CONTROLLING THE OOSTERSCHELDE STORM-SURGE BARRIER—A POLICY ANALYSIS OF ALTERNATIVE STRATEGIES
VOL. III, PREDICTING NORTH SEA WATER LEVELS

PREPARED FOR THE NETHERLANDS RIJKSWATERSTAAT

LOUIS CATLETT, GAINEFORD HALL, JR.

R-2444/3-NETH
SEPTEMBER 1979

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This report was prepared with the support of The Netherlands Rijkswaterstaat under Contract No. DED-1770.

Library of Congress Cataloging in Publication Data

Main entry under title:

Controlling the Oosterschelde storm-surge barrier.

([Report] - Rand Corporation ; R-2444/1-4-METH)


Rijkswaterstaat. III. Title. IV. Series: Rand Corporation. Rand report ; R-2444/1-4-METH.

AS36.R3 R-2444/1-4 [TC558.N42067] 081s

ISBN 0-8330-0266-6 (v. 3) [627'.42] 79-26169

The Rand Publications Series: The Report is the principal publication documenting and transmitting Rand's major research findings and final research results. The Rand Note reports other outputs of sponsored research for general distribution. Publications of The Rand Corporation do not necessarily reflect the opinions or policies of the sponsors of Rand research.

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PREFACE

In February 1953, a storm of unprecedented severity from the North Sea flooded much of the Delta region of the Netherlands, killing nearly 2000 people and inundating 130,000 hectares. As a result of this disaster, the Dutch government embarked on a massive construction program called the Delta Plan to enhance protection from floods caused by the North Sea in the Netherlands and, especially, in the estuaries of the Delta region, southwest of Rotterdam. By 1974, the new dams, dikes, and other works were complete, or nearly so, in all the Delta estuaries except the largest—the Oosterschelde. There, building had barely begun when it was interrupted by controversy.

The original plan had been to construct an impermeable dam across the mouth of the Oosterschelde, thereby closing off the estuary from the sea. This, however, threatened the Oosterschelde's rich and rare ecology and its oyster and mussel industries. In response to growing opposition, the Dutch Cabinet directed the Rijkswaterstaat, the government agency responsible for water control and public works, to study an alternative approach. But there were several possible approaches, each with many variations.

It soon became clear that the process of comparing and choosing among the Oosterschelde alternatives would be difficult, for their potential consequences were many, varied, and hard to assess. To aid the decisionmaking process, the Policy Analysis of the Oosterschelde (POLANO I) Project was established, in April 1975, as a joint research project between Rand (a nonprofit corporation)¹ and the Rijkswaterstaat.²

In April 1976 Rand presented a briefing to the Rijkswaterstaat describing the methodological framework that had been developed and summarizing the results of the POLANO analysis. The Rijkswaterstaat combined this work with several special studies of its own and, in May 1976, submitted its report to the Cabinet, which recommended the storm-surge barrier plan to Parliament. The barrier was to be a flow-through dam containing many large gates that would be closed in a severe storm. In normal weather, the gates would be open to allow a reduced tide to pass into the basin, the size of the tide being governed by the aperture in the barrier. The plan was adopted in June 1976, but no aperture size was specified for the barrier. After additional analysis by the Rijkswaterstaat to help determine the aperture size, Parliament approved an aperture of 14,000 square meters in September 1977.

The POLANO II analysis, conducted between April 1976 and April 1977, had two main thrusts. One was aimed at documenting the POLANO I study,³ the other at identifying necessary new research for the storm-surge barrier project. One of the new research areas was to specify and explore alternative barrier control

¹ Rand had had extensive experience with similar kinds of analysis and had been working with the Rijkswaterstaat for several years on other problems.
² The Rand contract was officially with the Delta Service of the Rijkswaterstaat, which had direct responsibility for the protection of the Oosterschelde.
strategies, their implications for the design of the barrier, and their other consequences or "impacts." This work led to the establishment of the Barrier Control (BARCON) Project in April 1977. The Rijkswaterstaat contracted with Rand for the study, and also set up a Dutch counterpart research team. The study has been a joint effort.

The primary purpose of the BARCON study was to perform research and analysis to assist the Rijkswaterstaat in a policy analysis of alternative control strategies for operating the storm-surge barrier. For each of the alternatives, the project analyzed several impacts, including the safety of the dikes along the Oosterschelde; the effects on the ecology and the shellfish and fishing industries of the region; the impacts on water management and shipping in the basin; and the implications for the design of the barrier and its control system.

The methodology and results of the BARCON project are described in a series of Rand reports entitled Controlling the Oosterschelde Storm-Surge Barrier—A Policy Analysis of Alternative Strategies. In addition to the present volume, the following volumes in the series have been published:


Volume I describes the approach and summarizes the results of the complete analysis. It presents and compares, in a common framework, the several impacts of three promising control strategies.

Volume II describes the sensitivity analysis that was conducted. This analysis has two purposes: to show why we selected two specific strategy representations from two of the three promising barrier control strategy categories for further evaluation (presented in Vol. I), and to explore the effects on performance of varying specific elements of the control strategies.

Volume IV describes the simulation model of the Oosterschelde basin and the storm-surge barrier used to estimate the variation with time of different water levels inside the basin, given specified sets of storms outside the barrier. It discusses the capabilities of the model (called SIMPLIC), the storm sets and tidal shapes used, and the model's inputs and outputs.

The present report, Vol. III in the BARCON series, describes and evaluates several models for predicting North Sea water levels outside the barrier. The models include prediction based on observed local water levels (correlation over time), on observed remote water levels (correlation over space), on observed weather conditions (including short-term forecasts), and on 48-hour weather forecasts. This technical report is intended to provide the Delta Service with a basis for further study of hydraulic conditions in the North Sea as relates to the control of the storm-surge barrier. It should also be of interest to others as an introduction to the subject.

Three comments about this series of reports are appropriate. First, although formally published by Rand, the series is a joint Rand/Rijkswaterstaat research
effort; whereas only one of the reports lists Dutch coauthors, all have Dutch contributors, as can be seen from the acknowledgments pages.

Second, the methodology and results described in these reports are expanded and refined versions of those presented by RAND in a February 1979 all-day briefing to the Delta Service.

Third, Vols. II, III, and IV are not intended to stand alone, and should be read in conjunction with the Summary Report (Vol. I), which contains most of the contextual and evaluative material.
SUMMARY

In this report we explore a number of statistical techniques for predicting storm surges that might prove useful in operating the SSB (storm-surge barrier) across the Oosterschelde. Our approach was to develop an understanding of the ongoing research efforts elsewhere and to determine whether some of the previous results could be better adapted to the unique problems associated with the operation of the barrier.

There are three primary components of variation of water level in the North Sea: (1) the astronomic tide, with an amplitude of 1 to 2 m; (2) external surges, with an amplitude of up to ½ m; and (3) set-up (a piling up of water) caused by local weather conditions in the North Sea, with set-ups or surges of 1 to 2 m commonly occurring under storm conditions and 3 or more meters occurring rarely.

The winter storms that give rise to appreciable set-up in the North Sea have a number of similar characteristics. They begin in the North Atlantic south of Iceland as a depression, which moves across the British Isles and the North Sea, and then onto the Continent, where it dissipates. As the storm crosses the North Sea, winds blow from the south, then west, then north.

Set-up, in the direction of the wind, occurs in shallow bodies of water, such as the Oosterschelde and the North Sea. In the Netherlands, a mathematical simulation model of this phenomenon in the North Sea is used for surge prediction.

The SSB introduces the need for several areas of emphasis in prediction: (1) very short predictions, an hour or so in advance, for operational control of the barrier with some potential control strategies; (2) predictions several hours (6 to 12) in advance for operational control with other strategies; and (3) long-term predictions, several days in advance, for conducting maintenance, providing alert, and so on. The body of this report explores the first two of these prediction areas, and App. B briefly examines the third area.

SURGE PREDICTION BY CORRELATION OF WATER LEVELS

We explored the properties of surges, tides, and their composite (i.e., total water level) as they occur in the North Sea. Surge is highly correlated over time (of a comparable amplitude for several hours at a given location) and space (of a comparable amplitude over wide regions in the North Sea at a given time). One would therefore expect that a fairly accurate estimate of existing surge could be made at a specified location, and a short-term prediction of an hour or so could be projected with confidence. But such accuracy is not generally possible. Uncertainties in tide shape and arrival time dominate and preclude simple extrapolation, except at specific instances in time when the effects of uncertainties are minimal. This is at the moments of observed high and low tides. Maximum tidal rise rates typically approach 2 m per hour; surge rise rates are an order of magnitude less. Therefore, the tidal rise rate completely dominates an accurate observation of surge at the time when it is of most interest, that is, during a rising tide. An early arriving tide
can be interpreted as a large, steeply rising surge. A late arriving tide can give the appearance of a receding surge, when, in fact, it is increasing.

The next possibility is the prediction and filtering of tidal frequency components (e.g., arrival time) by correlation of observations over time and space. Our attempts to filter these components met with only minimal success. The differences between observed tidal frequency components and astronomic predictions of the tides are surprisingly uncorrelated over time and among even nearby locations. For example, differences at Vlissingen have little relationship to differences at Hoek van Holland. Thus, we concluded that a good, although not perfect, estimate of surge can only be obtained at the moment of high and low water.

Appreciable correlation of surge amplitude exists (typically about 0.6 correlation coefficient) over the six or so hours between high and low tides. Thus, prediction of surge can be made on observed water levels, but it is limited to discrete points about 6 hours apart. We explored the possibility of prediction based on such successive discrete observations (called autoregressive prediction). Using the high and low tides at Vlissingen from 1970 to 1977, we modeled the surge as a Markov process of order 6. The model enables us to make a prediction a half tide cycle ahead that reduces the root mean square error (RMSE)\(^1\) in peak water level (from the predicted astronomic tide) from about 23 to 15 cm. This one-third reduction in the prediction error is fairly consistent throughout the winter and summer months. In terms of percentages, slightly better predictions can be made under storm conditions. For the 74 high tides that precipitated some Storm Flood Warning Service (SVSD)\(^2\) activity between 1971 and 1977, the mean set-up at Vlissingen was 74 cm, with a RMSE of 84 cm from the predicted astronomic high tide. The autoregressive prediction underestimates the mean by 11 cm and has a standard deviation of 37 cm, giving a net RMSE in prediction of 39 cm. (We explore the possibility of using such a prediction scheme alone for control of the barrier in the Summary Report and find that it is inadequate.)

HISTORICAL PREDICTIONS OF STORM SURGES

We analyzed data from the SVSD on predictions for 224 high tides during storm conditions for Vlissingen and Hoek van Holland from 1954 to mid-1977. One hundred and fifty of these predictions were made before September 1971 with the previous prediction model. A noticeable improvement in predictions occurred with the current Royal Dutch Meteorological Institute (KNMI)\(^3\) operational model, which was used to predict 74 high tides in 40 storms between late 1971 and mid-1977. As mentioned above, these 74 tides had a mean set-up of 74 cm. The prediction error had a mean value of 18 cm (overprediction) and a RMSE of 23 cm. A regression corrects for the overprediction and reduces the standard deviation of the error of prediction to 22 cm. (We also explore the possibility of using this kind of prediction for control of the barrier in the Summary Report.)

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\(^1\) The square root of the mean value of the square of the deviations about zero.

\(^2\) The RWS group charged with alerting organizations responsible for the dikes.

\(^3\) The KNMI provides surge predictions to the SVSD.
COMBINED PREDICTIONS

We tried to improve the accuracy of the prediction of the first\(^4\) high tide in a storm by combining the KNMI prediction with an autoregressive prediction. For the first high tides (at Vlissingen) in the 40 storms between 1971 and 1977, the mean set-up is 80 cm, and the standard deviation is 32 cm. Forecast accuracy with the SVSD prediction alone is about 21-cm standard deviation (after regression correction). Combining this prediction with the six previous values of observed set-up in a regression gives a slight improvement in the accuracy of prediction, about 18-cm standard deviation. Possibly, the set-down that sometimes precedes a storm surge is the principal additional information input.

We briefly analyzed predictions of set-ups at each high and low tide over a two-month period (November and December 1977) that were made at the KNMI with their extended computer model. The set-up during this rather stormy two months averages 16 cm, with a standard deviation of 47 cm. The KNMI predictions (corrected with a regression) give an error with a standard deviation of 14 cm. Including a regression on the six previously observed set-ups reduces the standard deviation to 11 cm.

POSSIBILITIES FOR IMPROVED PREDICTIONS

The KNMI extended model performs well in day-to-day conditions but does not perform any better than, if even as well as, their operational model under storm conditions. The combination of predictions with autoregression on set-up at previous high and low tides appears to give some marginal improvement in predicting set-up—both in day-to-day situations and at the onset of storms.

However, although the issue warrants further study and exploration, it does not appear that major improvements in storm-surge prediction accuracy will be forthcoming in the next decade. This implies that feasible operational strategies for the storm-surge barrier will have to be within the constraint bounds of water level prediction capabilities that exist today. In our analysis of alternative strategies in the Summary Report, we were fully aware of these bounds.

Appendix B briefly explores long-term (several days) prediction possibilities. It appears that a storm condition, or its absence, can be predicted with some confidence a few days in advance. The winter storms that create appreciable surges have characteristic patterns that persist over several days, but the extent of surge that might (or might not) occur with a storm is less predictable. The surge is too dependent on storm details that may or may not materialize to be forecast reliably. Nevertheless, forecasts several days in advance can provide useful information for maintenance and operation of the barrier.

\(^4\) First in the sense that it is the first recorded level in the storm.
ACKNOWLEDGMENTS

A policy analysis such as BARCON owes much to the advice and assistance of innumerable individuals because of the diversity of topics considered, the dependence on other research and studies for essential information, and the differences in language and location. It is impossible to acknowledge everyone who contributed in some way. We mention several names here—and the other volumes of the series mention more—but there are undoubtedly others who deserve our gratitude.

Acknowledging assistance from these many individuals and institutions does not imply that they are responsible for, or even necessarily agree with, our findings. If there are shortcomings in this report, the responsibility rests solely with the authors.

We are indebted to several high officials for the constructive questions and assistance they provided in several meetings and briefings. They include H. Engel, Head of the Delta Service; O. Boom, Chief Engineer-Director of the Directorate for Zeeland; J. F. Agema, head of the Delta Service Hydraulics Division; M. J. Loschacoff, head of the Delta Service Hydraulic Structures Division; and A. C. de Gaay, head of the Delta Service Environment and Regional Planning Division. Two ad hoc Dutch project groups provided invaluable assistance and served as major contacts. Members of the BARCON Project Group included:

J. Voogt, Chairman, Delta Service
J. P. Al, Delta Service
H. D. Rakhorst, Delta Service (replaced by G. van Houweninge)
F. J. Remery, Directorate of Bridges
A. Roos, Delta Service
H. L. F. Saeijs, Delta Service
H. N. J. Smits, Delta Service (replaced by K. J. Vriesman)
K. van der Spek, Delta Service
J. A. van Hiele, Directorate for Zeeland (replaced by J. Rus)

Members of the Project Group Oosterschelde Dikes (POD) included:

A. Roos, Chairman, Delta Service
J. W. Boehmer, Delta Service
H. Burger, Netherlands Dike Research Centre (replaced by A. Penning)
P. G. J. Davis, Delta Service
J. W. Honders, Delft Soil Mechanics Laboratory
P. van der Veer, Data Processing Division of RWS
P. C. van Goor, Directorate for Zeeland
M. H. Wilderom, Directorate for Water Management and Hydraulic Research (replaced by D. van Dam)

1 These organizational affiliations are those at the time of the study. Several individuals have since moved to other parts of the RWS or other organizations.
Three officials of the Delta Service played crucial roles both at the outset of the study, by helping to define its aims and structure the overall research, and during the study, by offering critical comments on our interim findings. They are T. Goe- mans, head of the Systems Management Division; J. Voogt of the Hydraulics Division and Chairman of the BARCON Project Group; and H. N. J. Smits of the Systems Management Division, who was also responsible for administrative matters.

A. Roos of the Delta Service Hydraulics Division deserves special thanks for several contributions. He was the principal liaison between Rand and the Delta Service for almost the entire duration of the project. He played an indispensable role in formulating and analyzing many of the barrier control strategies, in coordinating data-gathering research in the Netherlands, and in providing liaison with other studies and organizations. In addition, as a coauthor of Vol. I of the BARCON series, the Summary Report, he was responsible for the section on dike safety.

Rand was assisted in each major area of the BARCON project by a number of Dutch colleagues. F. Spaargaren and G. van Houweninge of the Delta Service Hydraulics Division supplied extensive background information for the overall design of the barrier and to establish the relation between the control strategies and the boundary conditions for design. F. J. Remery and D. P. van Wijk of the Directorate of Bridges provided important documentation for the control system of the barrier and related reliability problems. H. L. F. Saeijs, J. P. Al, and J. Visser of the Delta Service Environmental Division supplied many data and constructive comments on ecological matters, including salt marshes, intertidal areas, detritus, and the ecological balance. In addition, J. P. Al, as a coauthor of Vol. I, helped prepare the section on ecological impacts.

We thank W. J. Dek and T. Walhout of the Delta Service Water Management Division for compiling the basic data necessary to estimate water management and shipping impacts.

Three people were instrumental in providing us with information for the prediction of storm surges. In discussions with H. Timmerman of the Royal Dutch Meteorological Institute (KNMI), he introduced us to his North Sea set-up model as well as other weather models, and gave us valuable advice on the accuracy of predicting surges. A. van Urk of the Storm Flood Warning Service (SVSD) provided crucial data on observed and predicted water levels and familiarized us with the role of the SVSD. A. W. Donker of KNMI assisted us with information on the prediction of water levels in the Oosterschelde and the possibilities for long-term forecasting of storms and their associated surges.

We are grateful to P. H. van der Weele and P. C. van Goor of the Oosterschelde Dike Reinforcement Division of the RWS Directorate for Zeeland for their information on dike safety—the quality of the existing dikes and the current dike improvement program.

D. Kooman of the Delta Service Hydraulics Division supplied helpful information on the characteristics of storm surges, hydraulic conditions during closing, and possible barrier closing criteria.

We also acknowledge the assistance of many Rand colleagues. J. J. Leendertse, who was born and educated in the Netherlands, gave us valuable counsel on hydrological problems, the history of the Oosterschelde debate, and the organization and operation of the Netherlands government. B. F. Goeller, head of the previous
POLANO project, was the administrative director of the Rand team. We are grateful to him for providing broad general direction to the project and constructive comments during the preparation of interim and final study briefings, subsequently presented in the Netherlands. L. E. Catlett served as leader of the Rand BARCON team.

R. L. Petruschell originally suggested the need for the BARCON study, serving as its first project leader and developing its initial structure. In this early phase, D. L. Jaquette, T. F. Kirkwood, L. H. Wegner, and L. W. Miller (a Rand consultant) made important contributions to the study. In particular, A. F. Abrahamse performed preliminary analyses of several topics reported in this volume and was valuable to us as a counsel throughout the study. We thank D. J. Leinweber for his research on the reliability of the barrier control system and his briefings to the RWS. J. H. Bigelow, drawing on his extensive background in the POLANO study, counseled us on ecological subjects, in particular, detritus import. R. R. Rapp was the author of App. B in this volume.

We are grateful to J. E. Rolph and E. D. Harris, Rand reviewers, for their constructive comments that led to many improvements in substance and presentation of this volume.

E. T. Gernert edited this report for style, and served as managing editor for the BARCON series. Among the many artists who were involved in the project, we are especially grateful to J. H. Sloan.

M. P. Dobson provided expert secretarial services under difficult circumstances.
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GLOSSARY

Aperture (A): The total geometric area through which water may flow through the barrier. The aperture may vary from near zero when all gates are closed to about 18,000 sq m when all gates are fully open.

Attenuator strategy: A strategy that allows the barrier to be operated in a partially closed state to achieve desired effects, such as letting the basin gradually fill during a storm.

BARCON: A research effort between Rand and the Rijkswaterstaat. The study purpose is to perform research related to the policy analysis of alternative strategies for the Oosterschelde storm-surge barrier.

Barrier control strategy: A strategy that consists of (1) actions required to govern the time and rate of storm-surge barrier gate closing and opening; (2) the rules behind the decisions for these actions; and (3) the gathering and processing of information needed for decisionmaking.

Design storm set: Twelve variations of each of two extreme storm surges that are so severe that they could be expected to occur only once in several thousand years.

E-level: An emergency threshold trigger level based on observed outside water levels (known as alarmpeil in Dutch).

E-level strategy: A strategy that permits closing the barrier fully when the observed OWL exceeds E-level.

Exceedance frequency: For a given coastal location, the number of times per year that the water level exceeds a certain value.

Extended dike watch level: A water level above which the SVSD alerts provincial water boards, which then fully staff emergency control rooms and man local control posts. The extended dike watch level is exceeded on the average once in five to ten years. This is NAP + 3.10 m at Burghsluis (just inside the storm-surge barrier location) and higher farther inside the Oosterschelde.

Gate: The movable part of the storm-surge barrier used to adjust the barrier aperture. The current storm-surge barrier design calls for 63 gates of 40 m in width and ranging in height from 5.5 to 11.5 m.

Grenspeil: The once-in-two-year water level at a given location in the Netherlands. At Burghsluis, near the storm-surge barrier location, it is NAP + 2.75 m.

Head difference: The difference between outside and inside water levels at the barrier.

Historical storm set: A series of 44 historically recorded storms (between 1921 and 1970) that exceeded grenspeil somewhere along the Netherlands coast.

HSW: High slack water. HSW occurs at that moment when there is no flow through the barrier, as the water flow reverses from into the basin to out of the basin. It corresponds to a maximum mean basin IW.

Hydraulic jump: A phenomenon associated with certain flow conditions through the barrier in which the IW at the barrier drops below its expected level, thus increasing the head difference across the barrier or other parts of the barrier foundation.
IMPLIC: A general computer simulation model of hydraulic flow over a two-dimensional network adapted to simulate the Oosterschelde. The model was developed by the Rijkswaterstaat.

Inside translation wave: The difference between the IWL at the inside of the barrier and the mean basin IWL. (See Translation waves.)

IWL: Inside water level. This level ordinarily varies from place to place in the basin.

KNMI: The Royal Dutch Meteorological Institute.

Leakage: Water that passes under or around parts of the barrier, which is not totally impermeable.

Limited dike watch level: A water level above which the SVSD alerts provincial water boards, which then partially staff emergency control rooms and prepare for further developments. The limited dike watch level is exceeded on the average once a year. This is NAP + 2.60 m at Burghsluis (just inside the storm-surge barrier location) and higher farther inside the Oosterschelde.

LSW: Low slack water. LSW occurs at that moment when there is no flow through the barrier, as the water flow reverses from out of the basin to into the basin. It corresponds to a minimum mean basin IWL.

LSW strategy: The strategy to fully close the barrier at LSW on the basis of a predicted exceedance of the trigger OWL at the next high tide.

Mean basin IWL: A measure of the total water in the Oosterschelde basin. This is the water level that would exist throughout the basin if the water were static or stagnant; it is approximately equal to the level at Wemeldinge, near the center of the basin.

MOS: Model Output Statistics.

NAP (Normaal Amsterdams Peil): Essentially the mean or reference sea level in the Netherlands.

On-off strategies: Strategies that enable the barrier to be normally in either a fully open or fully closed state, with only a short period (an hour or so) of gate movement in between these states.

Outside translation wave: The difference between the OWL at the barrier and at the boundary to the Oosterschelde in the North Sea. (See Translation waves.)

OWL: Outside water level. This level can be measured either at the barrier or at the boundary in the North Sea.

P-level: A threshold trigger level based on predicted outside water level (known as sluippeil in Dutch).

POLANO (Policy Analysis of the Oosterschelde): A previous joint research effort between Rand and the Rijkswaterstaat to evaluate alternative methods of preventing flooding in areas surrounding the Oosterschelde.

Primary strategy: The strategy expected to be used predominantly in controlling the barrier. If uncertainties exist about the performance of this strategy, a backup strategy may also be employed.

PSU: Predicted set-up.

RMSE: Root mean square error.

RWS: Rijkswaterstaat.

Set-up (SU): The difference between the observed water level and the predicted astronomical tide that is caused by meteorological and other phenomena.

SIMPLIC: A simple mathematical computer simulation model of the Oosterschelde basin.
Slack water: The point at which inside and outside water levels at the barrier are equal, and there is momentarily no flow through the barrier.

Storm surge: The large set-up that occurs under storm conditions.

Storm-surge barrier (SSB): A flow-through dam containing many large movable gates at the mouth of the Oosterschelde.

SVSD: Storm Flood Warning Service.

TIWL strategy (target IWL strategy): A strategy that initiates full closure of the barrier to achieve an intermediate target IWL following a predicted exceedance of the trigger OWL at the next high tide.

Translation waves: Long waves that arise from the dynamic effects of changing water flow conditions through the channels into the Oosterschelde. (See Inside and Outside translation wave.)

Trigger level: A water level, either inside or outside the barrier, which if exceeded causes activation of some part of a barrier control strategy.

Wave overtopping: Large waves associated with high OWLs that actually break over the closed barrier with some consequent increase in IWL.

μA: Effective aperture—the actual geometric opening A multiplied by a flow contraction coefficient μ.

cm: centimeter.  kn: knot.
dm: decimeter. m: meter.
ha: hectare (= 10^4 sq m). mb: millibar.
km: kilometer.
Chapter 1
INTRODUCTION

The existence of a barrier across the mouth of the Oosterschelde basin—open with a restricted aperture in nonstormy weather and closed in stormy weather—will have a number of effects, called impacts, on the Oosterschelde environs. Such impacts include the safety of the dikes along the Oosterschelde, changes in the ecology and shellfish and fishing industries of the region, effects on water management and shipping in the basin, and loads on the barrier itself. The policy analysis of the BARCON study assesses these impacts for a number of alternative barrier control strategies, as discussed in the Summary Report.

These impacts are ultimately caused by the water level versus time profile inside the Oosterschelde basin, as it responds to water levels in the North Sea outside the barrier. In this report, we explore the physical and statistical characteristics of water levels in the southern part of the North Sea that are relevant to the operation of the storm-surge barrier. (The dynamic response of the Oosterschelde basin to North Sea water levels through the intervening barrier is modeled in the SIMPLIC computer program, described in Vol. IV.) The major emphasis is on the prediction of water levels, because prediction is the primary constraint on the feasibility of a variety of potentially desirable control strategies.

In this chapter we discuss (1) the nature and magnitude of the various disturbances that occur simultaneously in the North Sea; (2) the storm patterns that, historically, have produced large storm surges in the North Sea; and (3) the water level prediction model that is now used in the Netherlands.

1.1. WATER LEVEL VARIATIONS IN THE NORTH SEA

There are three primary components of variations in water level in the North Sea:

1. The astronomic tide.
2. External surges, caused by weather conditions outside the North Sea.
3. Set-up, caused by local weather conditions over the North Sea.

Each of these disturbances, once established, is propagated through the North Sea in a similar manner, and is generally indistinguishable from the others except perhaps in a statistical sense.

1.1.1. Astronomic Tides

Astronomic tides are generated in the large ocean masses of the world by highly predictable gravitational forces over time, created by the moon and the sun. These

1 For the reader who is unfamiliar with the Oosterschelde storm-surge barrier, a brief general description is given in App. A. In general, this report is intended as a supportive document to the Summary Report and is not intended to stand alone.
forces set up oscillations in the oceans that couple into the North Sea at the boundaries across the north and across the English Channel. The astronomic tides that appear at the boundaries have well-defined, predictable arrival times, directions, amplitudes, and shapes.

In the shallow, funnel-shaped North Sea, significant propagation velocity differences occur as a function of water depth. This gives rise to several effects on tidal propagation in the North Sea: First, the bottom profile and coastline create largely predictable, consistent distortions in the direction of tidal propagation. Second, the water level differences between high and low tide give a nonlinear distortion of the tide profile over time (generate harmonics of the fundamental tidal frequency) into characteristic shapes (again, largely predictable and consistent) for each location in the North Sea. In general, high tide tends to catch up with low tide, giving a characteristic fast rise from low to high tide and a more gradual decrease from high to low tide. Typically, at a given location in the North Sea, tides occur twice daily, or approximately every twelve hours, with comparable amplitude. Tidal amplitudes along the coasts of the southern part of the North Sea range from 1 to 2 m and have peak rise rates that approach 2 m per hour for a short time while the tide is rising.

A third effect on tidal propagation in the North Sea arises from random variations in water level that occur because of weather conditions, residual oscillations, etc. These tidal perturbations appear as (1) variations (of up to an hour or so) from the predicted arrival time of high and low tides; (2) variations (of up to 10 to 15 percent) from their predicted amplitudes; and (3) variations from the characteristic water level profile between high and low tides. Essentially, the perturbations appear as a random, slowly varying frequency and amplitude modulation on the predicted astronomic tide. These perturbations are particularly pronounced when there are severe disturbances in the North Sea and adjoining oceans, for example, when major storms are in the area.

1.1.2. Water-Level Variations (Set-Up) Caused by Weather Conditions

In contrast with water level variations at the astronomic tidal frequency, the water level variations caused by external surges (remote weather conditions) and the set-up due to local weather conditions tend to persist for many hours or even days and are geographically pervasive.

Physical Effects. The low atmospheric pressure and winds from the high pressure gradients of storm depressions create two effects on contiguous water levels. First, the atmospheric pressure profile of the storm directly affects the water level underneath. The water rises up in response to the decreased atmospheric pressure, with a 10-mb (millibar)4 pressure decrease equal to about 10 cm of water level increase. Thus, a depression at 960 mb would have a steady-state water level underneath it of about 40 cm above the ambient.5

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2 The predicted astronomic tides are published annually in a tidal almanac.
3 Thus, a narrow bandwidth filter centered at the tidal frequency should remove the astronomic tide and its perturbations from the total water level. In real time, such filtering is only partially effective, with a significant residual random component near the tidal frequency, as will be seen later in this report.
4 A millibar is 1/1000th of the standard atmospheric pressure.
5 This effect is generally direct and local, but Timmerman has demonstrated [1.1] that large depression gradients over the continental shelf to the north generate transient waves into the North Sea, and this is an important part of external surges.
Second, wind blowing over water creates a frictional force on the surface of the water proportional to the wind velocity squared. This force "sets up" the surface of the water in the direction of the wind until the surface gradient is sufficient to create a differential pressure that, when exerted over the vertical face of the water normal to the wind, creates a countreactive force equal to the frictional wind force on the surface. Thus, set-up caused by wind is directly proportional to the distance that the wind blows over the water (fetch) and the wind velocity squared, and inversely proportional to the depth of the water.

The North Sea and the Oosterschelde basin are shallow enough for this effect to be conspicuously manifest. With constant winds, the steady-state condition is established in the Oosterschelde basin in about an hour. In the North Sea, the response to wind-generated set-up is local and also remote. For example, northerly winds off Aberdeen, Scotland, create a steady-state local set-up that rises to the south. This increase in water level propagates to the south as a surge, with a velocity equal to the square root of the depth times the gravitational constant. With a nominal depth of 50 m, the propagation time to the Oosterschelde is about 9 hours—the same as for the astronomic tide or external surges created by winds and pressure gradients off the north coast of Scotland.

External Surges. External surges are generally caused by strong pressure gradients and the accompanying strong wind fields over the shallow waters and continental shelf north of Scotland. Once established, the surge propagates through the North Sea—usually down the English coast—to the south. External surges usually have amplitudes of 1/2 m or less in the southern part of the North Sea.

Set-Up Caused by Local Weather over the North Sea. As mentioned previously, local weather conditions over the North Sea create a slowly varying set-up that is geographically pervasive and predictable. In the southern part of the North Sea, the observed low-frequency set-up has a 13-cm standard deviation in the summer and 30 cm in the winter. Set-ups, or storm surges, of 1 to 2 m occur under storm conditions, and on rare occurrences reach 3 or more meters. The surge associated with a storm generally rises over several hours, with typical rise rates of 0.1 to 0.2 m/hr. One of our design storm surges, the modified 1953 storm, has a peak rise rate of about ½ m/hr. The other design storm surge, the displaced 1959 Bay of Biscay storm, has an extreme rise rate approaching 1 m/hr, which is comparable to the maximum tidal rise rate.

1.2. NORTH SEA STORMS

North Sea storms, and their resulting storm surges, are an integral part of European history. Figure 1.1 shows the occurrence, by month, of the 49 historical storms (1898-1956) discussed in the Delta Committee Report [1.3]. Figure 1.2 shows the occurrence of the 44 storms, representing 50 years of historical storms (1921-

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* Appendix C illustrates the development of set-up in the Oosterschelde basin as simulated by the IMPLIC computer program in the Netherlands.

* External surges have been analyzed by Timmerman [1.1] and Cartwright [1.2]. The creation of the surge is simulated in Timmerman's extended model, as discussed subsequently. Cartwright proposes observing the surge as it enters the North Sea at three stations.

* Extreme storms used in BARCON to help establish the maximum bounds of operating conditions.
Surge at Hellevoetsluis:

- \[ 160 < \text{surge} < 200 \text{ cm} \]
- \[ 200 \text{ cm} \leq \text{surge} \]

Fig. 1.1—Forty-nine storms, 1898-1956 (Ref. 1.2)

Fig. 1.2—Forty-four storms, 1920-1970, in which grenspel was exceeded somewhere in the Netherlands
1970), that we used in the Summary Report as boundary conditions in exploring the different control strategies. There are nine storms common to both studies.

All of these winter storms display some similar characteristics. Each begins as a depression that forms over the North Atlantic in the vicinity of, and to the south of, Iceland. The initial depression moves eastward across the British Isles, over the North Sea, and then onto the European land mass. Figure 1.3 shows the outside bounds of all of the tracks (of the depression center) of the 49 storms in Ref. 1.3. The center region contains 75 percent of the storm tracks.

The cyclonic (counterclockwise) wind patterns that develop around depressions in the Northern Hemisphere create a fairly predictable effect in the southern part

Fig. 1.3—Bounds of 49 depression tracks, 1898-1956, and track of 1953 storm
of the North Sea, as the storm track traverses the region shown in Fig. 1.3. Ahead of the depression, the wind is generally from the south. Then, as the depression moves eastward, the wind veers to the west and then to the north. These wind shifts can be very rapid when the depression path is nearby.

Also shown in Fig. 1.3 is the track of the disastrous 1953 storm, which we will next illustrate in detail. Figure 1.4 shows the location in the North Sea of the 970-mb low at 1200 GMT on January 31, 1953. The path and pressure of the depression are typical of many that occur, and the nominal set-up of 1.0 m in the Delta region is also typical. (Winds follow, slightly inward, the isobar lines. Wind speed is proportional to the gradient of pressure, or inversely proportional to the distance between the isobars.) Note that the set-up is generally piled up directly

Fig. 1.4—Atmospheric pressure and set-up in the North Sea, 1200 GMT, January 31, 1953
ahead of the local wind and that much of this set-up is attributable to the local, near-term wind of approximately 18 m/sec from the west.

The atypical part of Fig. 1.4 is the extremely high pressure gradient across eastern Scotland, caused by the high pressure area forming in the North Atlantic, as indicated. This creates very high winds over Scotland (35 m/sec at 1200 GMT)—a forewarning of the catastrophe to follow—as the depression and this high pressure gradient behind it move eastward over the North Sea. Figure 1.5 shows the situation six hours later. Local winds at the Oosterschelde have shifted to the northwest and increased to about 20 m/sec. This shift, and the delayed set-up effect of the extremely strong winds off Scotland several hours before, create a rising surge.

Fig. 1.5—Atmospheric pressure and set-up in the North Sea, 1800 GMT, January 31, 1953
Figure 1.6 shows the situation at the start of February 1. Local winds have increased to 25 m/sec, a wind pattern that pervades the North Sea and moves in a direction that focuses on the Delta region. This extreme situation persists for several hours (Fig. 1.7); then it gradually subsides as the depression moves over the European continent and gradually increases in pressure (Fig. 1.8).

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![Map of atmospheric pressure and surge](image)

**Fig. 1.6—Atmospheric pressure and set-up in the North Sea, 0000 GMT, February 1, 1953**

The 1953 design storm surge, used in the BARCON study, was created at KNMI* by moving the depression-high pair shown in Fig. 1.4 in such a way that the extreme gradient over Scotland moves to the south and faces the Delta region. This weather condition is estimated (Ref. 1.1) to give a maximum surge of almost 4.0 m, in contrast with the surge of 3+ m that actually occurred in the 1953 storm.

* The Royal Dutch Meteorological Institute.
1.3. CURRENT PREDICTION MODELS

Nations that border on the North Sea are very interested in developing a better understanding of set-up and its prediction. Efforts to model the North Sea and its response to weather patterns are under way in the Netherlands, the United Kingdom, Germany, and elsewhere. (See Refs. 1.1, 1.2, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 1.10.) Some of these efforts are based on years of extensive research. We did not intend to duplicate these efforts but rather to study them in order to determine whether some of the results could be better adapted to the almost unique problems associated with the operation of the barrier. In particular, we have drawn on the extensive
Fig. 1.8—Atmospheric pressure and set-up in the North Sea, 1200 GMT, February 1, 1953

modeling work of Timmerman at KNMI and on the statistical modeling research of Cartwright among others from the United Kingdom.

Timmerman, building on previous work by many researchers, particularly that of Schalkwijk [1.11] and Weenink [1.12], built a computer model of the North Sea laid out on a grid (approximately 250 elements) with simplified, linearized Navier-Stokes equations. He divided the North Sea and English Channel into six areas, as shown in Fig. 1.9. For each of these areas, he applied a homogenous wind field and observed the steady-state model results (and the time required for this to occur) at a number of locations on the Dutch coast—particularly at Vlissingen, Hoek van Holland, Harlingen, and Delfzijl. He compiled these results into tables for each of the locations and for various wind speeds and isobar directions. The model is
Fig. 1.9—Schematic of KNMI operational surge prediction model
essentially linear and the effects of superposition apply. Thus, the local set-up from each of the six regions can simply be added to obtain total set-up; this, in turn, can be added to astronomic tide and external surge effect, if any, to obtain total water level.

The KNMI has used Timmerman's model as their operational model to predict storm surges in the Netherlands since late 1971. When there is a storm in the North Sea with a possibility of a significant surge, the KNMI provides a set-up estimate to the SVSD, who combines this information with astronomic tide predictions and a variety of other information and judgments to derive an estimate of the potential hazards. When advisable, the SVSD issues alerts to threatened areas.

Current efforts are aimed at predicting storm surges several (6 to 18) hours ahead of the moment of high water. Introduction of the storm-surge barrier (SSB) creates two new areas of emphasis for estimation and prediction: (1) an accurate, continuous measurement of the existing surge before peak water level occurs could be invaluable for some classes of barrier control strategies that need only a short-term (about an hour ahead) prediction of water level; (2) if available several days in advance, predictions that storm conditions might or might not be expected could be useful for alerting or scheduling maintenance and certain other operations of the SSB.

The remainder of this report explores possibilities in the first new area, short-term prediction, and compares these possibilities with conventional prediction techniques. In Chap. 2, we analyze the feasibility of obtaining an accurate, continuous estimate of the surge in real time. We conclude that surge can be estimated with accuracy only at the moments of high and low tide.

In Chap. 3, we examine the following question: If surge can be accurately estimated only at high and low tide, is it possible, because of the very low-frequency properties of surges, to accurately predict ahead to the next high tide from surge observations at the several preceding low and high tides? Using statistical techniques, we find we can predict the day-to-day set-up and the set-up in storms with some degree of success. Unfortunately, as demonstrated in the Summary Report, such predictions are still inadequate for operation of the barrier.

Chapter 4 addresses the question of how well the KNMI operational model performs under storm conditions. We find that its predictions are much more accurate than those of the autoregressive prediction techniques explored in Chap. 3. (In the Summary Report we illustrate the probably adequate performance of current prediction capabilities for operation of the barrier.)

Finally, in Chap. 5 we assess how well improved prediction models might perform. We analyze results from, and explore possible improvements to, a newer model developed at the KNMI. Timmerman has extended the "restricted" (operational) model discussed above to include large areas of the ocean north of Scotland and west of the English Channel. This computer program, known as the "extended model II," has provisions for automatically handling large volumes of pressure information to derive wind fields over the North Sea and the "external surge" created by pressure gradients over the continental shelf and winds over the shallow areas of adjacent oceans. The extended model has been used for experimental analysis at the KNMI throughout the 1970s. It gives a running forecast of the set-up

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10 Storm Flood Warning Service, a division of the Rijkswaterstaat (RWS).
at each high and low tide on a nearly continuous, ongoing basis, using routine weather data. This extended model performs well in routine day-to-day forecasts but does not perform any better than, if even as well as, the current operational model under storm conditions.

Although the issue certainly warrants further examination and research, major improvements in storm-surge prediction accuracy do not appear possible in the near future, that is, over the next decade. This implies that the feasible operational strategies for the SSB will have to be within the constraint bounds of water level prediction capabilities that exist today. In our analysis of alternative strategies in the Summary Report and Vol. II, we were fully aware of these bounds.

Appendix B briefly explores the second new area for emphasis in prediction: long-term (several days ahead) prediction possibilities for scheduling maintenance and other operations of the SSB.

REFERENCES


Chapter 2

ESTIMATION AND PREDICTION OF SURGE
BY CORRELATION OF WATER LEVELS
OVER TIME AND SPACE

Let us hypothesize that we can obtain, from observed total water levels, a fairly accurate, continuous estimate in real time of set-up (or surge) cleanly separated from the astronomic tide. If we obtained this estimate over the time period from low to high tide, we could make a simple extrapolation of the slowly varying surge an hour or so ahead with good prediction accuracy. We could then combine this rudimentary, but potentially accurate, prediction with the predicted astronomic tide to derive an accurate prediction of total water level an hour or two ahead. Such predictions could be adequate for control of the barrier with a variety of potentially attractive strategies.

In this chapter, we explore the feasibility of achieving the conditions of this hypothesis and come up with somewhat negative, but interesting, results. We also develop a definitive introductory description of the statistical characteristics of tides and surges, relevant to the succeeding chapters.

The observed water level at a given location differs from that predicted by the astronomic tide. This difference consists of two components: (1) There are low-frequency distortions (or modulations) of the astronomic tide. A random frequency modulation varies the tide arrival time from the predicted time, and a random nonlinear amplitude modulation varies the tide shape and amplitude from those predicted. (2) In addition, there is a very low-frequency set-up or surge that is caused by winds, barometric pressure, oscillations in the North Sea basin, external surges, and so on. (There is also some nonlinear coupling between tide and surge.)

We will discuss the statistical characteristics of each of these two components in turn. Because considerably more data are available for Vlissingen and Hoek van Holland than for any other location between them, that is, at the Oosterschelde, we use Vlissingen for much of our discussion here.¹

2.1. FILTERING OF TIDAL FREQUENCY COMPONENTS
FROM OBSERVED WATER LEVELS

We will next discuss several possibilities for separating, or filtering, the tidal frequency components from the observed water level to obtain an ongoing measure of set-up or surge.

2.1.1. Traditional Techniques

The technique currently used in the Netherlands (e.g., at the SVSD) to separate surge from observed water levels is simply to subtract the predicted astronomic tide from the observed water levels.

¹ These locations are indicated below in Fig. 2.11.
Figure 2.1 shows the astronomic tide water level versus time profile at Vlissingen and Hoek van Holland for spring (large) and neap (small) tides [2.1]. Considerable harmonics of the fundamental frequency exist because of nonlinear propagation conditions. A characteristic of all tides in the vicinity of the Netherlands is a sharp rise rate during the flood time period from low to high tide, and a more gradual decrease during the ebb period from high to low tide. This characteristic shape is attributable to the shallow water propagation conditions in the North Sea. Because propagation velocity is proportional to the square root of water depth, the high tide crest propagates faster than the low tide trough. Reference 2.1 gives a procedure for interpolating the curves in Fig. 2.1 for intermediate tidal ranges. We computerized this interpolation routine to derive the complete astronomic tide profile for Vlissingen for the years 1971 and 1972.

We also had hourly water level observations for Vlissingen for these same years, and we computed the difference between these two water levels (astronomic and observed) for subsequent analysis. Figure 2.2 shows a section of this residual difference for the period before and during a storm surge that occurred on November 21, 1971. As a check on our procedure, the residual difference precisely matches the surge derived in the Netherlands by the SVSD and provided to us for this same time period. (We use this same time sector (November 18-23, 1971) for a variety of illustrations discussed below.)

It can be seen from Fig. 2.2 that an appreciable tidal frequency component still exists in the surge residual after the astronomic tide is subtracted out. In the next two sections, we outline several alternative techniques we tried in order to better filter out this residual tidal frequency component by ongoing regression corrections to the astronomic tide derived (1) from local observed water levels over time and (2) from remote and local observed water levels over time.

2.1.2. Correlation over Time

The time of arrival of high and low tides can deviate considerably from the predicted astronomic time. A shift in arrival time can result in an apparent surge. For example, an early arriving high tide can appear to be a positive surge coupled with a later tide. Figure 2.3 illustrates this "apparent" surge. The surge "bump" created by an early tide appears in many water level profiles, similar to the one on November 21 in Fig. 2.2. Here the bump appears superimposed on an appreciable rising surge to give the momentary effect of an awesome, rapidly rising surge that would prove disastrous if it continued until the time of normal high tide. But the momentary, apparent surge rapidly diminishes to below 1 m before high tide arrives.²

With a positive surge, one would expect that both high and low tides would arrive early, with a more marked difference for low tides because of the effects of water depth on propagation velocity (proportional to the square root of depth). Figure 2.4 shows the time of arrival difference superimposed on the tide and surge plots of Fig. 2.2. There does appear to be a pattern of correlation; in particular, low tides seem to arrive early under conditions of positive surge. We will explore this pattern further.

² Another "characteristic" pattern that seems to occur in Fig. 2.2 is a tendency for the apparent surge to be higher at low tide and lower at high tide. This is equivalent to a reduction in the astronomic tidal amplitude, but we have not been able to verify this occurrence statistically.
Fig. 2.1—Astronomic tide shape at Vlissingen and Hoek van Holland (Ref. 2.1)
Fig. 2.2—Astronomic tide and hourly observed water levels at Vlissingen, November 1971.
The standard deviation of the difference between actual arrival time of high and low tides and predicted astronomic time is 0.186 hr for the year 1971. We regressed the arrival time difference of high tides and low tides on the six previous high and low arrival time differences and on the present set-up and set-up at the six previous high-low tide points. These regressions reduced the standard deviation of prediction error of both high and low tides to about 0.12 hr. Table 2.1 lists the regression coefficients and t-statistics for the high and low tide regressions. In both cases, the results show a significant statistical correlation with several previous arrival times. The low tide arrival time is highly correlated with the present and past surge conditions. The high tide arrival time has a much lower correlation with surge, as anticipated. Figure 2.5 shows the error in predicted arrival time using the regression for prediction. The improvement in prediction error (from a standard deviation of 0.186 to 0.12 hr) is apparent. Figure 2.5 also shows the surge derived using the regressive predicted times for high and low tides, rather than the times from the astronomic tide tables. There is little, if any, improvement in the separation, or filtering, of the tidal frequencies from the low-frequency set-up or surge. (We verified this finding with a detailed analysis of the residual over 1971. See below.)

We used a number of other techniques to try to better filter the tidal frequency components from the surge. Figure 2.6 shows some of the results with four separate curves: (1) the originally derived surge (as given in Fig. 2.2); (2) the surge derived with the regression-corrected astronomic time (as given in Fig. 2.5); (3) a curve
Fig. 2.4—Time of arrival differences for high and low tides (astronomic time minus observed time)
Table 2.1

REGRESSION OF HIGH TIDE AND LOW TIDE ARRIVAL TIME ON PREVIOUS TIMES AND PRESENT AND PREVIOUS SURGES

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lag</th>
<th>High Tide Coefficient</th>
<th>t</th>
<th>Low Tide Coefficient</th>
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</tr>
</thead>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.540</td>
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<td>0.239</td>
<td>5.9</td>
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<td></td>
</tr>
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</table>

representing the time of the astronomic tide equated to the observed times of highs and lows; and (4) a curve for this same time match with a change in the astronomatic tide shape according to surge conditions. None of these techniques provided more than slight, if any, marginal improvement in filtering the tidal frequency components from the surge.

Figure 2.7 shows the originally derived surge and the residual component that remains after fitting the astronomic tide shape to the observed times and amplitudes of highs and lows. The original surge has a standard deviation of 24.5 cm over the year for 1971, and the residual has a standard deviation of 10.6 cm over the same year. We obtained comparable residuals using the regressive predicted time and the change in tide shape with surge, but the differences were slight in all cases.

2.1.3. Correlation over Space

If the tidal frequency components were highly correlated over a wide geographic area, we might be able to derive some additional information on the existing surge by spatial correlation. However, the random tidal frequency components appear to be uncorrelated from one location to another. As an example, Fig. 2.8 illustrates the arrival time differences for Zierikzee and Hoek van Holland superimposed on those already shown for Vlissingen. There is a surprising lack of correlation in arrival time error across the various locations, particularly when we consider the significant correlation between successive time errors at a single location, as shown in Table 2.1. And among even nearby locations, there is a corresponding lack of correlation between the tidal modulation shape and noise components. The higher frequency noise may be partially attributable to measurement error, where we would not expect a correlation. But the random low-frequency tidal modulation, in terms of shape, time, and amplitude, is surprisingly uncorrelated even among closely adjacent locations. This is further illustrated in Fig. 2.9, which

* Changed in the direction of the spring tide shape when a positive surge is present.
Fig. 2.5—Regressive prediction of time of arrival of peak tides: time differences and apparent surge
Fig. 2.7—Residual when astronomic tide shape is fitted to observed high and low amplitudes and times

Fig. 2.7—continued
Fig. 2.8—Arrival time differences at three locations
Fig. 2.9—Surge at Hoek van Holland compared with Vlissingen

Fig. 2.9—continued
shows segments of the surge at Hoek van Holland as compared with the previously derived surge at Vlissingen. We can clearly see the low correlation of the modulation components and the high correlation of the surge itself. Figure 2.10 shows the surge at other locations farther removed—at Lowestoft and Immingham on the English coast—and Fig. 2.11 shows these locations with respect to the coast of Holland. The surge occurs over the entire region of the southern part of the North Sea, but the residual differences after filtering have little, if any, correspondence between any of the locations.

The surge occurs nearly simultaneously at each of the four locations shown in Fig. 2.11, its appearance being dependent on the details of the storm behind it. Figures 2.12, 2.13, 2.14, and 2.15 show four other surges with a somewhat different timing between locations. The 1966 surge at Vlissingen in Fig. 2.15 contains a particularly large component of the tidal frequency. At the times of high tide, the surge is quite normal—less than 1 m. At other times, the apparent surge is of the order of 2 m.

2.1.4. Summary Comments

We have not been able to devise a satisfactory filtering technique to remove the tidal frequency components from the observed water level and thus could not derive an accurate, continuous estimate of surge. The nonlinear effects and propagation conditions in the North Sea are complex and too elusive for the detailed,

---

Fig. 2.10—Surge on English coast compared with Dutch coast, November 1971
Fig. 2.11—Locations of surges shown on Fig. 2.10
Fig. 2.12—Surge on English coast compared with Dutch coast, January 19/20, 1960

Fig. 2.13—Surge on English coast compared with Dutch coast, February 16/17, 1962
Fig. 2.14—Surge on English coast compared with Dutch coast, November 1/2, 1965

Fig. 2.15—Surge on English coast compared with Dutch coast, November 30/December 1, 1966
precise modeling that is necessary to appreciably improve the currently used, traditional techniques, which simply subtract the predicted astronomic tide from the observed water level. But, as we have seen, large errors can occur in attempting to estimate the "true" surge that exists during the transition periods between low and high tides.

Similar, but more complex, attempts have been made to derive a better solution to this problem. Cartwright concludes that an explicit nonlinear surge-tide interaction formula he devised "evidently accounts correctly for a small part of the modulation, but other physical interactions must also be present. . . . Self-prediction . . . sometimes improves and sometimes worsens the comparison. . . . The method(s) of this paper . . . compares favourably with, but is not markedly better than, the typical product of other methods" [2.2].

The most reliable estimate of surge can be made by observing the peak high and low water levels that occur and then subtracting the astronomic tide table values, without regard to the small differences in time at which they occur. Figure 2.16 shows the surge that this technique produces, as compared with the previous surge derived using hourly observed water levels. Some random tidal frequency (12-hr period) component is still apparent, but it is greatly reduced. Also shown is the surge at Hoek van Holland, derived by the same method. Again, the high correlation of the surge between the two locations is readily apparent. We use the surge as derived in this manner throughout the remainder of our study.

2.2. SOME CHARACTERISTICS OF LOW-FREQUENCY SET-UP OR SURGES

A number of statistical characteristics of low-frequency set-up or surge have been defined and used in the BARCON study.

2.2.1. Magnitude of Set-Up

Figure 2.17 shows the deviation with respect to the predicted level for high tides at Vlissingen throughout the year [2.1]. In the reference, a similar curve is given for low tides as well as curves for Hoek van Holland. Figure 2.18 shows the maximum (winter) and minimum (summer) of these curves translated to probability paper. The vertical scale is such that a normal distribution is a straight line. As shown, the deviation about zero is approximately normal and very similar at both Hoek van Holland and Vlissingen. This similarity between the two locations is not surprising because, as we have seen above, the surge component is of a slowly varying amplitude with a high correlation over a wide geographic area.

2.2.2. Time and Space Correlation of Set-Up

The surge condition is of long duration and exists simultaneously over wide geographic areas. Figure 2.19 shows the autocorrelation of the surge component, as derived from the hourly data for Vlissingen for the year 1971. Although the high correlation indicates that a very good prediction of surge can be made a few hours ahead by simply observing present surge, we are limited in practice to 6-hr predictions because, as developed above, surge observations at times other than high or
Fig. 2.16—Surge profile using peak high and peak low water levels only

Fig. 2.16—continued
low tide are very inaccurate. At six hours (the time from low to high tide), the correlation is still above 0.6, which is adequate for some prediction. In Chap. 3 we develop this form of prediction, and in the Summary Report we explore its usefulness for control of the barrier.

2.2.3. Frequency Spectrum of Set-Up*

A high correlation over appreciable periods of time is synonymous with a very low-frequency spectral distribution. Figure 2.20 shows the results of a Fourier decomposition of the February 1, 1953, surge into its steady-state and harmonic components. The results of a similar analysis of a number of surges are shown in Fig. 2.21. In all cases, most of the spectral energy occurs at very low frequencies, well below the tidal frequency with a 12-hr period. Of course, a large residual energy spectrum also exists in a narrow band about the 12-hr period, as discussed above.

* Allan Abrahamse of Rand performed this spectral analysis in the early phases of the BARCON study. See Ref. 2.3 for a general discussion of spectral analysis techniques.
Fig. 2.18—Random component of high tides

Fig. 2.19—Typical autocorrelation over time of tide residual or surge at Vlissingen, 1971 (hourly observations)
2.3. FINAL COMMENTS

The random surge is of a very low-frequency distribution and is highly correlated over wide areas in the North Sea basin. But surge can only be observed with some accuracy at the moments of high or low tide. Thus, an accurate surge reading at Vlissingen can be made an hour or so before the high tide at Hoek van Holland. In the interim, however, a larger surge can be moving down the coast. We do not see any way that correlation of surge measurements among different locations can provide information of sufficient and timely accuracy to be useful for controlling the storm-surge barrier.
Fig. 2.21—Amplitude of spectral components of selected surges (based on a Fourier analysis by A. F. Abrahamse)

REFERENCES


Chapter 3

A TIME-SERIES ANALYSIS OF WATER LEVELS

3.1. INTRODUCTION

Chapter 2 described the difficulty in obtaining an accurate measurement of set-up at times other than high and low water. In this chapter, we explore the next question: If surge can only be accurately estimated at high and low tide, is it possible, because of the very low-frequency properties of surges, to accurately predict ahead to the next high tide from surge measurements at the several preceding low and high tides?

The nature of the analysis of such self-prediction techniques was largely exploratory. We were trying to assess the feasibility of forecasting set-up one-half tide cycle in advance with sufficient accuracy for operation of the storm-surge barrier.¹

In what follows, we describe the data we used and the general time-series modeling methodology; the preliminary data analysis—the statistical correlation properties and the seasonality of the data; the development of the several time-series models, including our assumptions and conclusions about each; and finally a summary of the prediction accuracy that can be achieved.

3.2. DATA FOR WATER LEVELS

3.2.1. Data Source

We obtained data on observed water levels in relation to NAP² from the RWS for the years 1970 through 1977.³ We analyzed the data on a yearly basis, that is, as eight separate time series. Among the several locations on the Dutch coast for which data were available, we selected Vlissingen for our data base because of its site near the mouth of the Oosterschelde and its similar tidal conditions. (See Fig. 2.11.)

3.2.2. Transforming the Data

Because the raw water levels at high and low tide have cyclic variations due to the astronomical tides, we must remove these periodicities so that the resulting

¹ Although we achieve some degree of success here, in the Summary Report we illustrate the inadequacy of such self-prediction for operation of the barrier.

² Essentially the mean sea level. NAP is an abbreviation for "Normaal Amsterdams Peil," a term dating from the 1600s, when it presumably indicated an average water level at Amsterdam.

³ The RWS' Yearbook of Water Heights [3.1] gives the measured water level for each high and low tide for various locations along the Dutch coast and rivers, as well as the times of high and low water levels. We had copies of the Yearbooks for 1970 through 1972 and received computer printouts of the water heights for Vlissingen and Hoek van Holland for the years 1973 through 1977. (These will be printed in the Yearbooks when they are published.)
set-up data may be treated as a (relatively) stationary time series. To remove the astronomical tide, we use the predicted astronomical tide levels as published by the RWS [3.2], 1970 through 1977. As before, we assume that the water level $WL_t$ is the sum of the astronomical tide $AT_t$ and set-up, denoted by $SU_t$. Thus,

$$SU_t = WL_t - AT_t.$$

As we have seen, a time plot of set-up reveals that set-up generally fluctuates slowly around the value zero, sometimes taking on large values (150 to 200 cm or more) during storm surges and also reaching values of $-50$ cm and less (termed negative surge).

### 3.3. GENERAL MODELING METHODOLOGY

#### 3.3.1. Approach

Most of the methodology used to analyze these series was developed by Box and Jenkins [3.3]. They define three basic stages in the modeling effort:

1. **Model identification.** The several considerations in this stage include the selection of an appropriate transformation of the raw data (if necessary)\(^4\) and the selection of an appropriate time-series model for the data. The model selected is an autoregressive (or Markov) process. Section 3.3.2 gives a general description of this model and also presents two important tools in model identification, the autocorrelation function and the partial autocorrelation function.
2. **Fitting the model.** In this phase estimates of the model parameters are derived from the data.
3. **Checking the fit.** Various diagnostic checks are applied to the fitted model to determine how well the model fits the data. These checks include time plots of the data together with predictions, as well as plots of the autocorrelation function of the fitted residuals, described in Sec. 3.5.

#### 3.3.2. Autoregressive Models

We model set-up ($SU_t$) by expressing it as a function of its own past history and a random shock $a_t$. That is, we express $SU_t$ as

$$SU_t = f(SU_{t-1}, SU_{t-2}, \ldots) + a_t, \quad 1 \leq t \leq T,$$

where $T$ is usually 1410, the number of high and low tides per year (this number varied from 1410 to 1415 for the eight years). The error terms or shocks, $a_t$, are assumed to be independent with mean zero and constant variance. The function $f$

---

\(^4\) The observations were made at high and low tides, which are about 6\(^\frac{1}{4}\) hr apart. In our analysis, we assumed that the observations were made at equally spaced points in time. This should not have any significant effect on the results.

\(^5\) Because the plots indicated that set-up constituted a relatively stationary time series, no further preliminary transformation of the data was performed.
in Eq. 3.1 is a function of p previous values $SU_{t-1}, \ldots, SU_{t-p}$, where p must be determined. Thus Eq. 3.1 becomes

$$SU_t = \mu + \sum_{j=1}^{p} \phi_j SU_{t-j} + a_t,$$

where the constant $\mu$ in effect determines the level or mean of the series.

Thus, Eq. 3.2 expresses set-up at time t as a finite linear combination of previous values of set-up and a current shock term $a_t$, caused by current wind stress, barometric pressure, and other meteorological factors.

Time series expressed in the form of Eq. 3.2 are termed autoregressive (or Markov) series. Two key tools that are used to determine whether Eq. 3.2 may adequately model the data are the autocorrelation function (or ACOR) and the partial autocorrelation function (or PACOR).

The autocorrelation function is defined as the correlation of a series with itself at various lags:

$$ACOR(k) = \text{Correlation} (SU_t, SU_{t-k}), \quad k = 1, 2, \ldots$$

The partial autocorrelation function is obtained by regressing the series $SU_t$ on various lags of the series. If we write

$$SU_t = \mu + \phi_1 SU_{t-1} + \ldots + \phi_k SU_{t-k} + \epsilon_t, \quad k = 1, 2, 3, \ldots,$$

the partial autocorrelation at lag $k$ is

$$PACOR(k) = \phi_k.$$

If $SU_t$ is a stationary autoregressive series of order p, written AR(p), then from Eq. 3.2 PACOR(k) = 0 for $k > p$. Moreover, in general the autocorrelation function (ACOR(k)) will not die out (as does the partial autocorrelation function PACOR), but instead will tail off to zero as a mixture of damped exponentials and damped sine waves [3.3, p. 55].

The next step in the analysis is to plot the sample (or estimated) autocorrelation function ACOR and the sample partial autocorrelation function PACOR (computed for each series). When we examine these graphs to assess the patterns in ACOR and to determine the lag at which PACOR effectively dies out, we can determine the order of a potentially suitable autoregressive model.

3.4. PRELIMINARY DATA ANALYSIS

3.4.1. Yearly Autocorrelation and Partial Autocorrelation Functions: Model Identification

The sample ACOR and the sample PACOR were plotted for each year, 1970 through 1977. We found that for the years 1970 through 1973, the PACOR effective-
ly died out at about lag six, and the ACOR resembled a relatively smooth graph that eventually converged to zero, as expected. Figure 3.1a plots ACOR of set-up and Fig. 3.1b PACOR of set-up for the year 1971.

For each of the years 1974 through 1977, however, ACOR exhibited a pronounced periodicity of order two, and the plots did not tail off to zero. This indicated that a strong diurnal component (corresponding to the tidal frequency) was still present in SU. Figure 3.2 plots ACOR for the year 1977. We concluded from these plots that subtracting the predicted astronomical tide from the observed water level did not remove all of the strong diurnal component.

To remove this remaining tide cycle component from SU and to determine the magnitude of this component for each year, we divided the data into two sets, one for set-up at high tide and the other for set-up at low tide.

Defining HSU\_t as set-up at high tide (for even t) and LSU\_t as set-up at low tide (for odd t), we can write

\[
\begin{align*}
\text{HSU}_t &= A + c + \text{HSU}^*_t, \\
\text{LSU}_t &= -A + c + \text{LSU}^*_t,
\end{align*}
\]

where \( c = (\text{HSU} + \text{LSU})/2 \) is the average set-up, and \( A = (\text{HSU} - \text{LSU})/2 \) is the tidal component still remaining in the data.

\( \text{HSU}^*_t \) and \( \text{LSU}^*_t \) are set-up at high and low tide, respectively, with the strong diurnal component (A) and the overall mean (c) removed. Since \( A + c = \text{HSU} \) and \( c - A = \text{LSU} \), we may rewrite Eq. 3.3 as

\[
\begin{align*}
\text{HSU}_t &= \text{HSU} + \text{HSU}^*_t, \\
\text{LSU}_t &= \text{LSU} + \text{LSU}^*_t.
\end{align*}
\]

The hypothesis test that \( A = 0 \) (no remaining diurnal component) is equivalent to the test that \( \mu_{\text{HSU}} = \mu_{\text{LSU}} \), where \( \mu_{\text{HSU}} \) and \( \mu_{\text{LSU}} \) are the population means of HSU and LSU, respectively. The t-statistics for each of the years examined are all significant. Thus set-up for each year still has a considerable tidal component. The estimates of A for each year are presented in Table 3.1. Because \( \text{SU}_t = \text{WL}_t - \text{AT}_t \), the predicted high astronomical tides are generally too low and the predicted low astronomical tides are too high, or the observed tidal amplitude is larger than is given in the tide tables. The ACOR plot of \( \text{SU}^*_t \) for 1977 is presented in Fig. 3.3. It is much smoother than the graph of Fig. 3.2 and tends to tail off to zero, as expected.

The representation of Eq. 3.3 is a simple model and assumes, in particular, that the amplitude A is constant throughout the year. This is probably not true. However, this simple model does indicate that some error exists in the predictions of astronomical tide for Vlissingen.\(^7\)

When we examine the plot of PACOR of \( \text{SU}^*_t \) for each of the eight years, we see that PACOR does indeed die out at about the sixth lag for each year. The plot of ACOR for \( \text{SU}^*_t \) appears to tail off to zero.

3.4.2. Analysis of Seasonal Variation

We examined the seasonal variation of the sample mean and the sample standard deviation of surge or set-up.

\(^7\) The increase in error beginning about 1974 could be caused by the effects of the Delta works or by the new tide prediction schemes introduced about that time.
Fig. 3.1a—Autocorrelogram of set-up, 1971

Fig. 3.1b—Partial autocorrelation function of set-up, 1971
Fig. 3.2—Autocorrelogram of set-up, 1977

Table 3.1

ESTIMATES OF TIDAL AMPLITUDE $A$

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<td>1977</td>
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Figure 3.4 gives a plot of the monthly average (mean) of set-up for each year from 1970 to 1977, and Fig. 3.5 gives the monthly sample standard deviation. It is clear that there is much more variation in set-up during the stormy winter months than in summer, as would be expected. There is also considerable variation from year to year during the winter months but not much during the summer months. The curve on Fig. 3.5 is the observed root mean square deviation from the astronomic tide as derived from Ref. 3.4.

3.5. INITIAL MODELS

Because the model identification stage suggested that an autoregressive model would be appropriate, we first fit a sixth-order autoregressive model to the entire year's data for the different years. This model assumes that the autoregressive parameters do not vary from month to month. (We realize that such a model does not account for seasonality and will return to this point in Sec. 3.6.)

Table 3.2 displays the estimates of the autoregressive parameters for the years 1970 through 1977, together with $R^2$ and $\hat{\sigma}$ and the estimated standard errors of
Fig. 3.4—Average monthly mean of set-up, 1970-1977
Fig. 3.5—Standard deviations of monthly set-up, 1970-1977
### Table 3.2

**Autoregression Parameter Estimates, 1970-1977**

#### 1970

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Table 3.2—continued

1974
Estimated standard deviation = 1.7068D 01
R² = 0.6863

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1975
Estimated standard deviation = 1.6061D 01
R² = 0.5309

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1976
Estimated standard deviation = 1.6021D 01
R² = 0.5755

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<td>SU...6</td>
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1977
Estimated standard deviation = 1.4599D 01
R² = 0.6401

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<td>6.9745D-01</td>
<td>2.6788D-02</td>
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<td>SU...2</td>
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<td>SU...5</td>
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<td>6</td>
<td>SU...6</td>
<td>1.2793D-01</td>
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</table>
the estimates. Generally we found that

- The estimate of the partial autocorrelation at lag 1, $\phi_1$, varied from 0.7 to 0.8.
- Both $\phi_3$ and $\phi_4$ were consistently negative.
- $R^2$ varied from 0.57 to 0.64.

Some parameter variability occurs from year to year, probably because the number of storms (and their severity) varies from year to year. However, the use of parameters averaged over the entire 8-year period does not cause much loss in the accuracy of predictions. The moderate $R^2$ value indicates that the model performs only moderately well.

The last stage of model building is to check the fit of the model. Figure 3.6 gives a plot of the actual data, together with predictions from the fitted sixth-order autoregressive model for part of November 1971. Large increases in set-up during a 6½-hr period (one-half tide cycle) caused by the arrival of a storm are not accurately anticipated by the model and are usually underpredicted. This was generally found to be true for each of the years that was modeled.

The plot of ACOR for the computed residuals $\hat{a}_t = SU_t - \hat{SU}_t$ indicates whether we can assume that the residuals are “white noise.” The plot in Fig. 3.7 of ACOR for 1971 reveals no sharp spikes or patterns. Thus it appears that $\hat{a}_t$ does behave as uncorrelated noise, and the model does reasonably well at predicting set-up.

3.6. SEASONAL MODELS

A shortcoming in the model developed in Sec. 3.5 is that it fails to account for a marked seasonality in the data, a phenomenon reflected in time plots of the fitted residuals. These plots are inhomogeneous in that the residuals tend to vary much more in the winter months than in the summer months.

Consequently, we made a different fit of a sixth-order autoregressive model to the data corresponding only to the winter months. We selected the months of October, November, December, and January for several winters because these four months tend to be the stormiest and they are relatively homogeneous, as the plots of monthly sample means and sample standard deviations revealed.

The results for several winters (but not all) are presented in Table 3.3. Fewer lags seem to be necessary in the model, as evidenced by the values of the t-statistics for the higher lags. (We are generally “overfitting” the model.) This is not a serious problem because we are only losing a few degrees of freedom in overfitting the

---

* We computed the tabulated numbers in double precision and displayed them in scientific notation. For example, in Table 3.2, the estimated standard deviation for the year 1970, namely 1.6552D01, equals 16.552. We use the letter D rather than the usual E to denote double precision.

* $R^2$, the coefficient of determination, varies between 0 and 1 and is a measure of how well the estimated autoregression fits the data.

* These estimates were based on the set-up data without adjusting for the tide cycle residual, as described in Sec. 3.4.1.

* Given the estimates $\hat{\mu}$ and $\hat{\phi}_1, \ldots, \hat{\phi}_p$, the prediction of $SU_t$ is $\hat{SU}_t = \hat{\mu} + \sum_{i=1}^{p} \hat{\phi}_i SU_{t-i}$.

* These parameter estimates are based on data obtained by removing the still-remaining diurnal component from the set-up.
Fig. 3.6—Set-up and predictions, November 1971

Fig. 3.7—Autocorrelogram of residuals, 1971
Table 3.3

AUTOREGRESSIVE PARAMETER ESTIMATES,
WINTER MONTHS, 1970-1977

<table>
<thead>
<tr>
<th>Year</th>
<th>Estimated standard deviation</th>
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<td>1971-1972</td>
<td>$= 2.0334 D; 01$</td>
<td>$= 0.5779$</td>
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<tr>
<td>1974-1975</td>
<td>$= 2.3369 D; 01$</td>
<td>$= 0.4538$</td>
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<td>1975-1976</td>
<td>$= 2.2756 D; 01$</td>
<td>$= 0.5110$</td>
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<td>1976-1977</td>
<td>$= 1.5301 D; 01$</td>
<td>$= 0.4817$</td>
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<td>4.6756D-02</td>
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model, and there are about 460 observations (high and low tides) during a four-
month period.

A comparison of Fig. 3.8 with Fig. 3.6 indicates that introducing seasonality into
the model (by only fitting the winter months) does not significantly increase the
capability of predicting set-up. Again, the model predictions "lag behind" the large
increase in set-up for November 21 and 22, 1971.

3.7. PREDICTION ACCURACY

The goal of the analysis was to determine how accurately we could forecast
water levels by means of observed set-up alone. The model developed here enables
us to make predictions a half tide cycle ahead that reduce the root mean square
error (RMSE) in peak water level (deviation from the predicted astronomic tide)
from about 23 to 15 cm. This one-third reduction in the prediction error is fairly
consistent throughout the winter and summer months. In terms of percentages,
slightly better predictions can be made under storm conditions. For the 74 high
tides that precipitated some SVSD activity between 1971 and 1977, the mean set-up
at Vlissingen was 74 cm, with an RMSE of 84 cm from the predicted astronomic
high tide. For these same high tides, the autoregressive predictions underestimate
the mean by 11 cm and have a standard deviation of 37 cm, giving a net RMSE in
prediction of 39 cm. In percentages, we do better, but absolutely we do worse. This
can be attributed to the fact that storms are an outside influence that disturb the
normal day-to-day set-up by sending a "shock" or "impulse" into the system at
random time intervals. In the Summary Report we illustrate the inadequacy of
such predictions for operation of the barrier.

![Graph](image)

**Fig. 3.8—Set-up and predictions for seasonal model, winter 1971**
REFERENCES


Chapter 4

ANALYSIS OF THE STORM FLOOD WARNING SERVICE DATA

4.1. INTRODUCTION

If observed water level (including self-prediction as discussed in the preceding two chapters) does not provide us with enough information to operate the barrier under potentially desirable control strategies, we are prompted to ask: Can we use current surge predictions, derived for other purposes, for operating the barrier with these strategies?

In Chap. 1, we briefly described the model used by the KNMI since late 1971 for predicting storm surges. When there is a possibility of a significant surge from a storm in the North Sea, the KNMI uses this model to estimate the set-up for several locations and transmits this information to the SVSD of the RWS.¹ The SVSD provided us with the data on the KNMI surge predictions for Vlissingen and Hoek van Holland between late 1971 and mid-1977 (74 high tides in 40 separate storms). They also provided us with similar data for the period 1954 to late 1971, obtained with the previous KNMI surge prediction model (150 high tides).² In this chapter, we analyze the statistical characteristics of these predictions. (In the Summary Report, we illustrate the probable adequacy of these predictions for operating the barrier.)

In what follows we describe in detail the data set used in our analysis and summarize the analyses performed on the KNMI-SVSD data set. Next we present (1) an assessment of the accuracy of the KNMI-SVSD predictions; (2) a regression analysis that provides improved predictions; (3) forecast errors for these improved predictions; and (4) an analytical model that incorporates information from locally observed water levels into the forecasting process.

4.2. DESCRIPTION OF THE DATA

There are predictions of 150 storm surges at high tide from 1954 to spring 1971 for both Hoek van Holland and Vlissingen from the old operational model, and there are predictions of 74 surges at high tide from fall 1971 to spring 1977 for these two locations (see Fig. 2.11) from the current operational model.³ To simplify the analysis, we classified the predictions according to whether they were made from 0 to 3 hr in advance of the high tide arrival, 3 to 6 hr in advance, 6 to 9, 9 to 12, 12 to 15, and so on. If a prediction was made from 6 to 9 hr in advance, say, and

¹ A detailed description of the SVSD operation is given in the Summary Report.
² Thus, we have prediction data on 224 high tides over the 24-year period, or an average of about 10 high tides per year of the more than 700 that occur each year. The distribution of predicted water levels for high tide has been severely "censored" in the data set, a point we will discuss in detail in Sec. 4.2.
³ Not all of the 224 observations have large storm surges. That is, occasionally a high water level was predicted, but a large storm surge did not materialize (there was, in fact, a quite small set-up).
no further predictions were made until the arrival of the crest, the 6 to 9-hr prediction was also recorded as a 3 to 6-hr prediction and a 0 to 3-hr prediction, because the prediction had not changed from the time it was first made. We carried out this procedure for all of the time-of-prediction classifications. Thus, only for the 0 to 3-hr category do we have a prediction for each of the 224 set-ups from 1954 to 1977. We shall focus our analysis on the 0 to 3-hr predictions.

The variables for which we have data from the SVSD are:

\[ \begin{align*}
    AT_i &= \text{predicted astronomical high tide for } i\text{th datum},^* \\
    O_i &= \text{observed water level for } i\text{th datum}, \\
    SU_i &= \text{set-up for } i\text{th datum } = O_i - AT_i, \\
    PSU_i &= \text{predicted set-up for } i\text{th datum}, \\
    P_i &= \text{predicted water level for } i\text{th datum } = PSU_i + AT_i.
\end{align*} \]

We have already noted that the data were collected by "censoring" the variable \( P \) (the predicted water level). Let \( L \) denote the number of locations for which the KNMI makes storm-surge predictions, let \( P\) denote the predicted water level for the \( t \)th location, and let \( O_t \) denote the observed water level for location \( t \), \( 1 \leq t \leq L \). For each location \( t \) there is a constant \( c_t \), such that if \( P_t \geq c_t \) for at least one location, the SVSD is contacted and relevant information is given. If \( P_{Vliss} \) denotes the location Vlissingen, for example, we may form the \((L+1)\)-dimensional vector \((O_{Vliss}, P_{Vliss}, P_2, \ldots, P_L)\). Unfortunately, because \( P_2, \ldots, P_L \) are not generally observed, we do not have data on these variables.

From the above definitions, we see that

\[ \begin{align*}
    O &= SU + AT, \\
    P &= PSU + AT.
\end{align*} \]

Because the tidal component \( AT \) is such a dominant component of observed water level, it must be removed to determine the relationship between set-up and predicted set-up. Thus, rather than examining the variables \( P \) and \( O \), we analyze the variables \( PSU \) and \( SU \).

4.3. ASSESSING THE ACCURACY OF KNMI PREDICTIONS

Our assessment of the accuracy of the KNMI predictions is based on both the old and current operational models. Although the current model is much more accurate than its predecessor, both models tend to overpredict the observed surges in storms. The current operational model predicts set-up fairly well, reducing the RMSE in predicted water level from 85 cm (using only the astronomic tide tables) to 28 to 32 cm. (Recall that the self-prediction model described in Chap. 3 predicts this same set of high tides with an RMSE of 39 cm.)

Table 4.1 presents basic statistics for the data sets of the 0 to 3-hr predictions. In our notation, \( \bar{X} \) and \( \sigma_X \), respectively, denote the sample mean and sample standard deviation for a random variable \( X \). From the seventh row of this table, we see that the average difference \( SU - PSU \) between set-up (SU) and predicted

* The astronomical tide used in this analysis was as given; we did not correct for the residual tidal component described in Chap. 3.
Table 4.1

**BASIC STATISTICS FOR THE SVSD DATA**
(In centimeters)

<table>
<thead>
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<th>Parameters</th>
<th>Old Operational Model</th>
<th>Current Operational Model</th>
</tr>
</thead>
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<td>Hoek van Holland</td>
</tr>
<tr>
<td></td>
<td>Vlissingen</td>
<td>Hoek van Holland</td>
</tr>
<tr>
<td>Sample mean of set-up</td>
<td>SU (cm)</td>
<td>74.5</td>
</tr>
<tr>
<td>Sample standard deviation of set-up</td>
<td>(\hat{\sigma}_{SU}) (cm)</td>
<td>30.4</td>
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<tr>
<td>Sample mean of predicted set-up</td>
<td>PSU (cm)</td>
<td>91.7</td>
</tr>
<tr>
<td>Sample standard deviation of predicted set-up</td>
<td>(\hat{\sigma}_{PSU}) (cm)</td>
<td>30.5</td>
</tr>
<tr>
<td>Correlation coefficient between SU and PSU</td>
<td>(\hat{\rho}_{SU, PSU})</td>
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</tr>
<tr>
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<td>(\hat{\rho}_{S, SU, PSU})</td>
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</tr>
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<td>SU - PSU (cm)</td>
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<td>(\hat{\sigma}_{SU-PSU}) (cm)</td>
<td>28.2</td>
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<tr>
<td>Root mean square error</td>
<td>RMSE (cm)</td>
<td>33.0</td>
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</tbody>
</table>

set-up (PSU) is negative for both Vlissingen and Hoek van Holland and for both operational models. Under the old operational model, all the sample means differ from zero by a statistically significant amount, except for Hoek van Holland. Clearly, the operational models tend to overpredict surges caused by storms. (Informal conversations with H. Timmerman of the KNMI indicate that this might be due to a conservative "rounding up" of prediction model outputs by the duty forecaster at the KNMI.)

The estimated correlation coefficients \(\hat{\rho}_{SU, PSU}\) between SU and PSU in row five show that there is higher correlation between set-up and predicted set-up for the current model than for the previous model. Assuming that SU and PSU are jointly normally distributed, we used Fisher's z-transformation [4.1] to transform the estimated correlation coefficients into (approximately) normally distributed random variables. We found that the (positive) difference between the two transformed statistics for the current and old operational models is more than two standard deviations away from zero. Although SU and PSU are almost certainly not jointly normal (particularly in view of the fact that PSU is a "censored" variable, as described earlier), Fisher's z-transformation indicates that the correlation between SU and PSU for the current operational model is definitely higher than

---

5 Since \(SU - PSU\) is an estimate of the mean difference based on a sample of size \(n = 74\), its estimated standard deviation is \(S = 1/\sqrt{n} \hat{\sigma}_{SU-PSU}\), and its t-statistic is \(t = (SU - PSU)/S\). Under the old operational model, each of the computed t-statistics is much larger than 2.0, except for Hoek van Holland, whose value is 1.47. With this exception, therefore, all sample means are different from zero at the 5-percent significance level.
that for the old model. Row six presents the Spearman nonparametric rank-order correlation coefficient [4.1]. Similarity between these estimates and those for the parametric correlation coefficient (row five) confirms that the correlation between SU and PSU is higher with the current model. But the correlation without censoring might be considerably different from that developed here with censoring.

The last row of Table 4.1 presents the RMSE of prediction for the two operational models. The RMSE is a measure of the error in predicting SU by PSU. Its value is determined by the formula

\[
\text{RMSE} = \left[ \frac{1}{n} \sum_{i=1}^{n} (SU_i - PSU_i)^2 \right]^{\frac{1}{2}}.
\]

For the current operational model, the RMSE at Vlissingen is 28 cm and at Hoek van Holland, 32 cm. The values of RMSE are inflated over those of \( \hat{\sigma}_{SU-PSU} \) (the estimated standard deviation of the difference) largely because of the tendency of these models to overpredict surge.

4.4. IMPROVING THE PREDICTIONS

4.4.1. Approach and Summary of Results

To improve the prediction of set-up (SU) from the current operational model, we perform a regression analysis of SU (observed set-up) on PSU (predicted set-up). The assumed model is a simple linear model:

\[
SU = \alpha + \beta \text{ PSU} + \epsilon,
\]

where \( \epsilon \) represents "error" or "noise" in the system, and \( \alpha \) and \( \beta \) (intercept and slope, respectively) are parameters to be estimated from the data.

Our analysis shows that the model

\[
SU = 0.79 \text{ PSU} + \epsilon
\]

provides a good fit to the data for both Vlissingen and Hoek van Holland. Hence, if PSU = 100 cm, our best estimate is SU = 79 cm, and the larger the PSU, the greater the difference between PSU and the improved estimate SU = 0.79 PSU. The standard deviation \( \sigma_\epsilon \) of \( \epsilon \) is estimated to be \( \sigma_\epsilon = 22 \text{ cm} \) for both Vlissingen and Hoek van Holland, which represents some improvement over the RMSE values of 28 to 32 cm indicated in Table 4.1.

4.4.2. Analysis

If we were to plot a set of forecasts and observations (a forecast-observation plot, as shown in Figs. 4.1a and b) and if the forecasts were perfect, all pairs of points would lie on a 45-degree line (the "line of perfect forecasts"). If instead we obtained some other exact curve \( SU = f(PSU) \), we could define a second-stage forecast by
Fig. 4.1a—Predicted set-up versus observed set-up for Vlissingen
Fig. 4.1b—Predicted set-up versus observed set-up for Hoek van Holland
\[ \hat{PSU} = f(PSU) \]

and use \( \hat{PSU} \) as a "perfect forecast" of SU.

However, as we can see from Figs. 4.1a and b, the forecast-observation plot exhibits some randomness; it does reveal that the relationship between SU and PSU is fairly linear on average. Consequently, we use linear regression methods to obtain forecasts (linear as a function of PSU) that will yield more accurate predictions of set-up for the new operational model (see Ref. 4.2 for a further discussion of statistical forecast techniques). Thus, we are led to consider a linear regression model in which SU is regressed on PSU; that is, we consider Model A:

\[ SU_i = \alpha + \beta \cdot PSU_i + \epsilon_i, \quad 1 \leq i \leq n, \]  

(4.1)

where \( \epsilon \) represents noise. As is usual, we assume that the "noise" terms \( \epsilon_i \), \( 1 \leq i \leq n \), are uncorrelated random variables (not necessarily Gaussian) with common mean zero and common variance. Thus, we are tacitly assuming that

- The error in prediction of set-up is independent of the magnitude of set-up.
- Once the current operational model was put into use, no further changes were made in any of the model's parameters.
- Although in some cases three or four sequential data points may be observed on consecutive high tides during a single storm, the errors in predicting set-up for these consecutive high tides are not correlated.

Table 4.2 presents the estimates \( \hat{\alpha} \) and \( \hat{\beta} \) of \( \alpha \) and \( \beta \), respectively, and the standard error of the estimate \( \hat{\sigma}_\epsilon \), which is an estimate of the standard deviation \( \sigma \), of the error term \( \epsilon \). The numbers in parentheses are the standard errors of the regression coefficients.

Several interesting hypotheses are suggested by examining both Fig. 4.1 and the regression results of Table 4.2. The hypothesis of greatest interest is that for each location, the intercept is zero and the slope is one, that is,

\[ SU = PSU + \epsilon. \]

If this model is accepted, we may conclude that \( E(SU \mid PSU) = PSU \); that is, given PSU, PSU itself (and not some other linear function of PSU) is the best estimate of SU.

A formal test for each location that \( \alpha = 0.0 \) and \( \beta = 1.0 \) rejects this hypothesis at the 5-percent significance level.\(^6\) This result is illustrated graphically in Figs. 4.2a and b, which show the estimated regression line and the corresponding 95-percent Working-Hotelling confidence band on the regression line.\(^7\) (See Ref. 4.1.) We see that the 45-degree line (i.e., the hypothesis that \( \alpha = 0.0 \) and \( \beta = 1.0 \)) is not contained in the confidence bands.

The data in Table 4.2 are consistent with \( \alpha_H = \alpha_V = 0.0 \) and \( \beta_V = \beta_H \). (Here \( \alpha_H, \beta_H \) and \( \alpha_V, \beta_V \) are the regression parameters for Hoek van Holland and Vlissingen, respectively.) That is, both regression lines pass through the origin and are determined by the same slope parameter.

\(^6\) The computed F-statistic for Vlissingen (or Hoek van Holland) is 28.11 (or 38.37) with 2 and 74 - 2 = 72 degrees of freedom. These quantities are significant at the 0.1-percent level.

\(^7\) The Working-Hotelling confidence band is that for the whole regression line.
Fig. 4.2a—Regression line and confidence band for Vlissingen
Fig. 4.2b—Regression line and confidence band for Hoek van Holland
Table 4.2

Regression Estimates for the SVSD Data, Model A

<table>
<thead>
<tr>
<th></th>
<th>Vlissingen</th>
<th>Hoek van Holland</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\hat{\alpha}$</td>
<td>-8.47 (6.82)</td>
<td>-1.53 (6.97)</td>
</tr>
<tr>
<td>$\hat{\beta}$</td>
<td>0.894 (0.069)</td>
<td>0.800 (0.065)</td>
</tr>
<tr>
<td>$\hat{\sigma}_\varepsilon$</td>
<td>21.5$^a$</td>
<td>22.5$^a$</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.700$^b$</td>
<td>0.678$^b$</td>
</tr>
</tbody>
</table>

NOTE: The numbers in parentheses are the estimated standard deviations of the coefficient estimators.

$^a$ Estimated standard deviation.

$^b$ Coefficient of determination.

Some care must be exercised in testing this hypothesis, however, because there is a high correlation between set-up for the two locations (as well as a high correlation between the predictions for the two locations). This suggests that the hypothesis be tested within the framework of a "seemingly unrelated regressions" model,* that is, for Hoek van Holland and Vlissingen, respectively, we can write the model with an obvious notation:

$$SU_{iH} = \alpha_H + \beta_H PSU_{iH} + \varepsilon_{iH},$$

$$SU_{iv} = \alpha_V + \beta_V PSU_{iv} + \varepsilon_{iv}, \quad 1 \leq i \leq n,$$

where for each observation i, $(\varepsilon_{iH}, \varepsilon_{iv})$ has a variance-covariance matrix

$$
\Sigma = \begin{pmatrix}
\sigma^2_{\varepsilon_H} & \rho \sigma_{\varepsilon_H} \sigma_{\varepsilon_V} \\
\rho \sigma_{\varepsilon_H} \sigma_{\varepsilon_V} & \sigma^2_{\varepsilon_V}
\end{pmatrix},
$$

and where $(\varepsilon_{iH}, \varepsilon_{iv})$ and $(\varepsilon_{iH}, \varepsilon_{iv})$ are independent for i ≠ j.

This model differs from the ordinary least squares model and the multivariate regression model as follows:

1. $\varepsilon_{iH}$ and $\varepsilon_{iv}$ are assumed to be correlated (i.e., $\rho \neq 0$. The computed residuals from the two separate regressions of Model A yielded a correlation coefficient estimate of $\hat{\rho} = 0.76$, indicating that the error terms are indeed correlated).

2. The explanatory variables are different for the two locations.

The regression results for this "seemingly unrelated regressions" model are presented in Table 4.3. These estimates are only slightly different from those for

* For a more thorough discussion of this model, see Ref. 4.3.
the ordinary least squares case (Model A), because of the correlation among the residuals for the two locations.

The formal hypothesis test that \( \alpha_H = \alpha_V = 0.0 \) and \( \beta_H = \beta_V \) yielded an F-statistic of 1.80, with 3 and 144 degrees of freedom. Thus we may accept the null hypothesis that \( \alpha_V = \alpha_H = 0.0 \) and \( \beta_H = \beta_V \) at the 5-percent significance level. Hence for either Vlissingen or Hoek van Holland, we may write the regression model as Model B:

\[
SU = \beta \text{ PSU} + \epsilon . \quad \text{(Model B)}
\]

The joint estimate of \( \beta \) from the "seemingly unrelated regressions" model is \( \hat{\beta} = 0.79 \). The estimated standard deviation of this estimate is \( \hat{\sigma}_\beta = 0.023 \). A hypothesis test (based on Table 4.2) that the two (correlated) variances \( \sigma_{\epsilon_H}^2 \) and \( \sigma_{\epsilon_V}^2 \) are equal is accepted at the 5-percent level (see App. D). The common value of the estimated standard deviations is \( \sigma_{\epsilon_H} = \sigma_{\epsilon_V} = 22 \). Thus, the common model for Hoek van Holland and Vlissingen is given by

\[
SU = 0.79 \text{ PSU} + \epsilon , \quad \hat{\sigma}_\epsilon = 22 \text{ cm} . \quad (4.2)
\]

The standard error of the estimate for both Vlissingen and Hoek van Holland is only 22 cm, whereas as noted in Sec. 4.3 the forecast error in using PSU alone (the RMSE) is 28 cm for Vlissingen and 32 cm for Hoek van Holland. Thus, the regression analysis provides a 25-percent reduction in the forecast error. From Model B, given a value of PSU, for Vlissingen (and Hoek van Holland), the estimate of SU at Vlissingen (and Hoek van Holland) is

\[
\hat{SU} = 0.79 \text{ PSU} . \quad (4.3)
\]

### 4.5. FORECAST ERRORS FOR IMPROVED PREDICTIONS

This section briefly describes the derivation of prediction bands for Model B. If \( \hat{\beta}(\cdot) \) is the estimated regression function from Model B, the forecast error is \( E(SU - \hat{h}(\text{PSU}))^2 \), the mean square error.

Under Model B, the forecast error is

\[
\text{MSE}_B(\text{PSU}) = \text{PSU}^2 \text{ Var } \hat{\beta} + \sigma_\epsilon^2 . \quad (4.4)
\]
For each location, this is approximately equal to the more familiar expression (from Ref. 4.2):

\[
\text{MSE}_H(\text{PSU}) = \sigma_e^2 \left[ 1 + \frac{\text{PSU}^2}{\Sigma_i \text{PSU}_i^2} \right].
\] (4.5)

Figures 4.3a and b plot the regression line \( \text{SU} = \beta \text{PSU} \) with prediction bands \( \pm 2\text{MSE}_H(\text{PSU})^{\text{th}} \). Most of the data points are contained within the prediction bands.

### 4.6. POSSIBILITY OF IMPROVING PREDICTIONS BY USING LOCALLY OBSERVED SET-UP

The final question is whether we can add to our predictive capability by incorporating previously observed local set-up into the model. We use the data from the current operational model for Vlissingen. Specifically, let

- \( \text{HSU}_i \) = actual surge at high tide for \( i^{\text{th}} \) observation,
- \( \text{LSU}_i \) = observed set-up at previous low tide,
- \( \text{PSU}_i \) = KNMI prediction of HSU.

We then postulate the model:

\[
\text{HSU} = \alpha + \beta_1 \text{PSU} + \beta_2 \text{LSU} + \epsilon .
\] (4.6)

In this analysis we used the 3 to 6-hr predictions for PSU, rather than the 0 to 3-hr predictions. Because the difference between these two sets of predictions is small, it has little effect on the analysis.

Tables 4.4a and b present some basic statistics for the variables HSU, PSU, and LSU. The interesting feature of Table 4.4b is that the correlation between HSU and PSU is high but that between HSU and LSU is low. Table 4.5 presents the results of regressing HSU on PSU, results that are quite similar to those of Table 4.2; the 0 to 3-hr predictions perform only slightly better than the 3 to 6-hr predictions.

The results from the regression of HSU on PSU and LSU are given in Table 4.6. It is clear that the inclusion of the variable LSU in the regression model adds little to our predictive capability.

Consequently, it appears that the most reasonable second-stage prediction model (of the ones considered) for forecasting set-up from the KNMI predictions is

\[
\text{SU} = 0.79 \text{PSU} .
\] (4.7)

---

9 In fact, the two sets of predictions were the same, except for 22 pairs of predictions, and the members of each pair were similar to one another. Only in three cases did it happen that no 3 to 6-hr prediction occurred; we used the corresponding 0 to 3-hr prediction instead. Appendix E lists the data for the 0 to 3-hr predictions and the 3 to 6-hr predictions.

10 The 3 to 6-hr predictions were used to facilitate comparison of these results with those of Chap. 5. In addition, we wanted to use the set of predictions that were made at approximately the time of the preceding low tide.
Fig. 4.3a—Regression line and prediction band for Vlissingen, Model B
Fig. 4.3b—Regression line and prediction band for Hoek van Holland, Model B
Table 4.4a

Basic Statistics for HSU, PSU, and LSU

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSU</td>
<td>73.8</td>
<td>39.0</td>
</tr>
<tr>
<td>PSU</td>
<td>93.0</td>
<td>38.0</td>
</tr>
<tr>
<td>LSU</td>
<td>83.6</td>
<td>45.6</td>
</tr>
</tbody>
</table>

Table 4.4b

Correlation Matrix of HSU, PSU, and LSU

<table>
<thead>
<tr>
<th>Variable</th>
<th>HSU</th>
<th>PSU</th>
<th>LSU</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSU</td>
<td>1.0</td>
<td>0.813</td>
<td>0.411</td>
</tr>
<tr>
<td>PSU</td>
<td>1.0</td>
<td>1.0</td>
<td>0.489</td>
</tr>
<tr>
<td>LSU</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.5

Regression Estimates for 3 to 6-Hour Predictions

\[ \hat{\alpha} = -3.88 (7.08) \]
\[ \hat{\beta} = 0.835 (0.071) \]
\[ \hat{\sigma}_\varepsilon = 22.9 \]
\[ R^2 = 0.661 \]

NOTE: The numbers in parentheses are the estimated standard deviations of the coefficient estimators.

Table 4.6

Estimates for the Multiple Regression Model

\[ \hat{\alpha} = -5.30 (7.37) \]
\[ \hat{\beta}_1 = 0.807 (0.081) \]
\[ \hat{\beta}_2 = 0.049 (0.068) \]
\[ \hat{\sigma}_\varepsilon = 23.0 \]
\[ R^2 = 0.663 \]

NOTE: The numbers in parentheses are the estimated standard deviations of the coefficient estimators.
REFERENCES


Chapter 5

ANALYSIS OF KNMI DAILY PREDICTIONS

5.1. INTRODUCTION

Chapter 4 explored the relationship between set-up at high tide and the corresponding predicted set-up from the KNMI operational model under conditions where the predicted high water level data were severely censored. (In fact, predictions are not routinely made with the operational model under nonstorm conditions.) Thus, the analysis in Chap. 4 only covers the relationship of set-up to predicted set-up in the "tail" of the distribution of predicted set-up.

As discussed in Chap. 1, the KNMI does make routine, day-to-day forecasts of set-up with a newer "extended model II" computer program. Following our request to the KMNI for daily predictions for Vlissingen for an extended period of time during one winter, H. Timmerman provided us with information for November and December 1977. We wanted to briefly explore the relationship nearer the "center" of the distribution of predicted set-up. We also wanted to familiarize ourselves with the quality of the extended model as an indicator of what possibilities existed for improvement in prediction accuracy.

The next section presents a preliminary analysis of the relationship between the daily predicted and observed set-up. The following section describes regression models that relate set-up at high tide to the prediction of set-up and to previous values of set-up (at low and high tides). Finally, we compare the results with those obtained in Chap. 4.

5.2. PRELIMINARY ANALYSIS OF KNMI DAILY PREDICTIONS

KNMI daily predictions during November and December 1977 indicate that correlation between set-up at high tide and predicted set-up is 0.92, compared with 0.83 using the operational model under storm conditions, as discussed in Chap. 4. The data consist of observations on set-up (SU) and predicted set-up (PSU) at high and low tides for the two-month period. Both SU and PSU are treated as stationary time series.

Table 5.1a presents some basic statistics for SU and PSU. Table 5.1b gives similar statistics for set-up at high tide (HSU) and predicted high-tide set-up (HPSU) and set-up at low tide (LSU) and predicted low-tide set-up (LPSU). These statistics are based on the raw data for set-up, which has not been corrected for systematic differences in the tide, as discussed in Chap. 3. Using an analysis similar to that in Chap. 3, we found that the corrected high and low set-up, HSU* and LSU*, for these data are related to set-up at high tide and at low tide (HSU and LSU), respectively, by the equations

\[ \text{Here, and in the remainder of the chapter, only the tidal amplitude A was removed from the data and not the average value of the set-up.} \]
### Table 5.1a
**Basic Statistics for SU and PSU**  
(In centimeters)

<table>
<thead>
<tr>
<th></th>
<th>SU</th>
<th>PSU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample mean of set-up</td>
<td>16.3</td>
<td>15.3</td>
</tr>
<tr>
<td>Standard deviation of set-up</td>
<td>47.2</td>
<td>49.5</td>
</tr>
<tr>
<td>Sample mean of difference SU - PSU</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Standard deviation of difference SU - PSU</td>
<td>26.2</td>
<td></td>
</tr>
<tr>
<td>Correlation between set-up and predicted set-up</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td>Root mean square error RMSE</td>
<td>26.2</td>
<td></td>
</tr>
</tbody>
</table>

### Table 5.1b
**Basic Statistics for HSU, HPSU, LSU, and LPSU**  
(In centimeters)

**High-Tide Statistics**

<table>
<thead>
<tr>
<th></th>
<th>HSU</th>
<th>HPSU</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24.6</td>
<td>15.9</td>
</tr>
<tr>
<td></td>
<td>34.6</td>
<td>50.0</td>
</tr>
</tbody>
</table>

|        | HSU - HPSU | 8.8 |
|        | HSU - HPSU  | 22.9 |
|        | H        | 0.92 |
|        | RMSE_H    | 24.5 |

**Low-Tide Statistics**

<table>
<thead>
<tr>
<th></th>
<th>LSU</th>
<th>LPSU</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7.9</td>
<td>14.7</td>
</tr>
<tr>
<td></td>
<td>44.8</td>
<td>49.3</td>
</tr>
</tbody>
</table>

|        | LSU - LPSU | 6.8 |
|        | LSU - LPSU  | 26.4 |
|        | L        | 0.85 |
|        | RMSE_L    | 27.3 |
\[ \text{HSU}^* = \text{HSU} - 8.4, \]
\[ \text{LSU}^* = \text{LSU} + 8.4. \]

Thus,
\[ \text{HSU}^* - \text{HPSU} = 0.4 \text{ cm}, \]
\[ \text{LSU}^* - \text{LPSU} = 1.6 \text{ cm}. \]

This equation indicates that after correction for systematic differences in the tide, under day-to-day conditions the KNMI computer model does not tend to over- or underpredict set-up.

We next present the analysis of the data for the corrected high set-up (HSU*) and the predicted set-up (HPSU) only.

5.3. Regression Analysis of KNMI Daily Predictions

We developed two regression models and tested their accuracy as follows.

Using Model A of Chap. 4, we performed a regression analysis relating HSU to HPSU with the model

\[ \text{HSU}^* = \alpha + \beta \text{ HPSU} + \epsilon, \]

where HSU* = HSU - 8.4 is set-up at high tide, corrected for the diurnal tidal component. The results are shown in Table 5.2a. It may be of interest to compare these results with those in Table 4.2, but it should be remembered that we are treating two entirely different data sets. Perhaps the most meaningful comparison is in the fractional reduction of uncertainty of water level. In Chap. 4, we found that the operational model, regression corrected, reduced the RMSE in water level from 85 to 22 cm, a reduction to about one-quarter. Here we see that the extended model reduces an RMSE of 50 to 14 cm, a comparable fractional reduction.

We also see that the residuals are mildly correlated. Table 5.2b presents the estimated autocorrelation coefficients of the residuals for lags one through four. The presence of correlation in the residuals has several effects on the analysis. For example, the model may look better, or worse, than it actually is.

There are a number of methods available for approaching the problem of correlated errors. One cause of error correlation is the omission of important variables from the specified model. Having found in Chap. 3 that set-up is well fit by an autoregressive model of order 6, we augmented the regression model (Eq. 5.2) by including three lags each on HSU* and LSU* as explanatory variables, in addition to the current prediction HPSU*. The resulting regression equation may be expressed as

\[ \text{HSU}^*_s = \alpha + \gamma \text{ HPSU}_s + \sum_{i=1}^{3} \beta_i \text{HSU}^*_{s-2i} + \sum_{i=1}^{3} \lambda_i \text{LSU}^*_{s-2i+1}, \]

where the time index s indicates an observation only at high tide. The regression results are presented in Table 5.3. Among the several interesting features in this table, the most important is that \( R^2 \) is larger than that of Table 5.2a, and the
Table 5.2a

**REGRESSION ANALYSIS (Eq. 5.2)**

Estimated standard deviation = 1.3881D 01
R² = 0.8406

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Est. Std. Dev.</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6.1452D 00</td>
<td>1.3415D 00</td>
<td>4.5809</td>
</tr>
<tr>
<td>1</td>
<td>6.3522D-01</td>
<td>2.5687D-02</td>
<td>24.7290</td>
</tr>
</tbody>
</table>

Table 5.2b

**ESTIMATED AUTOCORRELATION COEFFICIENTS OF RESIDUALS**

- ρ(1) = 0.193
- ρ(2) = 0.041
- ρ(3) = 0.139
- ρ(4) = 0.236

Table 5.3

**REGRESSION ESTIMATES FOR MODEL (Eq. 5.3)**

Estimated standard deviation = 1.1115D 01
R² = 0.8946

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Est. Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.2579D-00</td>
<td>1.2173D-00</td>
</tr>
<tr>
<td>1</td>
<td>3.8568D-01</td>
<td>4.7263D-02</td>
</tr>
<tr>
<td>2</td>
<td>3.5338D-02</td>
<td>8.7263D-02</td>
</tr>
<tr>
<td>3</td>
<td>1.6489D-01</td>
<td>9.4579D-02</td>
</tr>
<tr>
<td>4</td>
<td>5.8351D-02</td>
<td>5.9170D-02</td>
</tr>
<tr>
<td>5</td>
<td>3.5718D-01</td>
<td>5.7422D-02</td>
</tr>
<tr>
<td>6</td>
<td>-1.0392D-01</td>
<td>6.4888D-02</td>
</tr>
<tr>
<td>7</td>
<td>-1.2151D-01</td>
<td>6.0211D-02</td>
</tr>
</tbody>
</table>
estimated standard deviation is smaller. Moreover, the autocorrelation of the residuals was decreased, and a formal test rejected the hypothesis that all $\beta$s and $\lambda$s are simultaneously zero.

Thus, all indications are that the model (Eq. 5.3) yields a somewhat better representation of the data than the simple linear regression model (Eq. 5.2). It appears that there is considerably more value in incorporating previously observed set-up into the regression model than was found in Chap. 4 (under storm conditions).

5.4. CONCLUDING COMMENTS

Our analysis indicates that the complex extended model has a performance comparable to that of the simple operational model. Although the issue certainly warrants further study and exploration, it does not currently appear that major improvements in storm-surge prediction accuracy will be forthcoming in the next decade. This implies that the feasible operational strategies for the storm-surge barrier will have to be within the constraint bounds of water level prediction capabilities that exist today: In our analysis of alternative strategies in the Summary Report, we were fully aware of these bounds, as discussed further there.
Appendix A

THE STORM-SURGE BARRIER: A BRIEF DESCRIPTION

The storm-surge barrier will be built along a curving trajectory across the mouth of the Oosterschelde from Schouwen on the north to Noord Beveland on the south (see Fig. A.1). The total distance along the trajectory is approximately 9 km. But the barrier itself, to be built in three sections across three gaps, will be about 2.8 km in length. The southern section across the Roompot Gap is 1440 m long and connects Noord Beveland with the southern work island. (The pillars for the barrier will be constructed on this work island.) The middle section across the Schaar van Roggenplaat Gap is 720 m in length and connects the two work islands. The northern section across the Hammen Gap is 675 m in length and connects the northern work island with Schouwen. There is bottom protection extending out on both sides of the barrier 650 m on each side in the Hammen and Roompot sections and 550 m in the Schaar section.

The current barrier design calls for 66 pillars with 63 openings between them, to be closed off by gates, with 32 gates in the Roompot section, 16 in the Schaar section, and 15 in the Hammen section (see Fig. A.2). Each opening is 40 m long.

Fig. A.1—The storm-surge barrier across the mouth of the Oosterschelde
Fig. A.2—The three sections of the storm surge barrier
The upper level is at NAP + 1 m, and the lower level varies between 4.5 and 10.5 m below NAP. Thus, the gates that close off the openings vary in height from 5.5 m for the shallowest to 11.5 m for the deepest. In the BARCON study, we have assumed a nominal effective aperture of 15,000 sq m when the barrier is fully open.

Figure A.3 shows a cutaway perspective of the barrier at the deepest gate. The massive reinforced concrete pillars, some 50 by 25 m at their base, with heights up to 45 m, rise to 15 m above NAP. The pillars are set on a prepared bottom, and a sill is constructed between and around them. Upper and lower concrete beams are placed between the pillars. The steel gates move vertically in a slot in the pillars. The current design calls for the gates to be moved by massive hydraulic cylinders, although an alternative all-mechanical design is under consideration. There will also be a road over the barrier some 12 m above NAP.
Fig. A.3—Cutaway perspective of barrier at deepest gate
Appendix B

PREDICTION OF STORM SURGES 24 TO 48 HOURS BEFORE THEIR OCCURRENCE

by R. R. Rapp

B.1. INTRODUCTION

The KNMI operational and computer models described in the body of this report depend on accurate pressure and wind data over the North Sea. This appendix first describes an attempt to use 48-hr prognostic charts as a source of wind data with the operational model and then discusses its shortcomings. Next we present a less precise approach that does not provide quantitative information but uses the same skills as in predicting the gross features of the prognostic chart to estimate the probability of significant surges 24 to 48 hr in advance of their occurrence.

B.2. SIMPLE APPLICATION OF THE OPERATIONAL MODEL

As described in Chap. 1, the operational model consists of tables that are used to predict the set-up with estimated surface winds over six areas, five in the North Sea and one over the English Channel. In practice, the winds are estimated by an elegant method developed by Bijvoet [B.1]. We did not have the facilities to use this method and relied instead on a simple geostrophic wind scale—with a correction for surface friction effects—to estimate the wind over each of the areas. The data available were fifteen 48-hr prognostic charts for midnight, together with charts constructed from observed data at these same times—one prognostic and one observed chart from November 16, 1971, to December 2, 1971, with the prognostics from November 22 and 29 missing.

We used the measured winds from both the prognostic and the observed charts with the operational model's tables to predict the set-up at Vlissingen at about six hours after the time of the map. (The tables actually are designed to use wind data from three charts spaced at three-hour intervals. We made the tacit assumption that the wind would not change appreciably from three hours before to three hours after the values read from the charts.) Figure B.1 shows the relation between the two calculations of the resultant set-up with the prognostic results on the abscissa and the observed results on the ordinate. The correlation between prognostic and observed is 0.66, but the regression shows that the prognostic charts overforecast on the average by a factor of two. If $T$ is the computation from the observed chart and $F$ is the computation from the 48-hr prognostic chart, $T$ can be estimated from $F$ by

$$\hat{T} = 0.001 + 0.46F$$

with a standard error of estimate of 1.54 dm. If the above calculations were based on a large sample, they could be used to estimate the accuracy of a 48-hr prediction.
However, with only 15 cases containing no really large computed values of set-up, we can have but little confidence in these results.

There were three significant surges during the first seven days of this period, but in only one case did the forecast time (0000) coincide with the time of peak set-up. Figure B.2 shows the values of set-up for the high and low tides from November 16 through November 22. Also shown are the set-ups as calculated from the prognostic and observed charts. Only the calculations for the first low tide on November 19 came close to being near a peak, and neither the 6- nor the 54-hr forecast accurately predicted this event. Part of the difficulty may be in the method we used to evaluate the wind.
B.3. A GROSS APPROACH

A comparison of the prognostic and observed charts indicates that the prognostic charts fail to forecast many of the small details of the pressure pattern that can significantly affect the calculations. If, for purposes of providing advance warning of potential surges, the concept of detailed computation of set-up is abandoned, a scheme may be devised based only on the broad features of the prognostic charts.

To investigate the patterns of major storm surges, we plotted the wind directions and speed that gave the maximum contribution to set-up for the six areas of the operational model. From this scant information, we constructed an “ideal” storm-surge weather chart, Fig. B.3, which places a deep low in southern Norway and a strong high pressure near Ireland. To determine how closely this pattern matches historical data, we consulted the U.S. Northern Hemisphere Charts for the tracks of low pressure areas before the peak of large observed set-ups at

\[\text{The scale of these historical weather charts is much too small to measure winds.}\]
Vlissingen. Figure B.4 shows the locations of the low and high centers six hours before the peak set-up for 11 cases where set-up exceeded 10 dm. Table B.1 gives the dates and times for these 11 cases. Also shown in Fig. B.4 and Table B.1 are data for the large surge of the February 1, 1953, storm.

The locations of the major highs and lows are, of course, insufficient to completely define the surge situation. Because the details of the 48-hr prognostic charts are not sufficiently accurate for detailed wind computations, some method should be found to use them to forecast even grossly the possibility of surge conditions.

On the premise that a significant low pressure system must be in the hatched area of Fig. B.4 and that the high pressure system in the Atlantic is well enough developed to produce a strong pressure gradient from a northwesterly direction across the North Sea, it may be possible to use the observed and prognostic charts
Fig. B.4—Low and high positions approximately 6 hours before the peak surge

to determine when a surge is likely to develop. A simple examination of the possible chart change between an observed map and the 48-hr prognostic map permits us to construct a sample of the type of qualitative forecasts that might have been made between November 14 and 22, 1971. Table B.2 is the sequence of forecasts that might have been issued. This chronology was based on interpolation of weather systems movement between the observed and prognostic maps. Lacking a forecast chart for November 22, we based the forecast for the 20th on a simple extrapolation of the large low in the central Atlantic. The interpolation between the observed map on the 21st and the prognostic map for the 23d clearly indicated the development of a classic strong surge beginning near midnight on the 21st. The remainder of the sample contained no combination of observed and prognostic maps suggesting any significant positive set-up.
Table B.1

**OBSERVED SURGE SITUATIONS**

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Table B.2

**SEQUENCE OF FORECASTS**

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<th>Date of Forecast (issued at 0000)</th>
<th>General Outlook for Vlissingen</th>
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<td>Nov. 14, 1971</td>
<td>Set-up declining; no significant set-up on November 15</td>
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<td>Nov. 15, 1971</td>
<td>Significant set-up near midday on the 16th, continuing past midnight</td>
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<td>Nov. 16, 1971</td>
<td>Significant set-up near midnight tonight, continuing into the morning of the 18th</td>
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<td>Nov. 17, 1971</td>
<td>Continued moderate set-up through today and tomorrow</td>
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<td>Nov. 18, 1971</td>
<td>Moderate set-up this morning, with another surge on the 19th</td>
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<td>Nov. 19, 1971</td>
<td>Moderate set-up late today or early tomorrow, decreasing during the day tomorrow</td>
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<tr>
<td>Nov. 20, 1971</td>
<td>No significant set-up expected today or early tomorrow (Note: we had no 48-hr. prognosis for November 22)</td>
</tr>
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<td>Nov. 21, 1971</td>
<td>No significant set-up until late tonight or early tomorrow when a strong surge may be expected</td>
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<tr>
<td>Nov. 22, 1971</td>
<td>The current high set-up should diminish during the day; no significant set-up is expected tomorrow</td>
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</table>
B.4. CONCLUSIONS

Although the prognostic maps that were available for study contain useful information, they are not suitable for the direct application of the operational model for two reasons. First is the lack of detail in the charts. With few exceptions, the prognostic charts capture the large-scale features of the developing weather patterns, but the prediction of pressure gradients across the North Sea was not sufficiently accurate. Second, and perhaps more important, the strict application of the model provides only a single time prediction 54 hr after the forecast time. We believe a more general prediction of the conditions conducive to surge conditions during a 24 to 48-hr period would be more helpful for barrier management.

These conclusions are based on a very small sample of 48-hr prognostic charts prepared in 1971. Since then, the numerical methods for constructing prognostic charts have greatly improved. These advances may modify our objections in two ways: First, more frequent prognostics can be produced; and second, more detail can be captured. There will, of course, always be errors in prognostic charts, and the errors in delineating the pressure field will always add to the inherent errors of this or any other model.

Another approach to predicting surges 24 to 48 hr in advance might be along the lines of the U.S. National Weather Service method called Model Output Statistics (MOS). The MOS method correlates rain, cloudiness, wind, and temperature at weather stations, with values of pressure and temperature predicted by a numerical model at fixed grid points. With a large sample of weather charts and the accompanying values of set-up, statistical relations of pressure at points with accompanying set-up could provide a method of predicting set-up 24 to 48 hr before its occurrence.

REFERENCE

Appendix C
SET-UP IN THE OOSTERSCHELDE

To derive an understanding of dynamic and steady-state set-up in the Oosterschelde, a series of IMPLIC runs were made in the Netherlands with the barrier fully closed, no leakage, and basin water level at NAP and stagnant. Constant wind speeds of 25, 50, and 75 kn were applied along the direction of the axis of the Oosterschelde, and the water level versus time was recorded at a number of locations along the basin.

Figure C.1 shows the final steady-state set-up for each of the winds at a number of locations along the axis of the Oosterschelde and separately in the northern branch. As would be expected, a nearly quadratic relationship to wind speed is observed to hold; that is, set-up is approximately proportional to the square of the wind velocity. (As a reference, the estimated wind conditions for a 1/4000-year storm situation are 60 kn exceeded for 6 hr.)

The steady-state set-up near Wemeldinge is always near zero. This is consistent with our comment in Vol. IV that the observed water level at Wemeldinge is a good surrogate measure for the mean basin IWL. As demonstrated here, this includes the effects of set-up.

Figure C.2 shows the transient water levels before the steady-state conditions are established at the same locations along the Oosterschelde. Lightly damped oscillations occur with periods of 3 to 4 hr. Steady-state conditions are established some 7 hr after the initial steady-state wind is applied as a step input. Again, deviations from the mean basin IWL (NAP in this case) are minimal at Wemeldinge.

86
Fig. C.1—Steady-state set-up for different wind speeds along the axis of the Oosterschelde
Fig. C.2—Transient set-up for different wind speeds (step input) at various locations in the Oosterschelde
Appendix D

COMPARISON TEST OF TWO CORRELATED VARIABLES

In this appendix we describe the test that two correlated estimates of variance, $s_1^2$ and $s_2^2$, are each estimates of the same unknown population variance $\sigma^2$. Assume the random variables $X_1$ and $X_2$ have variances $\sigma_1^2$ and $\sigma_2^2$ and correlation $\rho$. (In our model of Chap. 4, $X_1$ and $X_2$ are the error terms $\epsilon_u$ and $\epsilon_v$, respectively.) We wish to test whether $\sigma_1 = \sigma_2$.

As described in Ref. D.1, the test statistic is

$$r^* = \frac{F - 1}{[(F + 1)^2 - 4r^2F]^{1/2}}$$

where $F = s_1^2 / s_2^2$ and $r$ is the sample correlation between $X_1$ and $X_2$. A significantly positive value of $r^*$ indicates that $\sigma_1^2 > \sigma_2^2$, whereas a significantly negative value indicates that $\sigma_1^2 < \sigma_2^2$.

REFERENCE

Appendix E

LIST OF 0 TO 3-HOUR PREDICTIONS AND 3 TO 6-HOUR PREDICTIONS FROM SVSD DATA SET

PSU0 denotes the 0 to 3-hour predictions,
PSU3 denotes the 3 to 6-hour predictions

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