Probability forecasts for water levels in the deltas of the Vecht and IJssel in the Netherlands

K.A. Wojciechowska, R.P. Nicolai & M. Kok
HKV CONSULTANTS, Lelystad, the Netherlands

ABSTRACT: Forecasting natural loads, such as river discharge or wind speed, is important in making operational flood risk assessments. Within the Flood Control 2015 program, a simple and fast method to obtain probability forecasts for water levels in the deltas of the rivers Vecht and IJssel has been developed. The method augments deterministic forecasts of water levels in the deltas with probability density functions that are based on a pre-processed database and predictive probability distributions of upstream discharges of the rivers, level of Lake IJssel and wind conditions. This article describes the method in detail. Moreover, a case study is presented, in which the method is applied to derive probability forecasts for water levels at three dikes.

1 INTRODUCTION

Forecasting natural loads, such as river discharge or wind speed, is important in making operational flood risk assessments. The computational power and capacity of computers have entailed that much attention is paid these days to probability forecasting, in which predictive probability distributions describe the occurrence of future values. For instance, the probability that water level exceeds some threshold several hours ahead is given instead of the information “water level will/will not exceed the threshold several hours ahead”. In the Netherlands, the Royal Dutch Meteorological Institute provides medium-range (48 to 240 hours ahead) probability forecasts for sea levels at several locations along the coast (De Vries 2009). In contrast to deterministic forecasts, probability forecasts make the inherent uncertainty, associated with future evolutions, explicit. Furthermore, the probability forecasts can be directly applied in the flood risk induced weighting of emergency measures. Finally, the probability forecasts separate the role of the meteorologist/hydrologist (an analyst) from the role of the crisis manager (a decision maker); (Reggiani & Weerts 2008, Verkade et al. 2011).

In the Netherlands, the WDIJ-team (in Dutch: “Waarschuwingdienst Dijken IJsselmeergebied”) warns dike managers in the deltas of the rivers Vecht and IJssel in the case of storm on Lake IJssel and/or high water danger. The warnings are based on information produced by FEWS-Meren, a newly introduced forecasting system. The system is a chain of models and techniques, e.g., it contains the 2-dimensional water flow simulation model WAQUA and the wave model SWAN. Input to the system consists of, e.g., forecasts of wind fields above the area, which are derived with the atmospheric model HIRLAM\(^1\), or forecasts of the IJssel discharge. Output of the system consists of deterministic forecasts of water levels and waves at several dike locations in the area up to approximately 30 hours ahead; the forecasts are given every 6 hours. Before FEWS-Meren became operational, a simple computer tool was used by the WDIJ-team to support generation of the warnings (Van Doorn 2006). The core of the tool is a pre-processed database of water levels and waves at dikes in the area, which are derived for different combinations of upstream discharges of the rivers, level of the downstream-situated Lake IJssel, wind speed and wind direction. Given deterministic forecasts or expected values of these variables, the tool searches the database for the corresponding water levels and waves, and subsequently indicates the dikes that might suffer from overflow or wave overtopping (TAW 2002). The tool is fast and simple. The main weakness of the tool is that it does not include temporal and spatial variability of wind. In contrast, FEWS-Meren includes such variability.

Presence of cities, such as Zwolle and Kampen, enhances the need of a good flood early warning system for the deltas. However, forecasting accurate and reliable water levels in the area is a challenge due to the number of relevant explanatory factors,

\(^{1}\) High Resolution Limited Area Model
i.e., natural loads such as discharges of the rivers, lake level, wind speed and wind direction. Therefore, deriving and presenting uncertainty margins together with the deterministic forecasts of water levels is required. The current forecasting system (FEWS-Meren) derives a single deterministic forecast in 6 hours for a specific combination of the natural loads. Running the system for multiple combinations (aiming to derive a probability forecast) is therefore not feasible. Within the Flood Control 2015 program, a method for deriving short-term (up to 24 hours ahead) probability forecasts for water levels in the water system has been developed, under constraints of efficiency and consistency with the existing technologies (Nicolai & Wojciechowska 2011). The method augments the deterministic forecast from FEWS-Meren with a probability distribution that is based on the pre-processed database and predictive probability distributions of upstream discharges of the rivers, the lake level, the wind speed and wind direction. This article describes the method in detail. Moreover, a case study is presented, in which the method is applied to derive probability forecasts for water levels at three locations.

In section 2, the deltas of the Vecht and IJssel are described. The method is presented in section 3. Predictive probability distributions of the natural loads are considered in section 4. The case study is presented in section 5. The main conclusions are summarized in section 6.

2 DELTAS OF THE RIVERS VECHT AND IJssel

The deltas of the rivers Vecht and IJssel are presented in Figure 1. Water levels in the system are influenced by upstream discharges of both rivers (measured at locations Dalfsen and Olst, respectively), level of the downstream-situated Lake IJssel, wind conditions above the area and the state of the Ramspol barrier (open or closed). The Vecht is a rain-fed river with an average discharge between 45 and 83 m$^3$/s. The river originates in Germany. The IJssel, with an average discharge of 250 m$^3$/s, is a Dutch branch of the Rhine. The design discharges (with exceedance frequency of 1/1250 per year) are equal to 550 and 2720 m$^3$/s for the Vecht and the IJssel, respectively (Geerse et al. 2011). The discharges of the two rivers are correlated and both flow into Lake IJssel, a freshwater basin with an area of 1100 km$^2$ and an average depth of 5.5 m. The aim of the Ramspol barrier is a temporary reduction of water levels in the Vecht, and hence a protection of the hinterland, in the case of a significant storm on Lake IJssel. The barrier is a worldwide unique hydraulic construction that consists of three inflatable rubber dams, and is activated when the local water level exceeds 0.5 m+NAP and when water flows from Lake IJssel into the Vecht. The barrier closes

\[ \text{Figure 1. Deltas of the rivers Vecht and IJssel in the Netherlands.} \]

\[ \text{2 Amsterdam Ordnance Datum} \]
on average once per year and the last closure took place in January 2012. In general, the wind from directions 270°, 300° and 330° (where 0° = 360° = North) leads to the highest water levels and waves in the area (Geerse et al. 2011).

3 DESCRIPTION OF THE METHOD

A practical approach to estimation of short-term (up to 24 hours ahead) probability forecasts for water levels in the deltas of the rivers Vecht and IJssel is introduced in this section (Nicolai & Wojciechowska 2011). The method is derived under constraints of efficiency and consistency with currently used techniques. For this area, no probability forecasting system has been developed yet.

The proposed method utilizes a pre-processed database that contains different combinations of upstream discharges of the rivers (locations Dalfsen and Olst), lake levels, wind speeds and wind directions above the area, and the corresponding water levels at different locations. In the database, the effect of the possible closure of the Ramspol barrier is not included. The database, used in the past in the computer tool of the WDIJ-team, is a function that associates different values of the natural loads with the local water levels (i.e., given a combination of the natural loads, it is straightforward to determine the corresponding water levels).

Having probability distribution functions of the upstream discharges of the rivers, the lake level, the wind speed and wind direction, a Monte Carlo simulation can be applied, first, to sample these natural loads according to their distributions, then, to evaluate water levels (at one dike location) for the sampled combinations using the database and, finally, to aggregate the outcomes into a probability distribution of the water level. This is the main idea behind the method, which is summarized in Figure 2.

To derive the probability forecasts for water levels, predictive probability distributions of the upstream discharges of the rivers, the lake level, the wind speed and wind direction are needed as inputs. The expected values are equal to deterministic forecasts of these loads. The standard deviations are predefined and based on a comparison of historical forecasts and observations, literature study or expert judgement. The parameters are functions of the lead-time (6, 12, 18 or 24 hours ahead). The standard deviations also depend on the expected values (e.g., for high expected values it is realistic that the standard deviations are also high). The resulting probability distribution of water level at a dike constitutes the probability forecast. However, since the database is pre-processed and does not necessarily reflect the considered situation, the expected value of the water level variable is replaced with the forecast derived with FEWS-Meren. In other words, the probability forecast is shifted to meet the corresponding deterministic forecast.

4 PREDICTIVE PROBABILITY DISTRIBUTIONS OF THE NATURAL LOADS

The predictive probability distributions of the upstream discharges of the rivers (locations Dalfsen and Olst), the lake level and the wind speed are assumed to be normal. The standard deviations of the IJssel discharge and the lake level are based on the mean absolute errors arising from comparison of observations and forecasts at different lead-times from the last three years (Nicolai & Wojciechowska 2011). A standard deviation of the lake level is assumed equal to the weighted average of standard deviations found at boundaries of the lake: Den Oever Binnen (weight = 0.215), Houtribsluizen Noord (weight = 0.353), Lemmer (weight = 0.128), Kornwerderzand Binnen (weight = 0.304). The resulting standard deviations are presented in Table 1. Due to the lack of historical forecasts and observations of the Vecht discharge at the moment of the analysis, the standard deviations are equal to 10% of the expected values following Beckers et al. (2009). The parameters related to the wind speed and wind direction are estimated using expert judgement. The standard deviations of the wind speed range from 1.6 to 3.2 m/s depending on the lead-time and the expected value. An increase of the lead-time and/or the expected value leads to an increase of the standard deviation. In general, the magnitudes of the standard deviations correspond to those found at the wind sta-
tion on Vlieland. The standard deviations at this location are estimated using historical forecast and observations and are equal to 1.6, 1.7, 1.8 and 2 m/s for the lead-times 6, 12, 18 and 24 hours ahead, respectively (Nicolai & Wojciechowska 2011). In the considered dataset, the mean observed wind speed is less than 10 m/s.

The future wind directions above the area are modelled using discrete random variables. Three wind directions are considered, namely, 270°, 300° and 330° (in fact, these are the only wind directions present in the pre-processed database). For example, probabilities of these wind directions 6 hours ahead when the expected direction is 270° are 0.9, 0.1 and 0, respectively. Probabilities of these wind directions 24 hours ahead when the expected direction is 300° are equal (i.e., 0.33). It is assumed that an increase of the lead-time leads to a discrete uniform distribution indicating less information available in the future.

Table 1. Standard deviations of the IJssel discharge and the level of Lake IJssel.

<table>
<thead>
<tr>
<th>Lead-time [hours ahead]</th>
<th>Standard deviation</th>
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<tbody>
<tr>
<td></td>
<td>IJssel discharge (Olst) [m³/s]</td>
</tr>
<tr>
<td>6</td>
<td>70</td>
</tr>
<tr>
<td>12</td>
<td>75</td>
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<tr>
<td>18</td>
<td>80</td>
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<td>24</td>
<td>85</td>
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5 CASE STUDY

In this section, the developed method is applied to derive probability forecasts for water levels at the three dikes shown in Figure 1. Although the data in the case study are fictive, the used inputs can occur in the reality. Table 2 gives deterministic forecasts of the upstream discharges, the lake level, the wind speed and wind direction. Table 3 presents deterministic forecasts of water levels at the three dikes.

For example, according to the method, the IJssel discharge 12 hours ahead is normally distributed with the expected value 1000 m³/s and the standard deviation 75 m³/s (Table 1). The Vecht discharge 6 hours ahead is normally distributed with expected value 250 m³/s and standard deviation 25 m³/s (i.e., 10% of 250 m³/s). The level of Lake IJssel 18 hours ahead is normally distributed with expected value 0.09 m+NAP and standard deviation 0.045 m (Table 1).

The method is applied using 50,000 Monte Carlo runs. In this case study, the forecasts from FEWS-Meren are assumed equal to the expected values of the resulting water level variables. The probability forecasts are shown in Figures 3-5 in the form of 95% and 98% uncertainty margins. Additionally, the figures present measured water levels at the time step 0 hours (without any uncertainty margins), the deterministic forecasts of water levels (dots), the alarm levels (dashed lines) and the heights of the dikes (solid lines).

The graphs suggest that the water levels, within the next 24 hours, might exceed the alarm levels or even reach the dike heights in the case of dikes 1 and 2. This is less probable in the case of dike 3. In general, the method allows deriving probabilities of exceeding alarm levels and dike heights.

1 Vlieland is a Dutch island in the north of the Netherlands surrounded by waters of the North Sea and the Wadden Sea.
6 CONCLUSIONS AND DISCUSSION

6.1 Verification

As all forecasts, probability forecasts for water levels, derived with the method, should be tested against observations. Different verification techniques can be found in the literature, e.g., the Brier skill score or the reliability diagram (Wilks 2011). The verification allows monitoring and improving quality of forecasts or comparing quality of different forecasting systems. To perform verification, large amounts of data (observations and forecasts) are usually required. In the case of the probability forecasts for water levels, it is interesting to know the quality under extreme conditions, i.e., when the forecasts are in the vicinity of the dike heights. The data for such situation are sparse, because of the high safety standards of Dutch water defences (in the deltas, some of the dikes must be able to withstand water level with annual exceedance frequency of 1/4000). The verification of the probability forecasts for lower thresholds should be a subject of future research. Also, the method will be tested using data from the high water situation that took place in January 2012 (hindcast).

6.2 Evaluation of the method

The presented method constitutes a simple and fast approach to derivation of probability forecasts for water levels in the deltas of the rivers Vecht and IJssel. The computing time of the current forecasting system (FEWS-Meren) is 6 hours. That is, the system needs 6 hours to derive a single deterministic forecast. Running the entire system for multiple combinations (aiming to derive a probability forecast) is therefore not feasible. The advantages and disadvantages of the developed method are summarized as follows.

The pre-processed input (i.e., the database of water levels and the standard deviations of the natural loads) allows for a fast and simultaneous production of the forecasts at several dike locations—this property is very important in the operational/real-time setting. Moreover, the database allows for a combination of the upstream discharges of the rivers, the lake level, the wind speed and wind direction, when these loads are uncertain. Because water levels in the deltas are functions of these variables, it is important to include uncertainties in all these variables when deriving the probability forecasts. It should be emphasized that the method is general and could be applied to other water systems.

On the other hand, the available database does not necessarily correspond to the situation at hand. For example, in the database, time and space variability of wind conditions above the area is not taken into account. Newly derived databases that include these aspects may improve the quality of the probability forecasts. Furthermore, it is recommended to analyse uncertainties in the natural loads using data from historical high water situations or stream gauges located further upstream.
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8 REFERENCES


