average storm duration at a fixed percentage below the peak for various threshold values (i.e. the threshold for selecting storm events). The duration at 25% below the peak has been derived for a number of threshold values, see Figure 11.13.

The column on the far right in Figure 11.13 is based on only 10 storms. This makes it very unreliable. Figure 11.13 does not show a clear trend, certainly not when the column on the far right with a threshold value of 22 m/s is excluded. If there is a trend, it is a slightly negative one. In the event of a negative trend, extreme storms will have a shorter duration than storms observed so far. This would suggest that the assumption of the independence of peak wind speed and storm duration is somewhat conservative. In short, the results are no reason to reject the assumption of independence. Figure 11.14 shows the standard deviation of the storm duration at 25% below the peak.

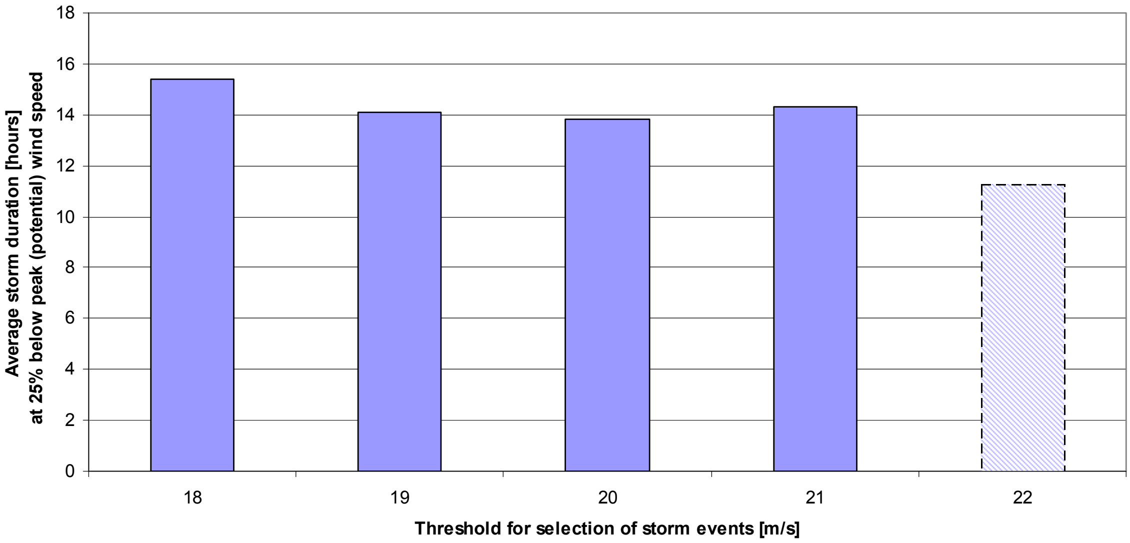

Figure 11.13 *Mean storm duration at 25% below the peak for storms selected with different threshold values. Note: the mean storm duration at 25% below the peak for a threshold value of 22 m/s (column on the far right) is based on only 10 storms, which makes it very unreliable.*

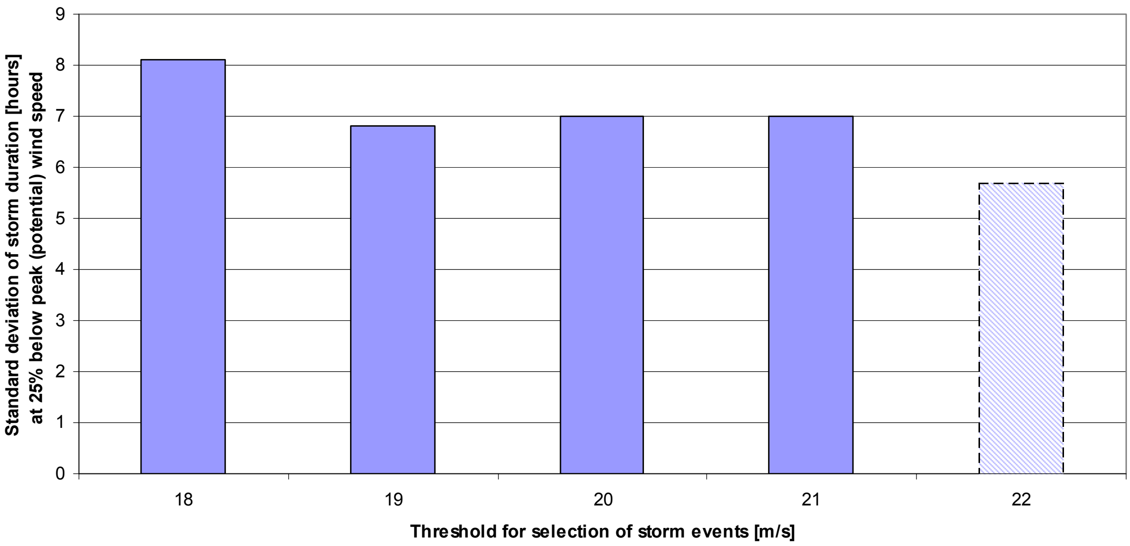

Figure 11.14 *Standard deviation of the storm duration at 25% below the peak for storms selected with different threshold values.*
Note: the mean storm duration at 25% below the peak for a threshold value of 22 m/s (column on the far right) is based on only 10 storms, which makes it very unreliable.

11.6 Conclusions

The extrapolation method is unsuitable for determining the storm duration because the method uses the exceedance duration of relatively low, irrelevant wind speeds. The scaling method does provide a suitable method for determining storm duration. However, with this method, it is inconvenient to determine duration at the 10 m/s level, which is the level that is used in the current schematisation in Hydra-B. That is why the current Hydra-B schematisation was not used in this study. Hydra-VIJ uses a schematisation with a storm duration at zero level (Figure 11.4), which is compatible with the scaling method. Therefore, for this study, it was decided to adopt a schematisation consistent with Hydra-VIJ, but not necessarily identical to the Hydra-VIJ schematisation.

A trapezium shape with a peak duration of 1 hour and a basic duration of 51 hours produces a good fit for the top 30% of the mean wind speed shape. If a schematisation is preferred for Hydra-B that is identical to the one for Hydra-VIJ, it can be concluded that the Hydra-VIJ schematisation (which is based on analyses from the Schiphol monitoring station), with a peak duration of 2 hours and a basic duration of 48 hours, also produces an acceptable fit for the top 30% of the mean wind speed shape. So the results for Hoek van Holland station are in line with those of Schiphol station. Compatible results have also been found for De Kooy station near Den Helder (unpublished Deltares memorandum).

Based on the analysis it is proposed to maintain the assumption of independence of peak wind speed and storm duration.

12 Conclusions and recommendations

12.1 Conclusions

The main conclusions from the study are as follows.

- For storm surge duration, a mean value was found of 46 hours above a threshold of 0 m and 30 hours above a threshold of 0.5 m. The results of this study better support the use of a threshold of 0.5 m as the basis for the schematised storm surge hydrograph for future computations with Hydra-B.
- For storm duration, a mean value was found of 51 hours above 0 m/s. The basic level of 10 m/s was abandoned.
- For storm duration, a comparison was made with an alternative schematisation, which is used in the Hydra-VIJ model for the IJssel and Vecht delta. This is a trapezium shape with a total duration of 48 hours. This shape also turned out to be a highly acceptable representation of the mean evolution of wind speed in time.
- For storm surge duration, the above value of 46 hours is a considerable increase compared to the current value of 29 hours. This is in line with earlier studies [13] suggesting that 29 hours is probably an underestimation.
- For storm duration, the current value of 29 hours refers to the length of time the wind speed is higher than a threshold value of 10 m/s with leading and trailing edges ending at 0 m/s. This corresponds to a period of 53 hours for a wind speed higher than 0 m/s. Consequently, the proposed new values of 48 or 51 hours are not major changes compared to the current schematisation.
- The current approach in Hydra-B, with a fixed surge duration, assumes that the surge duration is independent of the maximum surge. In the present study, no indications have been found that maximum surge level and surge duration are interdependent. This means the current assumption is acceptable.

12.2 Recommendations

The main recommendations from this study are the following:

Directly from this research

- We recommend adopting a mean storm surge duration of 30 hours above 0.5 m
- We recommend adopting a mean storm duration of 51 hours above 0 m/s. However, for consistency with Hydra-VIJ, adopting the schematisation from Hydra-VIJ in Hydra-B, together with the associated total storm duration of 48 hours, merits consideration.
- We also recommend making Hydra-B suitable in the future for more complex storm graphs, for instance with multiple peaks. For some applications, such as studies into storage of excess water, multiple peaks may be a highly relevant phenomenon.

Related to this research

- We recommend an analysis of the time difference between the maximum storm surge residual and the astronomical tide peak. Hydra-B currently assumes a time difference of 4.5 hours for all simulated storm events. A more realistic representation of this time difference seems appropriate and may significantly improve the estimates of design water levels. The proposed research should provide the necessary information for this adapted approach.

- We also advise improvements in the matching between Hydra-B and the strength models from the VTV. For instance, at present, the load duration is hardly incorporated, if at all, in the various models that describe the strength/resistance of flood defences.

13 Literature

[1] Beijk V. en C.P.M. Geerse, Opschaling van afvoergolven en stormen, RIZA, Lelystad, 2003

[2] Dillingh, D, L. de Haan, R. Helmers, G.P.Können en J. van Malde, De basispeilen langs de Nederlandse kust, statistisch onderzoek, Rijkswaterstaat, Den Haag, 1993

[3] Geerse, C.P.M., Probabilistisch model hydraulische randvoorwaarden Benedenrivierengebied, RIZA, Lelystad, 2003

[4] Geerse, C.P.M., Hydraulische Randvoorwaarden 2006 Vecht- en IJsseldelta, RIZA, Lelystad, 2006

[5] Godin, G., 1972, The Analysis of Tides. University of Toronto Press, Toronto, 264pp

[6] Jacobse, S., Analyse stormtermen, Deel 1: achtergronden, verschillen en synthese termen stormseizoen, stormduur en opzetduur, Royal Haskoning en Rijkswaterstaat, 2007

[7] RWS RIZA, 2007: Achtergrondrapport HR 2006 voor de Benedenrivieren, Thermometerrandvoorwaarden 2006, RWS RIZA rapport 2007.023.

[8] Ronde de, J., Wisselwerking tussen opzet en verticaal getij, Rijkswaterstaat, nota GWIO 85.003, 1985

[9] Tijssen A. en F. Diermanse, Stormopzet Hoek van Holland, Annex: gedetailleerde analyses en gevoeligheidsanalyse, Deltares, 2009

[10] Valk de, C.F. en H.J. Steetzel, Modelling statistics of storm duration to assess the reliability of dunes as flood protection – preliminary investigation, Argoss, Alkyon en Rijkswaterstaat/RIKZ, 1997

[11] Valk de, C.F., Bepaling van vorm en duur van opzet in afhankelijkheid van de hoogte, BMT ARGOSS memo ME_A09135b, Augustus 2009

[12] Waterdienst 2007b: Analyse watersysteem Rijn-Maasmonding; gevoeligheidsanalyse, WD rapport 2007.005, november 2007 (concept).

[13] Weerden van, J.J., J.P.F.M. Janssen en J.K. Vrijling, Effekt van variatie opzetduren op de hoogwaterstanden in het noordelijk deltabekken, DBW/RIZA, nota 87.054, 1987