THE APPLICATION OF A COUPLED WIND, WATER LEVEL AND WAVE MODEL IN A WARNING SYSTEM AGAINST FLOODING

E.J. Claessens, J.P. de Waal, H.C. van Twuiver and M. Bottema

Directorate-General of Public Works and Watermanegement,
Institute for Inland Water Management and Waste Water Treatment (RIZA)
Lelystad, The Netherlands

1 INTRODUCTION

The IJsselmeer and Markermeer (henceforth the IJsselmeer area) are two large shallow lakes ('meer' is Dutch for lake) in the Netherlands. The IJsselmeer area measures roughly 13-30 km in South-West North-East direction and 50 km in North-West South-East direction (see also figure 1).
The bottom of the lakes is fairly flat with a water depth between 4 and 5 meters. There is no open connection between the sea and the IJsselmeer area. This means, that the water level and waves are not influenced by incoming tides and swell. Fast water level variations and wave growth in the IJsselmeer area are mainly governed by the wind speed and direction. The wave growth depends not only on the wind, but also on the water level since wave growth is depth-limited. Both water level and waves are sensitive for changes in the wind. From our measurements it can be concluded that the water level in Den Oever responds within one and a half hour to a changing wind, whereas the water level in Ramspol responds within 2 hours. The waves at measurement location FL9 respond almost instantaneously to a wind change.

The Warning service Dikes IJsselmeer area (WDIJ) warns the dike responsibles of the dikes around the IJsselmeer area when a risk of flooding due to storm is expected to occur. The warning system of the WDIJ is a responsibility of the 'Hydrodynamics and safety against flooding' division of Rijkswaterstaat-RIZA. Our current warning system is based on a database. This database contains water level and waves on the IJsselmeer and Markermeer pertaining to the decisive moments within a strongly schematized storm. The current warning system operates well under most circumstances. The system fails however in case of sudden changes in wind speed or direction, not resembling the schematized storm. The reason for this is the impossibility to incorporate instationarity and spatial variability of a storm in our warning system. To be able to use the warning system under all circumstances, we want to use the following new techniques:

- Non-stationary calculations of storms with a hydraulic model, which computes the water levels and currents and a wave model. The calculations are performed continuously. Both models can incorporate changes in wind speed and direction with help of a forecasted wind in time and space. The water level and waves are also calculated using the existing wind setup instead of using the mean water level at the begin of the storm.
- KNMI is currently working on the downscaling of their high resolution weather prediction model XHIRLAM (Kallen, 1996). XHIRLAM has a resolution of 11 km x 11 km. The downscaling (www.knmi.nl/samenw/hydra/documents/geograph/index.html) interpolates the wind fields physically within this resolution to a grid of 500 m x 500 m. These wind fields will be used as an input for the water level and wave model.

This paper investigates the possibility of using online calculations with the wave model SWAN (Booij *et al.*, 1999) coupled with the water level model WAQUA (Stelling, 1984) and the downscaling of XHIRLAM. First, we will discuss the current warning system and the wind-water interaction in the IJsselmeer area. After explaining the application of the models in the warning system, the conclusions and an outlook to the future will be given.

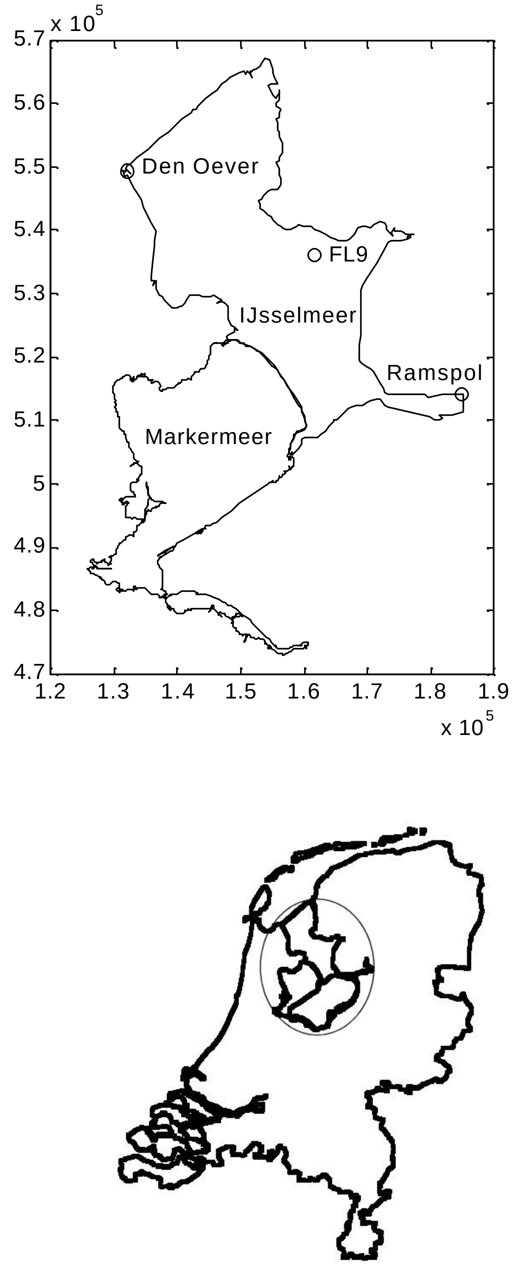

Figure 1 The IJsselmeer area.

2 THE CURRENT WARNING SYSTEM AND THE PHYSICS OF THE WATER SYSTEM

The current warning system of the WDIJ is based on a database. This database is filled with water levels, waves and the levels of hydraulic loads on the dike (this is the sum of the water level and the wave run up). This data is calculated for 1944 standardized storms (a combination of 12 different wind directions, 18 maximum wind speeds and 9 mean lake levels) at approximately 250 dike locations. An example of the wind speed during a standard storm is given in figure 2.

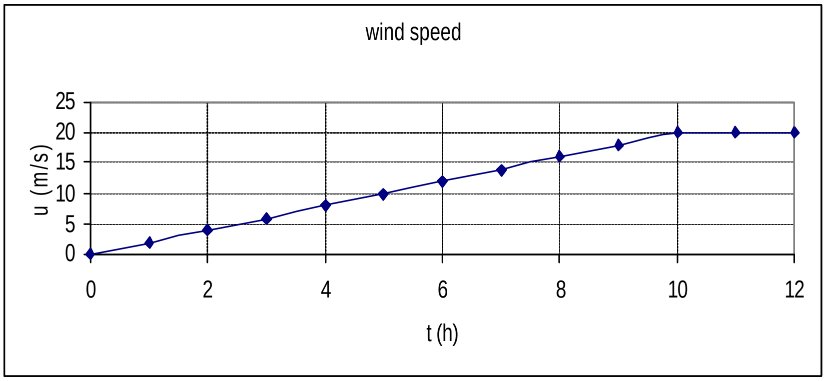

Figure 2 Example of the wind speed during one of the storms on which the database is based.

The forecasted wind speed, wind direction (in sectors of 30º) and the mean lake level are input of the warning system. The warning system searches the relating water levels, waves and the levels of hydraulic loads on all dikes in the database. A warning is produced when the levels of hydraulic loads exceed the level of warning for a certain dike.

The present system is fast and robust to apply. However, the disadvantage of using a database is the impossibility to incorporate the instationarity and spatial variability of a storm when the characteristics are expected to differ from the standardized storms. This is illustrated for a storm on May 28th 2000. This is a storm for which the wind direction changed dramatically.

Figure 3 shows the measured wind and the water levels in the IJsselmeer area for the storm of May 28th 2000. The wind starts veering from South-East to West at 14:00. The south-eastern wind up to 14:00 resulted in a wind setup in Den Oever of 0.17 m. The water level in Ramspol was -0.30 m at that moment. The south-eastern wind resulted in a wind setdown in Ramspol.

At 16:00 is the wind direction West, this is the situation for which the forecast was made. The warning system calculates the water levels and waves, assuming a mean lake level of -0.13 m for all locations at the start of the storm.

The water level at the eastern part of the IJsselmeer area (Ramspol) was overestimated at the end of the storm. The forecasted water level in Ramspol was 0.91 m, whereas the measured water level 0.20 m was. The reason for this is the wind setdown in Ramspol at 14:00. The warning system did not account for this wind setdown. The opposite was true for the western part of the IJsselmeer area (Den Oever). The warning system underestimated the water level at the end of the storm for Den Oever. The forecasted water level in Den Oever was -1 m, while the measured water level was -0.7 m. This is a result of neglecting the wind setup at 14:00.

The water level in Ramspol reacts within 2 hours to the changing wind direction. The western wind at the end of the storm results here in a wind setup. In Den Oever is the response of the water level faster. The western wind results within one and a half hour in a wind setdown.

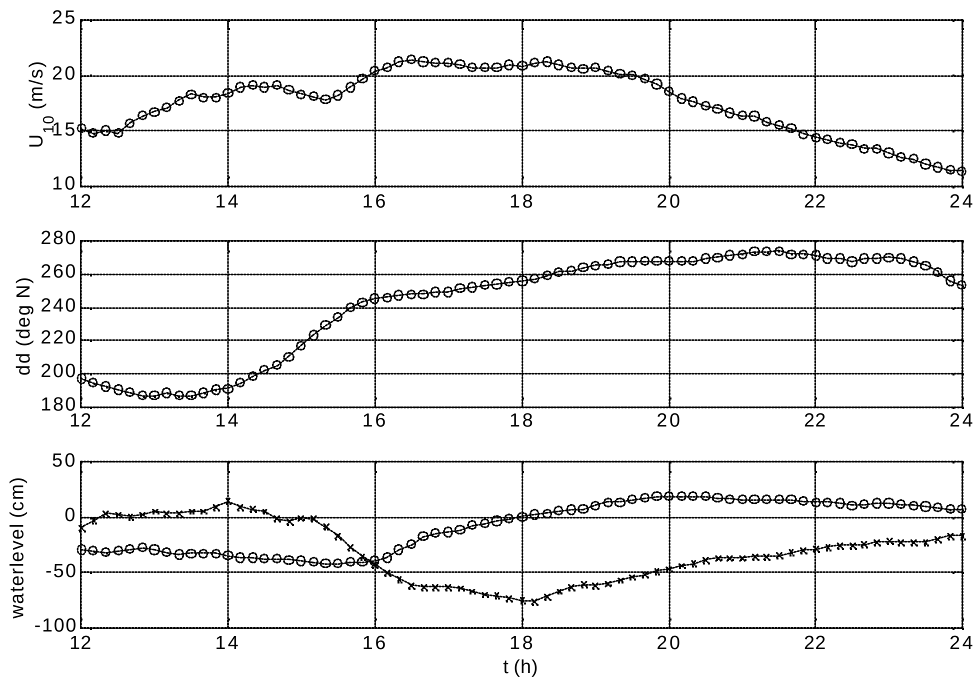

Figure 3 The wind speed and direction and the water level for theIJsselmeer area at May 28th 2000. The water level at Ramspol is given with circles, whereas the water level at Den Oever is given with the straight line.

The significant wave height at FL9 during the storm of 28 May 2000 is given in figure 4. From this figure it can be concluded, that the waves do not respond to the veering wind. The start of the storm is more interesting to show the physics of the storm. At 10:00 increases the wind speed. The waves respond almost instantaneously to this increasing wind.

The water level and the waves are indeed sensitive to a changing wind. The current warning system operates under most conditions well, giving us the opportunity to produce a fast and robust warning. Problems arise however in case of a changing wind.
Using the existing wind setup (in this case for Den Oever) or wind setdown (Ramspol) at the start of the storm can improve the forecast. Continuous calculations of the water levels and the waves make use of time series of computed water levels and waves. The instationarity of storms can be incorporated in this way. This is not only valid for changes in wind direction, but also for sharp changes in wind speed.
It is expected, that the forecasts improve already largely when the water levels are estimated more precisely, since a more precise forecast of the water level is also important for the waves. The wave growth is namely depth-limited.

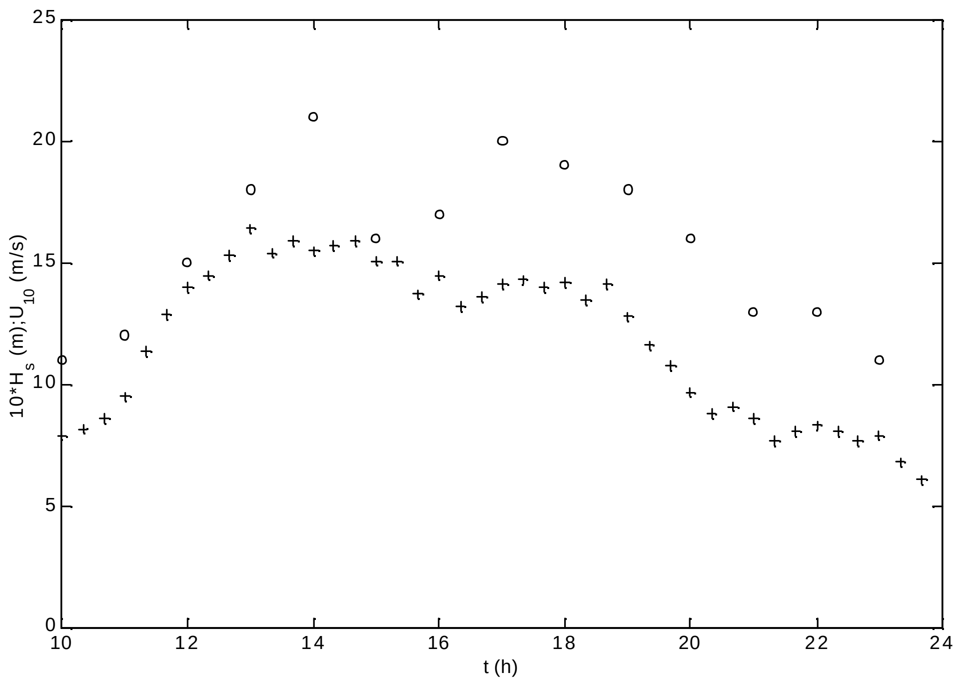

Figure 4 The wind speed (o) and the significant wave height (+) at FL9 for 28 May 2000.

The wind fields from the downscaling will be used as wind input for the continuous calculation of the water levels and waves. These wind fields are used instead of assuming a constant wind speed and direction over the whole IJsselmeer area. The wind fields from the downscaling give us the ability of incorporating the spatial and temporal variability of the wind in our forecasts. The application of the spatial variable wind fields and the hydrodynamic and wave model in the warning system of the WDIJ will be discussed in the next section.

3 APPLICATION OF THE MODELS IN THE WARNING SYSTEM OF THE WDIJ

First the principles of the downscaling of XHIRLAM will be explained in this section. The coupling of the models will be discussed secondly. The last section investigates whether the wave model can be used in the warning system of the WDIJ.

3.1 <u>The principles of downscaling</u>

The downscaling method is based on the two layer model of Wieringa (1986). This model is illustrated in figure 4.

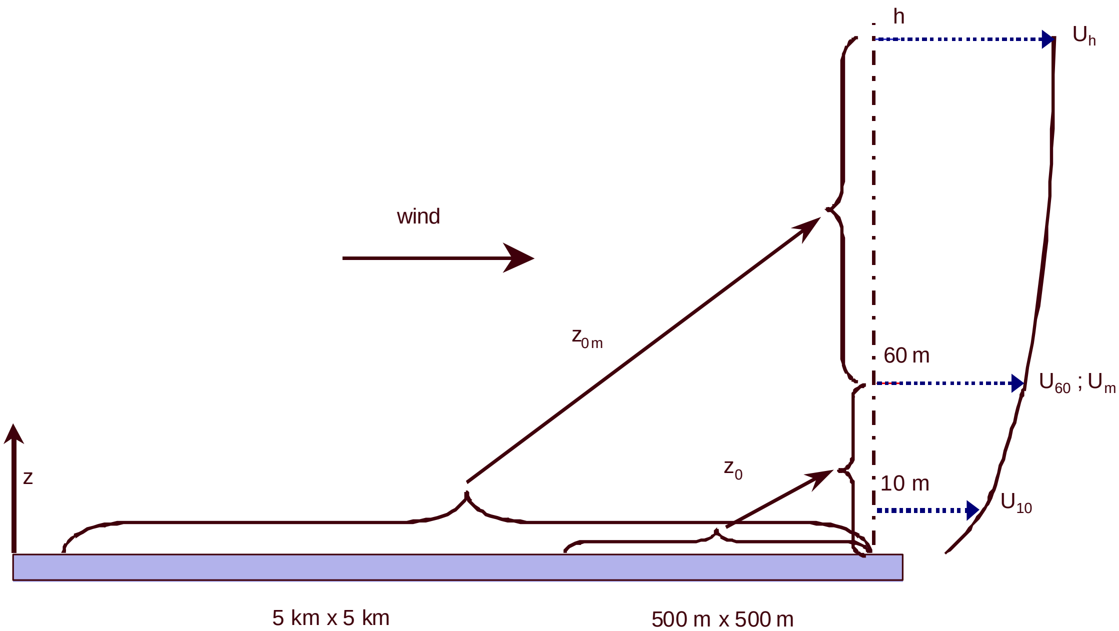

Figure 4 The two-layer model of Wieringa (1986). In this figure is z the height in m, h the boundary layer height in m, z_{0m} the roughness length in m at mesoscale, z_0 the roughness length in m, u_{10} the wind speed in m/s, u_{60}/u_m the mesowind in m/s and u_h the macrowind in m/s.

The two-layer model of Wieringa (1986) divides the boundary layer into two layers:

- The surface layer (0-60 m); the wind in this layer is influenced by the local roughness of the earth's surface.
- The Ekman layer (60 m - boundary layer height); the wind in this layer is influenced by the roughness which is representative for an area of 5 km x 5 km (mesoscale). The wind at 60 m is called the mesowind.

The wind above the boundary layer is called the macrowind. The macrowind is calculated by the high resolution weather prediction model XHIRLAM at a grid of 11 km x 11 km. The macrowind is not influenced by the roughness of the earth surface. This wind is in the downscaling therefore bilinearly interpolated to a grid of 500 m x 500 m. The mesowind is then determined by the roughness length at mesoscale, applying the geostrophic drag relations (Stull, 1988; Garratt, 1992; Kaimal and Finnigan,1994). Whereas the wind at 10 m (this wind is used as input for WAQUA and SWAN) can be calculated from the local roughness length, using the logarithmic wind profile (Tennekes, 1973):

$$u(z) = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right) \tag{1}$$

Wherein:

$u(z)$ the wind speed at height z in m/s;
u_* the friction velocity in m/s;
? the von Kármán constant 0.4;
z the height in m;
z_0 the local roughness length in m.

The logarithmic wind profile is valid for a neutral atmosphere in which turbulence is mainly caused by friction. This assumption is correct in case of high wind speeds and a clouded sky. We can use this method, since we are mainly interested in storms. The atmosphere above large water surfaces under storm conditions is usually neutral.

The difference in the spatial variability which is depicted by XHIRLAM and the downscaling method is given in figures 5 and 6. Figure 5 shows the wind over the IJsselmeer area as predicted for May the 28th 2000 15:00 with XHIRLAM on a 11km x 11km grid. The wind over the IJsselmeer area as predicted with the downscaling method is given in figure 6.
At 15:00 the wind over the IJsselmeer area veers to South-West. The wind speed and the fetch of the wind in the eastern part of the IJsselmeer near Ramspol (see also figure 1) are larger for the prediction done with the downscaling method. The long fetch and the high wind speed in Ramspol result in the wind setup shown in figure 3 (section 2).

The spatial variability of the wind is much better resolved with the downscaling method. This is especially the case at locations near the coasts of the IJsselmeer area, e.g. for the south-eastern part (Ramspol) of the IJsselmeer area.

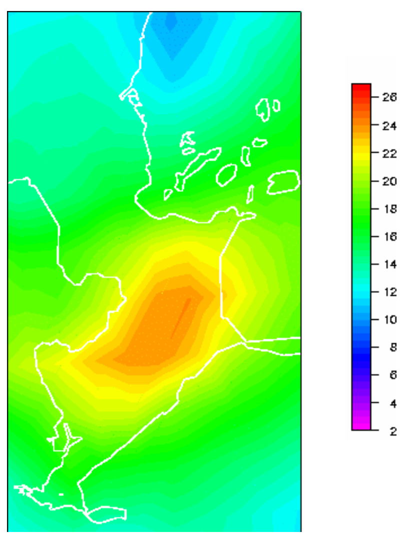

Figure 5 Wind speed in m/s over the IJsselmeer area as predicted by XHIRLAM for a storm on May 28th 2000 15:00. (Courtesy A.B.C. Tijm, http://www.knmi.nl/~tijm/).

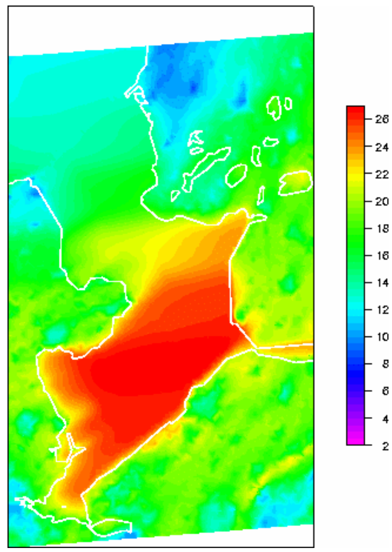

Figure 6 As for figure 5, but now predicted by the downscaling method. (Courtesy A.B.C. Tijm, http://www.knmi.nl/~tijm/).

3.2 Coupling the models

In section two it was concluded that the water level and the waves react sensitively to the wind. The forecast of the water levels is expected to improve when the downscaling method is used in the warning system of the WDIJ. The general idea is to couple the models and to use the wind fields from the downscaling method for the calculation of the water levels and the waves.
The models will make continuous online calculations to investigate the hydraulic situation in the IJsselmeer area. The warning system will produce a warning, when a risk of flooding is expected to occur. This is illustrated in figure 7.

The wind model (XHIRLAM combined with the downscaling method) will calculate the wind speed and direction at 10 m height at a 500 m x 500 m grid. This output, combined with the lake level will be used as input for the water level model (WAQUA) and the wave model (SWAN). Besides the wind input, SWAN will also use the water levels and possibly the currents as calculated by WAQUA, to calculate the wave characteristics. The forecasted hydraulic conditions will be used by the warning system to check whether the hydraulic loads on the dikes exceed the warning level of a certain dike.

This system is not yet operational. The first step to make the system operational is to couple XHIRLAM and WAQUA. At this moment, the first tests of this coupling are made. These tests give us the reason to be optimistic over coupling the downscaling method to WAQUA. WAQUA is quick and robust. The computational time on a SUN SOLARIS 8 4/01 work station with one processor for a simulation of 11 hours on a 196 x 114 grid size for the IJsselmeer, with a time step of 1 minute is 2 minutes (134 CPU).
As was concluded in the previous section, a more precise forecast for the water level means already a large improvement of the warning system. The possibility of using SWAN in the future warning system will be evaluated in the next section.

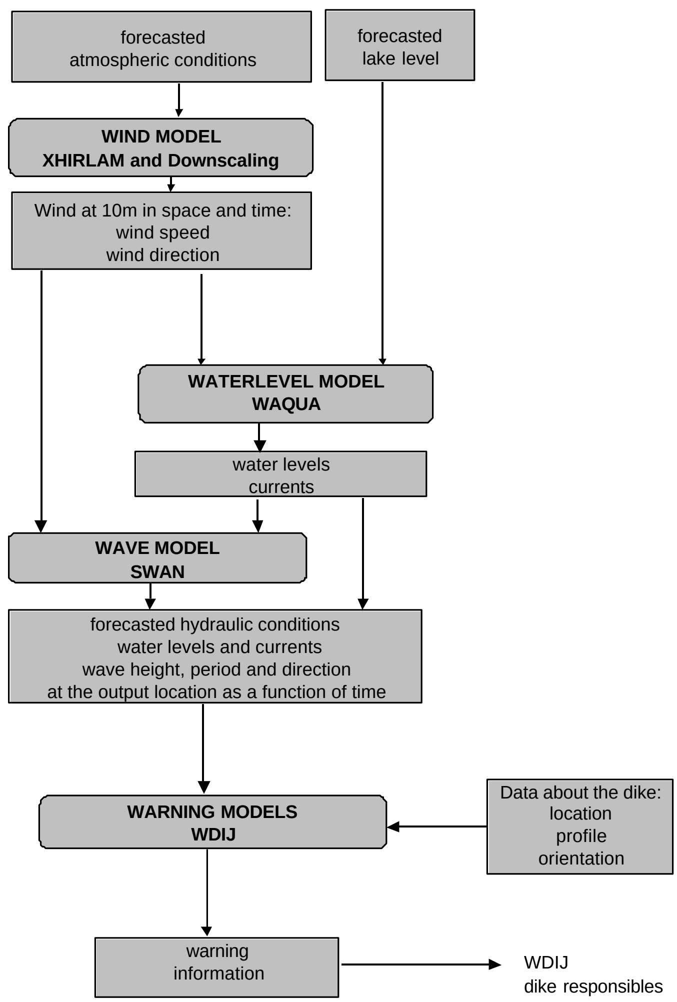

Figure 7 Coupling the models. Models are given in curved boxes, whereas information is given in rectangles.

3.3 The use of the non-stationary version of SWAN in the warning system

The dike responsibles wish to be warned at least six hours in advance. Not only the physical performance of SWAN is hence important, but also the computational performance. The stationary mode of SWAN is validated for the IJsselmeer area (see Bottema and Beyer, 2001). From this validation it was concluded that the stationary mode of SWAN predicts the waves quite well.

The non-stationary mode of SWAN needs to be tested against the following criteria:

- The computational performance.
- The wave response of the model on the wind. In section 2 it was concluded from measurements in the IJsselmeer area that the waves respond within 1-2 hours to a changing wind.
- A comparison of model results with measurements.

To validate the model on the first two criteria a front passage was simulated. The wind ahead of the front was South-West 8 m/s. The prevailing wind after the front was North with a wind speed of 18 m/s. Calculations were done for 72 hours. The front passes the output location after 36 hours. The numerical settings of the calculations which were done for SWAN version 40.16[1] are listed in table 1.

Table 1 The numerical settings of the SWAN runs. The resolution of the computational grid is 320 m x 320 m. The reference run is done with the default numerical settings. The PC on which the computations were performed was a 733 MHz PC with 1 GByte internal memory.

Run	maximum iterations	limiter constant[2]	time step	computational time
reference	1	0.1	20 minutes	19.43 hours
a	4	0.1	20 minutes	44.67 hours
b	1	0.1	5 minutes	37.28 hours
c	1	0.2	20 minutes	19.03 hours
d	4	0.2	20 minutes	35.72 hours
e	1	0.2	20 minutes	35.77 hours
f	4	0.2	5 minutes	139.8 hours

Experience from our wind and wave measurements tells that the waves respond almost instantaneously to a suddenly increasing wind speed. The results of the calculations done with SWAN are shown in figure 8. From this figure it can be concluded, that SWAN with the default numerical settings responds too slowly on the front passage (the waves respond within five hours to the suddenly increasing wind). Run d and f give the closest estimate of the wave response according to our wind and wave measurements. It is however difficult to make a good distinction between the physical and the numerical effects. The wave response to the wind, as calculated by SWAN, can still be faster if the maximum number of iterations increases or if the time step of the computation decreases.
Unfortunately, it can be concluded from table 1, that it is currently not feasable to use SWAN in the warning system (the average computational time in table 1 being 1.5 hour per hour storm duration). Having made this conclusion it is of no use to validate the non-stationary mode with help of wave measurements from the IJsselmeer area.

[1] This version has changed numerical limiter settings, but in other respects it is identical to the official SWAN 40.11 release. This numerical limiter in SWAN prevents large changes in energy density per iteration (see also Ris, 1997; page 36). This limiter in SWAN 40.16 is always active and the non-linear wave interactions (triads and quadruplets) can exist at the same moment (which is not true for the official version of SWAN).
[2] The maximum change in energy density per iteration is allowed to be 10%, if the limiter constant is 0.1.

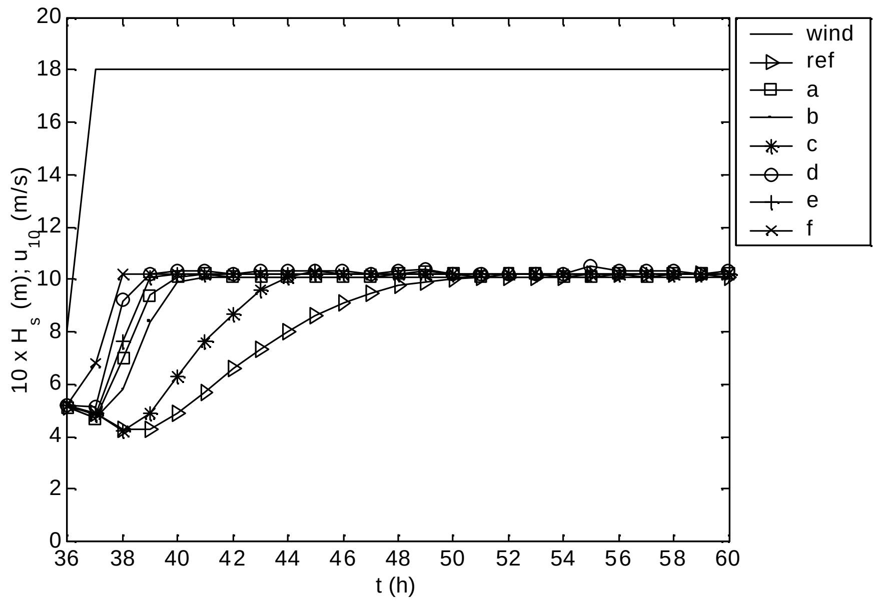

Figure 8 The significant wave height as calculated by SWAN, using the different numerical settings specified in table 1. The straight line represents the wind input.

4 CONCLUSIONS AND RECOMMENDATIONS

The dike responsibles of the dikes around the IJsselmeer area are warned when the hydraulic loads of the water level and waves exceed the warning level of the dike. The current warning system of the warning service operates fast and robust under most circumstances. It fails however in cases of sharp changing wind speed or direction, when the structure of the wind field does not meet the structure of the schematized storms. This paper investigates the use of two new techniques to be able to produce a robust forecast of water level and waves under all circumstances.

The first technique is the downscaling of the wind fields of the high resolution weather prediction model XHIRLAM to a grid of 500 m x 500 m. It was concluded that the downscaling method resolves the spatial variability better than XHIRLAM, especially near the coasts of the IJsselmeer area.

The wind fields from the downscaling method will be used in continuous computations of the water level with WAQUA and the waves with SWAN. This is the second technique.
Our expectations are that using the wind fields from the downscaling method in the hydrodynamic model WAQUA will not give to many difficulties. A more precise forecast of the water level is the first important improvement of the warning system.

Unfortuntately, it is currently not feasable to use the downscaling method in combination with the non-stationary mode of SWAN in our warning system. The average computational time of SWAN is 1.5 hour per hour storm

duration. It is important to warn the dike responsibles long enough in advance (at least six hours). This makes the long computational time indesirable.
Furthermore it is unclear whether the adaptation of the waves to the wind is caused by the numerical or the physical effects in SWAN. Both problems need further research. In the meantime, improvements in the forecasts of the water levels in the IJsselmeer area will be made.

REFERENCES

Booij, N., R.C. Ris and L.H. Holthuijsen, 1999: A third-generation wave model for coastal regions, Part I, Model description and validation. J. Geophys. Res. 104, C4, P 7649-7666.

Bottema, M. and D. Beyer, 2001: Evaluation of the SWAN wave model for the Dutch IJsselmeer area. 4th Int. Symp. on Ocean Wave Measurement and Analysis. San Francisco, Calif. Vol. 2, p. 580-589.

Garratt, J.R., 1992: The atmospheric boundary layer. Cambridge University Press. Cambridge.

Holthuijsen, L.H., N. Booij, T.H.C. Herbers, 1989: A prediction model for stationary, short-crested waves in shallow water with ambient currents. Coastal Engineering 13, p. 23-54.

Kaimal, J.C. and J.J. Finnigan, 1994: Atmospheric boundary layer flows. Oxford University Press. New York.

Kallen, E., 1996: Hirlam Documentation Manual, System 2.5. Available from SMHI, S-60176. Norrkoping Sweden.

Ris, R., 1997: Spectral modelling of wind waves in coastal areas. Ph D Thesis Delft University of Technology.

Stelling, G.S., 1983: On the construction of computational methods for shallow water flow problems. Ph D Thesis Delft University of Technology.

Stull, R.B., 1988: An introduction to boundary layer meteorology. Kluwer Academic Publishers. Dordrecht, the Netherlands.

Tennekes, H., 1973: The logarithmic wind profile. J. Atmos. Sci. 30, 234-238.

Wieringa, J., 1986: Roughness-dependent geographical interpolation of surface wind speed averages. Quart. J. Roy. Meteor. Soc. 112, 867-889.