

Real-time forecasting of morphological storm impacts: a case study in the Netherlands

F. Baart[†] and T. van der Kaaij[‡] and M. van Ormondt[‡] and A. van Dongeren[‡] and M. van Koningsveld^{†∞} and J. A. Roelvink^{‡§}

[†]Department of Hydraulic Engineering
Delft University of Technology, Delft
PO Box 5048, 2600GA, The Netherlands
f.baart@tudelft.nl

[‡] Marine and Coastal systems
Deltares, Delft
PO Box 177, 2600MH, The Netherlands

[∞]Van Oord
PO Box 8574
3009 AN Rotterdam
The Netherlands

[§] Department of
Water Engineering
UNESCO-IHE, Delft
PO Box 3015,
2601DA, The
Netherlands



ABSTRACT

F. Baart and T. van der Kaaij and M. van Ormondt and A. van Dongeren and M. van Koningsveld and J. A. Roelvink, 2009. Real-time forecasting of morphological storm impacts: a case study in the Netherlands, Journal of Coastal Research, SI 56 (Proceedings of the 10th International Coastal Symposium), 1617 – 1621. Lisbon, Portugal, ISSN 0749-0258.

Recent events like the Sumatra tsunami and Hurricane Katrina have reminded the world of the vulnerability of coastal areas to extreme events. Despite hydraulic engineering measures to minimize failure probability of coastal defence structures, a probability of failure, albeit small, remains. To assist local authorities and the population in their response to extreme events, timely access to relevant information of sufficient accuracy regarding impending natural threats is crucial. Current real-time systems do not include all relevant physics (e.g. morphodynamic response). This paper describes the efforts in the framework of the MICORE project to develop such an improved real-time system for the prediction of storm impacts. This paper addresses the proposed system architecture and some preliminary results. Also the paper addresses some aspects of the development environment that may be of more general interest than to this project alone.

ADDITIONAL INDEX WORDS: *Coastal, Windstorm, Erosion, Prediction, Operational, MICORE*

INTRODUCTION

The years 2004 and 2005 were characterised by a number of large coastal disasters around the world (i.e. the Sumatra tsunami in December 2004 and Hurricane Katrina in the US in August 2005). These powerful natural events have raised awareness that the coastal areas are vulnerable to natural disasters. The near miss of New Orleans by hurricane Gustav in August-September 2008, only three years after hurricane Katrina, made it clear that although extreme events by definition have a low probability of occurrence this does not mean that they could not in fact happen a number of times within a short period of time.

The exposure of Europe to comparable extreme events was demonstrated by European windstorm Kyrill which hit in January 2007. It was a mild winter in most of Europe when Kyrill caused severe loss of human lives, great property loss and infrastructure damage. Kyrill was a medium strength storm, which made landfall on the German and Dutch coasts on the afternoon of January 18th, affecting 8 countries causing the loss of 47 human lives and many small properties. The storm losses greatly affected insurance companies. The estimated damage in Germany alone was € 4.7 billion (ALOVISI, et al 2007).

Worldwide, numerous approaches have been developed to deal with extreme events. A concept outlining extreme event-related policies, that is widely applied in the Netherlands and useful for this paper, is the “safety chain” (RIKSWATERSTAAT 2005). The

safety chain distinguishes the following separate phases, viz.:

- pro-action and prevention,
- preparation,
- response and mitigation
- relief.

The phases of “pro-action and prevention, and preparation” can be characterised as strategic phases. They are strategic in the sense that a analysis of economically viable risk levels and policy approaches usually precedes them and resulting measures commonly take several years if not decades to implement. Common foci of measures implemented are related to hydraulic engineering works (i.e. dikes, dunes, sluices, barriers etc.) and reducing their failure probability, as well as reducing impacts in case of occurring disastrous events (e.g. spatial planning, zoning, set-back lines, etc.).

However, most engineering works are constrained by economics making the resulting policies a compromise between the potential threat to lives and property and the resources available for design and construction. Furthermore, the design of structures is based on predicted extreme events which themselves are subject to uncertainty, especially in a changing global climate. As a result a zero risk policy is not obtainable.

The phases of “response and mitigation, and relief” can be characterised as operational phases (even though many things can be planned beforehand). Operational in the sense that generally the lead time to these activities is very short (days to hours rather than

the pre-mentioned years to decades). Important decisions (e.g. allocation of levee patrol and emergency response, evacuation orders etc.) have to be made under high pressure, usually based on limited information only.

The strategic phases have traditionally received a great deal of attention. The more operational phases have received increased attention in more recent times. The EU FP7 Project MICORE analysed current storm response approaches in 9 European countries and concluded that amongst others, the study sites could be improved by implementing operational, quasi real-time, coastal risk assessment methods. Only two European countries have operational systems available predicting storm surge levels (FERREIRA, et al 2008). No real-time systems taking into account morphodynamics are available. It is the main objective of MICORE to develop such a system. It is the main objective of this paper to describe the architecture of the system proposed.

METHOD

For developing a real-time model system that predicts the morphological impacts of storms, it is important to first contemplate the potential end users of such a system and their envisaged information need. MICORE has considered the main end users of a real-time system to be local authorities that are responsible for emergency response and last-minute mitigation in case of an upcoming extreme event. In order to support their efforts they need:

1. timely access to
2. relevant information
3. of sufficient accuracy and precision

Relevant information in this case regards expected coastal hazards such as overtopping, overwashing, beach and dune erosion, dune breach and localised flooding. With this information responsible authorities may better allocate their scarce resources, e.g. allocating levee and dike patrol, selecting locations for emergency repairs, indicating safe areas for residents to evacuate to, etc.

Currently real-time information on water levels is available in the Netherlands. This information is taken as a trigger to take emergency response action. However, in most if not all cases water levels alone are not enough to predict events like overtopping, overwashing, beach and dune erosion, dune breach and localised flooding at the desired level of detail. Merely adding waves to the equation is not enough. Especially during extreme storm events the morphodynamic response of the coastal system can be significant. Depending on this response the influence of water levels and waves in turn may also be affected significantly. Adding the morphodynamic response to the model system is therefore of crucial importance to reproduce the relevant system behaviour.

Besides including the relevant physics in the model system and producing the proper output, the aggregation of model output data into information relevant for end users is of great importance. Examples of such aggregated results could be maps indicating not only areas of erosion and sedimentation but also separating areas of moderate erosion from those with severe erosion. Which parameters to choose is not a trivial matter, i.e. allocating emergency repair capacity the areas of erosion rates are of interest while indicating safest areas for evacuation whereas one might look at areas of no erosion. Timeliness of information is essential given the limited time available for (organising and executing) response activities. This has consequences on the available model runtime, bringing up the issue of weighing accuracy versus being on time.

Real-time storm impact: architecture

The above considerations have led to the following general design of a real-time model system for morphological storm impact forecasting involving a train of models of increased resolution.

First of all a large scale model ($O(1000 \times 1000 \text{ km})$) is needed to transform astronomical tides in combination with predicted wind and pressure fields into predicted current, water levels and waves. This model may be part of the model train, however, in some cases such models are already run by other organisations and tapping into these results using them as boundary conditions may be considered. Next a regional model ($O(100 \times 100 \text{ km})$) is needed to transfer the overall current, water levels and wave patterns towards the coastal region of interest. An additional refinement in the near shore area ($O(10 \times 10 \text{ km})$) is generally needed to generate input of sufficient spatial resolution to properly drive the local model ($O(1 \times 1 \text{ km})$) that resolves the detailed hydro- and morphodynamic processes that are of interest for decision makers dealing with response to extreme events. Depending on the modelled area the number of models needed may increase or decrease.

To generate real-time information the tailored model train is triggered by a task manager (in the Dutch case written in Matlab®) that starts the daily data collection, pre-processing, the model engines, the post-processing and publishes results to the web server.

Generally speaking the set-up of a system for real-time forecasting of morphological storm impacts involves the following steps:

4. *Model setup.* Beforehand model setup and establishment of input parameters.
5. *Data collection.* Scripts reading basic data (wind data, pressure data, bathymetric data etc.) from one or more data sources (e.g. using plain text files or OpenDAP protocol).
6. *Pre-processing.* Scripts converting the downloaded basic data to the proper input formats for the model engines.
7. *Running model engines.* Running the numerical implementations of the physical processes using the prepared input to generate predictions.
8. *Post-processing.* Scripts processing and aggregating the raw model output generating charts with information at the proper level of aggregation.
9. *Publishing.* Post-processed modeling results are published automatically to a webserver.

To illustrate the practical implementation of the steps described above their concrete implementation for a Dutch case is discussed.

Model setup

In the Dutch case developed for the MICORE project four model schematisations of increasing resolution are used to describe the hydrodynamic, wave and morphologic processes: 3 Delft3D models and 1 XBeach model. The schematisations are shown in Figure 1.

The three coarsest schematisations cover the North Sea, the Dutch coast and the Dutch coast near Egmond and are based on the Dutch Continental Shelf Model (GEBRAAD & PHILIPPART 1998). Domain decomposition is used to connect the hydrodynamic processes whereas nesting is used to connect the wave processes. The schematisation with the highest resolution, covering the Egmond beach area, is used to describe the morphological processes.

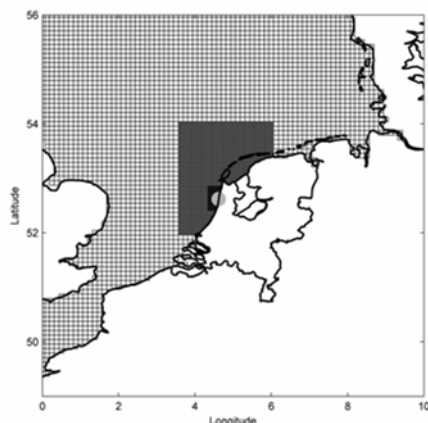


Figure 1: Schematisation of the operational model

Data collection

The following datasets are used for the operational morphologic predictions.

1. The online windfield predictions from the HIRLAM project. The High Resolution Limited Area Model, is a Numerical Weather Prediction (NWP) forecast system developed by the international HIRLAM programme. The latest predicted wind speed and wind direction are used.
2. The online water level predictions from the Multifunctional Access Tool foR Operational Ocean data Services (MATROOS). The MATROOS system is used to extract daily waterlevels.
3. The network of directional wave buoys of Rijkswaterstaat. The network of directional wave buoys is used to compare predicted to observed wave heights.
4. The annual transects of the JARKUS dataset (RIJKSWATERSTAAT, 2008). Annual coast measurements from Rijkswaterstaat. This dataset has a goal to evaluate annual changes in the coastline. The dataset covers both topography and bathymetry of the nearshore area. The latest bathymetry and topography is used from this dataset.

Pre-processing

The wind fields and water level predictions use the same schematisation for the coarsest grids and can be used directly as input for the combined wave/flow model run. The wave spectra and significant wave heights are used as boundary conditions.

For the three coarser schematisations the bathymetry of the Dutch Continental Shelf Model is used as a fixed bathymetry while the Egmond beach area uses the measurements from the JARKUS data. The predicted bathymetry is not used as input for the next prediction but the bathymetry is reset to the JARKUS observations at each run. Using an updated bathymetry of known precision will be an improvement.

Model engine

The hydrodynamics, waves and morphological processes were simulated with different model engines. The hydrodynamic and the wave models ran online (output exchanged bidirectional). The morphologic model was coupled offline (output exchanged unidirectional).

1. Hydrodynamic processes were simulated using the Delft3D-FLOW software (3.27) (STELLING, 1984).
2. Wave processes were simulated using the SWAN software (4051AB) (BOUW, *et al.*, 1999).
3. The morphodynamic processes were simulated using XBeach (ROELVINK, *et al.*, 2007). XBeach is a two-dimensional model which is used for sediment transport and morphological changes of the nearshore area, beaches and dunes.

The most relevant output variables for storm events, viz. water levels, significant wave height and bathymetry are saved with a 10 minutes interval.

Post-processing

In this step of the process normally the physical model results would be aggregated to present proper information for decision-makers. Information one could think of are: sedimentation erosion maps, inundation maps, maps pointing out suitable and non-suitable spots for emergency evacuation etc. However, as the MICORE project only started in July 2008 the main efforts so far focussed on getting the system up and running. For that reason post-processing activities so far have been limited to creating simple maps of bathymetry changes and water levels over time.

Publishing

Results of the runs were published to an internal wiki server using SOAP messages to the web application server (in the Dutch case a Confluence® wiki system). Version management was used to store old versions of the output.

Research Approach

Since the early 1990's a significant number of European funded coastal research projects have been granted, amongst others G6-M, G8-M, NOURTEC, SAFE, PACE, SASME, SEDMOC, Coast3D, CoastView and MICORE. For a more elaborate overview cf. (VAN KONINGSVELD, *et al.*, 2003). This ongoing line of research has greatly enhanced our knowledge on the modelling of coastal hydrodynamic and morphodynamic processes. Also these consecutive programs have provided effective training for researchers. Young researchers that were first educated in the early MAST programs are today's program managers.

To enhance the potential for training and growth the MICORE project pays attention to knowledge management regarding some of the most basic tools and ingredients that are common to all of these coastal projects:

1. *Data* - Measurement data are stored and made available during the course of coastal research projects. Relevant existing public domain datasets are also made available. ;
2. *Models* - Systems are put in place for establishing continuity and growth in model development trajectories by storing and disseminating model source codes and schematisations and putting them under version control; and
3. *Tools* - Systems are made available for establishing continuity and growth in tools and methods to analyse and aggregate measured as well as modelled data to generate information for end users.

The systems used for this management of basic information and tools are part of the OpenEarth-initiative. This initiative's main aim is to promote the transfer of knowledge throughout the coastal community in general and across project boundaries in particular. The benefits of the latter materialize amongst others in the long-term maintenance of a database with basic data relevant for coastal problems and a gradual (project-by-project) improvement and

quality increase of basic tools and models. Some benefits expected from adopting the OpenEarth approaches relate to cooperation, reproducibility, replaceability, automation, openness.

Cooperative

The OpenEarth initiative has a number of basic software tools in place to promote cooperation. Raw data, tools, model source code and schematisations are stored and put under version control in subversion repositories. These repositories are approachable via internet and allow researchers world-wide to share data, models and tools and cooperate efficiently in improving these.

Reproducible

Thanks to version control the reproducibility of changes in source code and schematisations is enhanced. For example, tailored scripts (generated in Matlab, Python, Perl, or whatever is common at each project partner) to reformat raw data into files in standardised formats. In these scripts all relevant meta-information is added. If new standards for meta-information are proposed, only the scripts have to be adapted to reformat the raw data according to the new standards.

Replaceable

The real-time system is set up in such a way that components of the system can be easily replaced. New bathymetric data that is entered into the database can trigger updates to the model bathymetry used. Also, in the context of the MICORE project regular improvements may be expected to the open source modelling package XBeach. Using subversion for keeping track of versions, it will be relatively straightforward to replace that part of the real-time model train.

Automated

Reproducing forecasts with changing data, models and tools is prone to errors or subjective decisions. Keeping track of the whole process, fully automating all changes from initial datasets to results, is a guarantee for reproducibility. Using a scripting language is a good way to automate processes like this. Automating also allows for errors to be corrected by simply rerunning the scripts which were used to create results.

Open

To allow for freedom to reuse, adapt, inspect and replace components, open source and open standards are used as much as possible. By publishing source code and keeping track of history, quality and accountability is improved.

RESULTS

A primary objective was to make an operational system for preparing timely predictions of morphological impacts. Using results from existing models, a scripting environment and an easy-to-use wiki system, we were able to setup a prototype of a coastal warning system which predicts the morphological impacts for the next 2 days.

Real-time storm impact: the Dutch case

Timely access

Forecasts of coastal erosion in the Dutch coast at Egmond have been produced since July 2008. Each 6 hours, new measurements become available. The current model runs within 12 hours. This

means that 50% of the input information is currently used to generate predictions. The forecasts were available over 92% of the time. When the forecasts were not available this was due to failing software caused by missing input. The uploading of results to the website worked, but it polluted the change log which is also used to mark popular content and allows to monitor usage and amount of contributions.

Relevant information

Currently the model only outputs the relevant physical data, i.e. water levels, wave heights and morphological change. Effort still needs to be invested in aggregating this information into state indicators that are useful for decision-makers.

Sufficient accuracy

By limiting the calculation time which is required for timely predictions, a balance is needed between model accuracy and speed. This requires to limit the number of processes taken into account and the detail of the schematisation used. Because we are limiting the accuracy of the model, it is important to present the results with known information about the precision and accuracy of the predictions.

The predicted water levels show a strong correlation with the observed water levels. The observed significant wave height as yet only shows a weak correlation with computed significant wave heights. No comparison has yet been made between expected and observed bathymetry. This will be done at a later stage in this project.

Research Approach

Using the described research approach it becomes easier to adapt existing modelling solutions to different sites. The Dutch case can for example be extended to the Belgian case by replacing the near shore schematisations thus making both the Dutch and Belgian case part of one overall model. To improve the cooperation between researchers sprint sessions are used, work sessions where people work together on models and software. These sprint sessions originate from the agile software development technique.

Also courses are organised to educate people in working with the different components. Courses were given on working with netcdf/cf, opendap, XBeach, subversion. Using this open approach over 25 different people of 5 institutes working on this approach have made well over 2000 unique contributions.

Using version management to keep track of changes of all steps of data processing from initial raw files to transformation scripts to model schematisations it is possible to reproduce how the final results are created. The versioning is split up for raw data together with processing scripts, tools and models. This setup allows to backtrack results to the original input. For example one should be able to trace back which bathymetric data is combined to form the ultimate model bathymetry. Although it seems trivial that a clear link between model bathymetry and source data should be established in practice this is often not the case.

Now that the model train is in place it should be possible to plug in improved versions of one or more of the components. E.g. the XBeach models are under constant development and upgraded versions can be added when available. Likewise updated bathymetric information will become available. This information should also be easily put into the system.

Manually keeping track of which components are combined with what is a lot of work. To ease this task scripting languages are used to perform all the steps from input to results.

Currently the MICORE project has adopted for the storage of data, model schematisations and pre- and post-processing tools the OpenEarth environment.

CONCLUSIONS AND FURTHER DEVELOPMENTS

This paper presented a system for predicting real-time morphological impacts of storms applied to the Dutch coast. The goal was to make the system which makes timely, accurate, precise and relevant predictions. This system is presented in combination with a research approach which aims for creating cooperative, reproducible, replaceable, automated and open tools, models and data

Real-time storm impact

The timely supply of information will be made possible by using parallel versions of XBeach and other model engines. This will also require attention in using parallel i/o for storing results and communicating between models.

To make sure the results are precise it is useful to look at using resampling and other techniques for creating confidence intervals around the predicted values. The addition of the prediction intervals can give users insight into the predictive power of the system.

To predict the extreme events which threaten the coast more precisely, we can optimise the number of parameters used for prediction and increase the number of observations. Sensitivity analysis can be used to fine tune the input parameters. By leaving out input parameters and examining the effect, insight can be gained in the individual or joined effect of parameters.

By increasing the number of observations the likelihood of observing extreme events can be increased. The number of observations can be increased looking back into observations from the past or by increasing the number of sites where measurements are done.

Although the results of the hydrodynamic model and the wave model were validated the most important aspect of the system, the morphological model, is not yet compared to measurements. For validation purposes, the Argus (HOLMAN & STANLEY, 2007) system at Egmond together with the application of BeachWizard (VAN DONGEREN *et al.*, 2008) will be used to compare the predictions to actual measurements.

To predict extreme events it is likely that other processes are involved than the coastal processes of every day. Therefore, it makes sense to work on and make use of the XBeach model which is specialised for these purposes. Using the BeachWizard for validation purposes we hope to get more insight in the accuracy of applying the XBeach engine in both storm and non-storm conditions.

When the results will prove to be valid and accurate and precise enough, the system can be extended beyond the beaches of Egmond to bigger parts of the Dutch Coast. Discussions with end users should lead to limiting the amount of aggregated information produced by the system to decision making.

Research approach

Applying the same research approach in different case studies in the MICORE project should further improve this method and improve its usefulness. Although the processes of data, models

and tools are kept with version and log information a lot of variation which prevents reproducible results comes from subjective decisions which are not always easily captured in automated form. Therefore experts working on the setup of systems like this should always keep track of the decisions they make during the process.

To make the components even more replaceable a more service-based approach could be used to connect the different components. Also the application of the system on different sites and the continuous use of the system will show it's robustness against change. The automation can be increased by using a more advanced logging and task scheduling environment. Source code is made publicly available. Further developments will become available on OpenEarthTools.

LITERATURE CITED

- ALOVISI, J.; SOUCH, C., and TOOTHILL, J. (2007). Windstorm Kyrril: A glimpse into the future? *Catastrophe risk management*.
- BOOIJ, N.; RIS, R.C., and HOLTHUIJSEN, L.H. (1999). A third-generation wave model for coastal regions 1. model description and validation. *Journal Of Geophysical Research*, 104(C4), p. 17.
- FERREIRA, O.; CIAVOLA, P., and ARMAROLI, C. (2008). Report on risk definition for each study site. Technical report, Micore. Project 202798 p. 177.
- GEBRAAD, A. and PHILIPPART, M. (1998). The Dutch Continental Shelf Model, dcm98: calibration using altimeter data. Werkdocument RIKZ/OS- 98.121x, RIKZ. (In Dutch)
- HOLMAN, R.A. and STANLEY, J. (2007). The history and technical capabilities of Argus. *Coastal Engineering*, 54(6-7), pp. 477–491.
- RIJKSWATERSTAAT (2005). Risicobeheersing in kustplaatsen. Document Basisinformatie RIKZ/2005.022, Rijkswaterstaat. (in Dutch).
- RIJKSWATERSTAAT (2008). De jaarlijkse kustmetingen (JARKUS). <http://www.watermarkt.nl/kustenzeebodem/>.
- ROELVINK, J.A.; RENIERS, A.; VAN DONGEREN, A.; VAN THIEL DE VRIES, J.; LESCINSKI, J., and MCCALL, R. (2008). Modeling storm impacts on beaches, dunes and barrier islands. *Proceedings of the ICCE 2008*, (Hamburg, Germany) in press.
- STELLING, G. (1984). *On the construction of computational methods for shallow water flowproblems*, volume 35 of *Rijkswaterstaat communications*. The Hague: Rijkswaterstaat.
- VAN DONGEREN, A.; PLANT, N.; COHEN, A.; ROELVINK, J.A.; HALLER, M.C., and CATALÁN, P. (2008). Beach wizard: Nearshore bathymetry estimation through assimilation of model computations and remote observations. *Coastal Engineering*, 55(12), pp. 1016–1027.
- VAN KONINGSVELD, M.; STIVE, M.; MULDER, J.; DE VRIEND, H.; DUNSBURG, D., and RUESSINK, B. (2003). Usefulness and effectiveness of coastal research. a matter of perception? *Journal of Coastal Research*, 19(2), pp. 441–461.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the [European Community's] Seventh Framework Programme ([FP7/2007-2013]) under grant agreement number [202798].