FEWS-WATERWAYS: TOOL FOR SHARING DATA BETWEEN INLAND STAKEHOLDERS

by

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ABSTRACT

This paper describes the FEWS-Waterways system for navigation that has been set up for optimizing inland water transport. The operational system computes water depths, flow velocities, and air clearances below bridges. These data are input for a trip advisor (so-called Economy Planner) that determines and visualizes the maximum laden draught or container height for which it is possible to pass the critical points on the route in addition to the optimal track in the navigation channel and ship speed during the trip to minimize fuel consumption.

1. INTRODUCTION

Accurate prediction of water depth in rivers and canals, air clearance under bridges and flow velocities enables maximizing the cargo volume during a trip, but also enables sailing with the optimal ship speed, in order to (a) arrive in time at the destination, and (b) reduce the fuel consumption and the carbon emission. Optimization becomes more important if the role of inland transport will increase. In the Netherlands this is the actual policy because road traffic results in congestion whereas there is plenty of space on the waterway network. Therefore, a tool has been in development to advise ship masters before and during their voyage, the so-called Economy Planner. An essential role in the Economy Planner plays FEWS-Waterways; this tool is based on the well-known Delft-FEWS which is an operational real time forecasting system which links data and models in real time. The paper describes FEWS-Waterways as part of a tool for economically and efficiently navigating on inland waterways.

2. ECONOMY PLANNER

The Dutch inland waterway network consists of the main navigation routes, so-called corridors, and many smaller canals. It also includes terminals and locks where the operating time influences the efficiency of the transport over water. The main waterways are rivers where the water depth and width vary due to seasonal fluctuations of the river discharge. During low discharge, water depth and width may become so small (Figure 1) that ships cannot be fully loaded and measures need to be taken such as passing restrictions. On the other hand, during high discharge or water levels, the air clearance under bridges becomes important for an efficient, safe and reliable network (Figure 2).

The Dutch project “Impulse Dynamic Traffic Management Inland Waterways” (IDVV) aims at delivering a modal shift in favor of inland navigation in order to handle the expected increase of the number of containers due to the “Maasvlakte II” development. Within the IDVV-project, tools have been developed to create a situation in which ships and waterways will be used optimally. One of the tools is the Economy Planner allowing skippers to transport the maximum cargo and to deliver the cargo in time at the required destination meanwhile reducing fuel consumption by energy-efficient ship operation.

The Economy Planner has the following two main goals:

1. <u>Before the trip starts</u>: a supporting tool for ship masters to determine the route, the amount of cargo to load, and the expected time of arrival (ETA).
2. <u>During the trip</u>: an advising tool for skippers aiming a reduction of the fuel consumption and of the carbon emission. Fuel reduction is possible by sailing slower at shallower locations and

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faster at deeper locations, and by sailing in the deeper parts of a cross-section. Therefore, the following advises are given by the Economy Planner:

- The most energy-saving track (i.e., the line to sail within the cross-section of the river) based on a navigation chart with actual water depths and flow velocities.
- The actual revolutions per minute (RPM) to apply, such that fuel consumption and emission are minimal while the destination is reached in time.

To be able to estimate the route and optimal amount of cargo (goal 1), future predictions of water depth and air clearance below bridges are needed along the entire route and during the entire trip (what will the skipper come across during his trip in the next couple of days). To be able to provide the optimal track and RPM (goal 2), actual water depths and flow velocities need to be available on a navigation chart. Therefore, an essential element in the Economy Planner is the calculation of both actual and future water depths, flow velocities, and air clearances below bridges. The next section describes the FEWS-Waterways system that has been set up to do so. As a start, the system has been developed for the Dutch waterways, but can be extended quite easily as soon as hydrodynamic and morphological models of other countries become available.

A very strong and important element in the Economy Planner is the sharing of data. During a trip, a ship often measures the water depth using an echo sounder signal. These data are collected and processed, and used in the calculation of water depths, flow velocities and air clearances. To be able to make accurate future predictions and an accurate actual navigation chart, this information is very valuable. A local shallow area may cause hindrance for navigation, but may be disappeared one week later, for instance due to dredging, an increase of water level or due to morphodynamic dampening of the shoal. The more ships collect and share their data with each other, the more detailed and accurate the actual navigation depth chart becomes, and the more accurate the future predictions become (since the calculation of future prediction needs the actual situation as input). In exchange for sharing his own data, the skipper obtains information that has been derived from all the other data of skippers. A point of attention is that the echo sounders do not measure the water depth, but measure underkeel-clearance, so the measurement has to be corrected for draught, trim and squat.

Figure 1. Low water in the river Waal. Source: https://beeldbank.rws.nl, Rijkswaterstaat, Ruimte voor de Rivier / martin van lokven

Figure 2. Insufficient air clearance below a bridge caused a collision.

3 FEWS WATERWAYS

3.1 General background Delft-FEWS software

Delft-FEWS is an open data handling platform initially developed as a hydrological forecasting and warning system. Essentially it is a sophisticated collection of modules designed for building a forecasting system (see for instance Werner et al, 2013, or www.deltares.nl). Because of its unique characteristics concerning data importing and model connections, Delft-FEWS is very suitable to interconnect and run several different operational models and update these models using new measurements. As an example, Figure 3 schematically shows what a Delft-FEWS system can do: (real-time) data are imported, numerical calculations are performed using these data, and the results of forecasts are exported/presented to an external server or website. A couple of hours later, the calculations are repeated automatically using the newest real-time data. Additional advanced tools can be added such as data assimilation methods or tools for disseminating forecasts.

Although Delft-FEWS was developed initially for flood early warning systems (abbreviation FEWS), nowadays it has also been implemented for other operational modeling systems (see Table 1 for some examples). Delft-FEWS allows importing various formats of data ranging from simple telemetry data to complex remote sensing data. Any hydrological, hydrodynamic and morphologic model can be used within Delft-FEWS. This flexibility allows the user to apply any desired software; the user is not dependent on the software of Deltares or any third party supplier. This offers any organization to set up an operational FEWS-system using their set of data and models, which are calibrated and used for a specific purpose.

Operational system based on Delft-FEWS	**Application area (few examples)**
Water Information System - to manage and control open water bodies.	Municipalities in The Netherlands
Temperature Forecasting System	Rhine River, The Netherlands
Drought Early Warning System	Countries in Africa, Indonesia, Italy
Reservoir Management	United States of America, Singapore
Canal Automation	The Netherlands
Ground Water Management	England and Wales
Water Quality Forecasting System	The Netherlands, Singapore
Coastal Early Warning System	Indonesia, Scotland

Table 1. Examples of Delft-FEWS systems and application area.

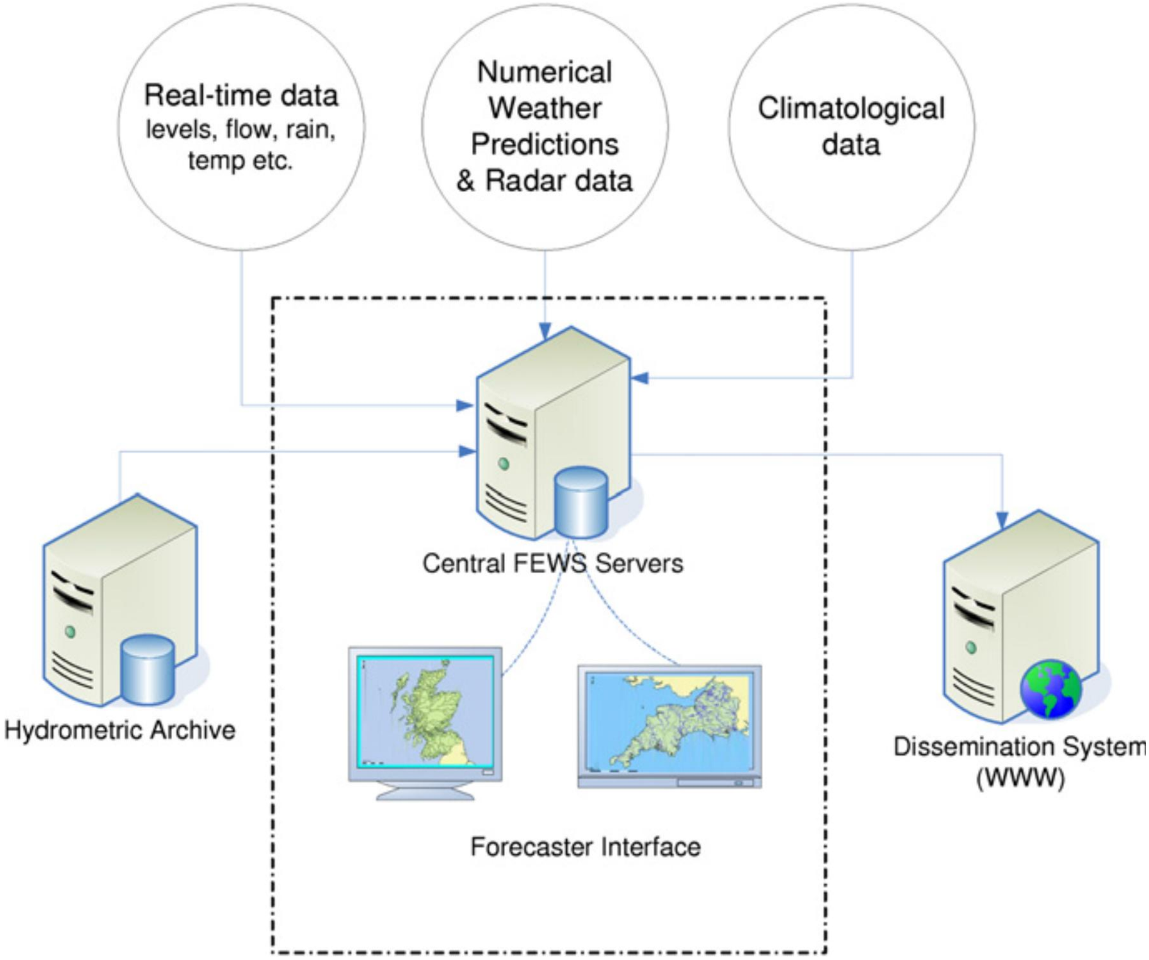

Figure 3. Schematic structure of an operational Delft-FEWS system (taken from Werner et al., 2013)

3.2 FEWS-Waterways

3.2.1 General setup of the system

We have set up an operational Delft-FEWS system for navigation, called FEWS-Waterways. As already explained in the previous section, the main reasons for using Delft-FEWS for forecasting the water depths, flow velocities and air clearances are flexibility and adaptability, and because it is an open-software system.

Figure 4 and Table 2 illustrate how the FEWS-Waterways system is set up. Hydrodynamic and morphological models (the 3 red blocks) are applied to predict among other things water levels, bed levels, water depths and flow velocities in the Dutch rivers and canals. These models are built using Delft3D, WAQUA, and SOBEK software. The FEWS-Waterways system is able to automatically start the simulations. The models need boundary conditions; these are automatically imported in the FEWS system. In the next sections, the calculations of the hydrodynamic and morphological models are discussed in more detail.

First relevant data (green import blocks) are imported; next, these data are used to perform the model simulations. Finally water depths, flow velocities and air clearances are exported to be used in the Economy Planner (blue export block). The data format which is sent to the Economy Planner is in standard NetCDF-CF format.

What:	Derived from (software):	Needed for:
Flow velocity (2D)	2DH hydrodynamic model (WAQUA)	o Correct echo sounder data for squat and trim o Most energy-saving track during the trip o RPM during the trip
Water level (1D)	1D hydrodynamic model (SOBEK)	Air clearance below bridges
Water level (2D)	2DH hydrodynamic model (WAQUA)	Actual and forecasted water depth
Bed level (2D)	2DH morphodynamic model (DELFT3D)	Actual and forecasted water depth

Table 2. Derived parameters and purpose.

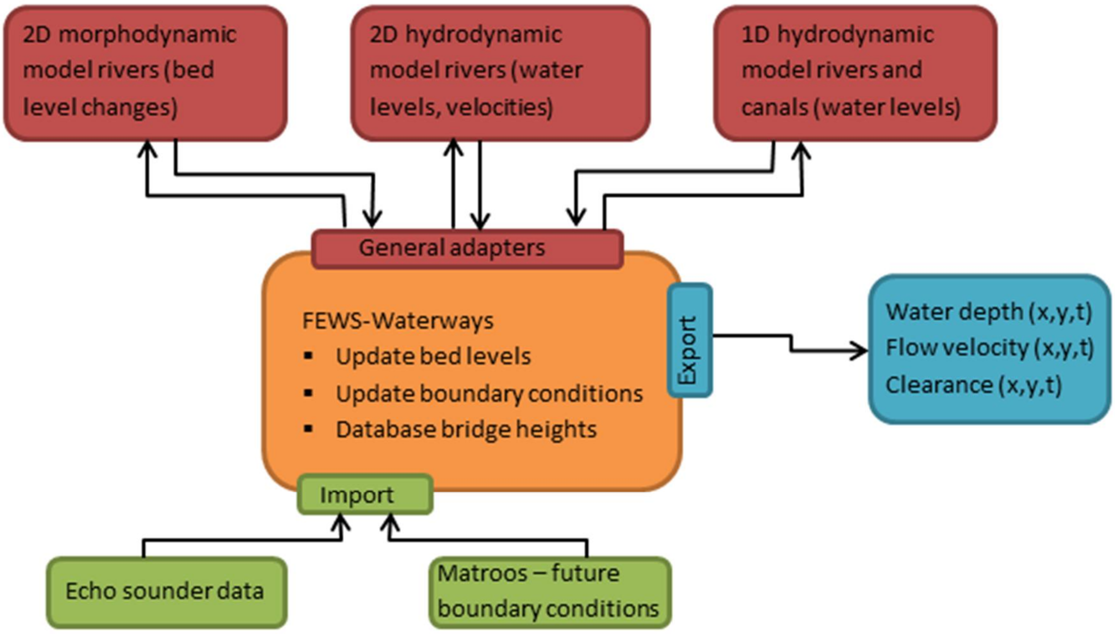

Figure 4. Overview of the operational FEWS-Waterways system.

3.2.2 2DH hydrodynamic model for water levels and velocities

Existing hydrodynamic models of the Dutch rivers (Figure 5) are used to calculate actual and forecasted water levels and velocities. The models run with WAQUA software. The models are so-called "twodimensional horizontal (2DH)" models, which means that the depth-averaged flow equations are solved and variations over the width of the river channel are calculated. To get an impression of what the model looks like, Figure 6 shows a detail of the Rhine River.

The boundary conditions are taken from Matroos, which is a database of Rijkswaterstaat (part of the Dutch Ministry of Infrastructure and the Environment which is responsible for the design, construction, management and maintenance of the main infrastructure facilities in the Netherlands). In Matroos measured and forecasted water levels and discharges at some key locations are stored. Figure 5 indicates the locations and the type (water level, discharge) of the boundary conditions.

Matroos also contains forecasted values, and these values are updated regularly. Therefore, in FEWS-Waterways, every four hours a new simulation starts automatically using the most up-to-date forecasted boundary conditions. This is further illustrated in Figure 7. We distinguish between a "state run" and a "forecast run". In the state run, we calculate using *measured* boundary conditions; in the forecast run we calculate using *forecasted* boundary conditions. The initial conditions in the model (namely water level and flow velocity for each grid cell) at the beginning of the simulation (T0-X) follow from an earlier computation ("warm state") or –if not available– from a best estimate ("cold state"). The length of the state run (value X) to play-in the model can be smaller for a warm state than for a cold state, as initial conditions match better with the actual situation. The modeled flow velocities and water levels are exported to be used to be used in the Economy Planner.

Flow velocity

Figure 8 illustrates calculated flow velocity (depth-averaged) in one of the Dutch Rhine branches. In the western part of the Netherlands the tide plays a role, and the velocities are directed landward part of the time. It can be seen that (for the chosen discharge and at this location) flood plains overflow and that velocities in the main river bed vary between roughly 1.5 and 2 m/s.

As a cooperative pilot study, a couple of ships that sail with an echo sounder on board are collecting and exporting their measured depths at the moment. They measure the depth below the ship every second. These measurements are corrected for squat and trim. The flow velocity is one of the parameters that are needed to correct the measurements. The point in time and location of the depth measurement of a ship (x_{ship}, y_{ship}, t_{ship}) are known; the (more or less) same point in time and location of the calculated velocity ($x_{velocity}$, $y_{velocity}$, $t_{velocity}$) are taken for the squat and trim correction. We say "more or less" because velocity is calculated on a computational grid rather than for each exact point, and because calculated velocity is stored every couple of minutes rather than every second. The calculated velocities that we use for correction, come from the "state run", so measured boundary conditions are applied.

The flow velocities will also be used in the Economy Planner to advice on the most energy-saving track to sail and on the RPM to apply during the trip. This implementation is still work in progress.

Water level

As explained before, the goal is to advice on the amount of cargo to load before leaving and on the most energy-saving track to sail and on the RPM to apply during the trip. To do so, actual and forecasted water depths are needed along the route. Water depth D at a certain location (x,y) and a certain moment in time (t) is defined as:

$$D(x,y,t) = H_{waterlevel}(x,y,t) - H_{bedlevel}(x,y,t) \qquad (1)$$

where H is defined as a level with respect to a certain datum.

Ideally, if all ships continually share their echo sounder depth measurements, a good estimate of the actual water depth within the navigation channel can be made. A predictive numerical model becomes essential if

1. the density of the sailed tracks is insufficient (there aren't enough ships sharing their data or the ships all sail the same tracks so that data is missing over the width of the channel), and
2. predictions of water depths occurring in the near future are needed.

Therefore, we have set up the FEWS-Waterways system such that water depths within the navigation channel (from both state run and forecast run) can be calculated and exported. The water level $H_{waterlevel}$ (x,y,t) is calculated using the 2DH hydrodynamic models. Figure 9 shows a result. As indicated in equation (1), water depth is also a function of the bed level. This is further discussed in the next Section 3.2.3.

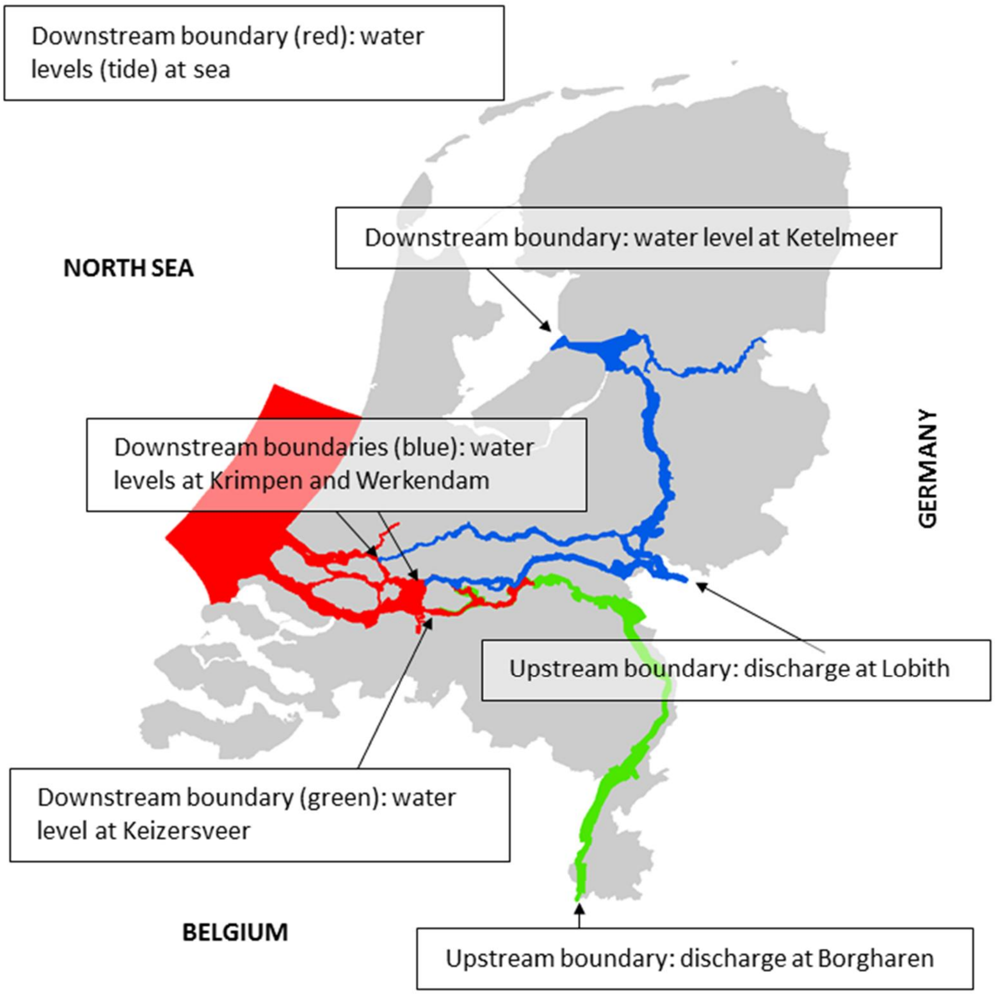

Figure 5. Computational grids of the hydrodynamic WAQUA models (in blue, red, green). The Netherlands is shown in grey. The main rivers of the Netherlands are captured by the models.

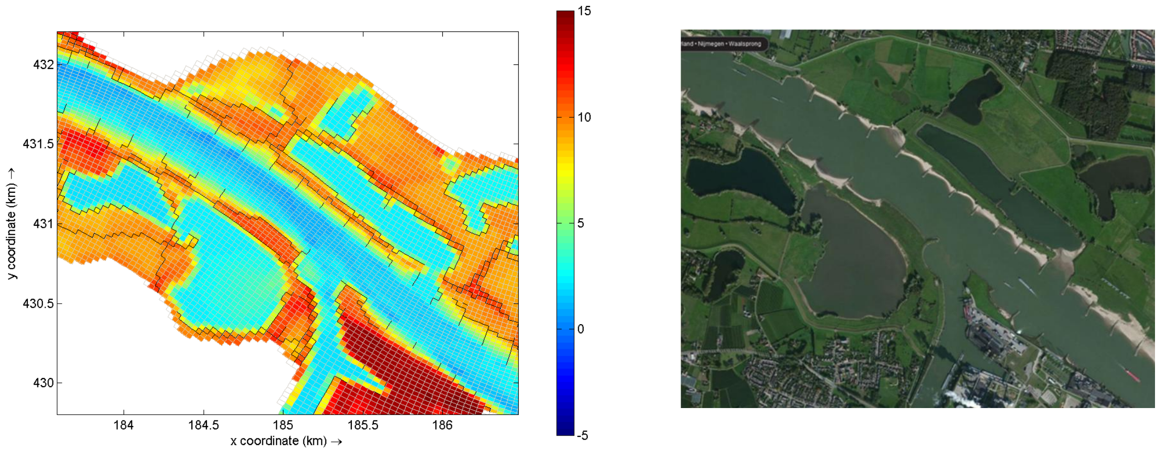

Figure 6. Detail of the hydrodynamic WAQUA model (left), compared to real situation of a Rhine branch in the Netherlands (right). Flow is from right to left. Colors indicate bed levels / terrain height in m + datum. Grey lines indicate the computational grid; black lines indicate groynes and dikes.

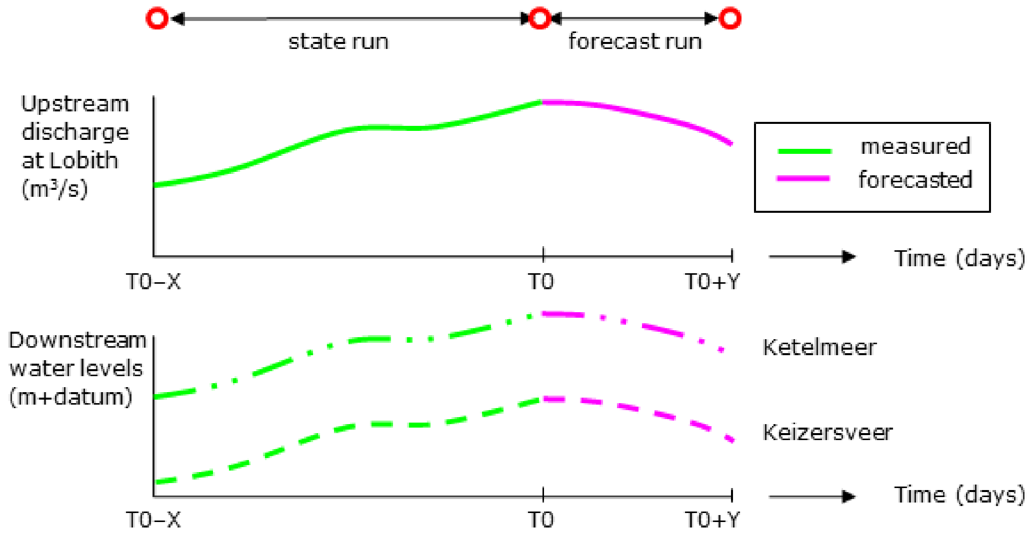

Figure 7. Time management of the operational FEWS-Waterways system.

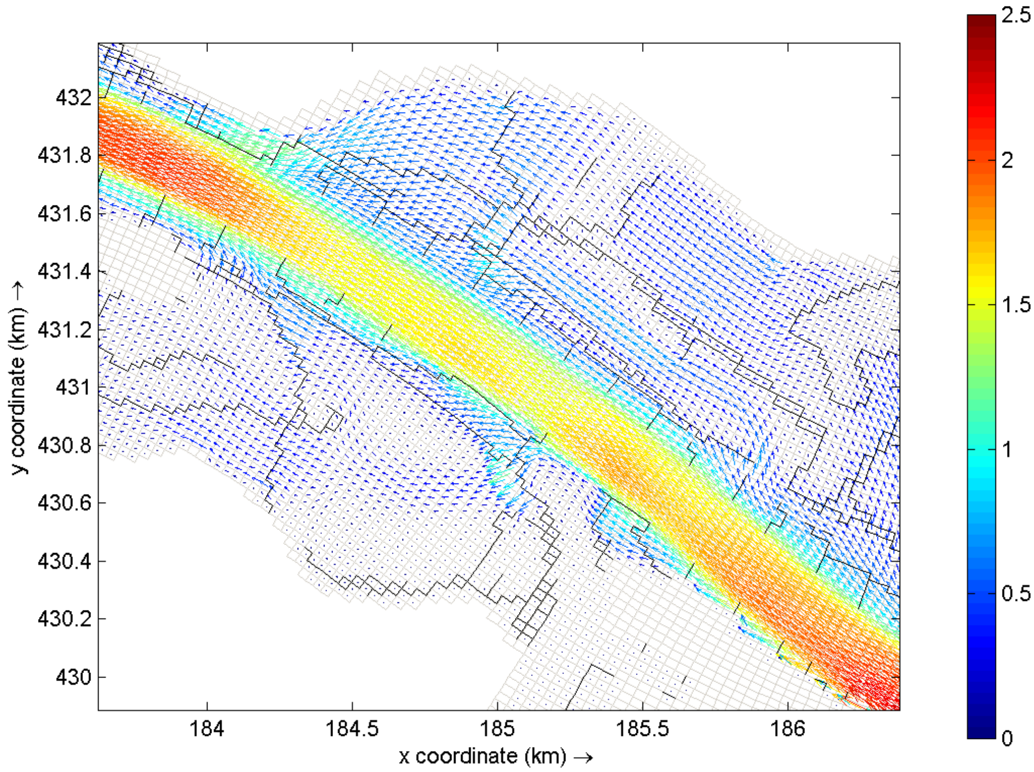

Figure 8. Calculated depth-averaged flow velocity vectors (direction and magnitude). Colors indicate magnitude in m/s. Location is the same as presented in Figure 6.

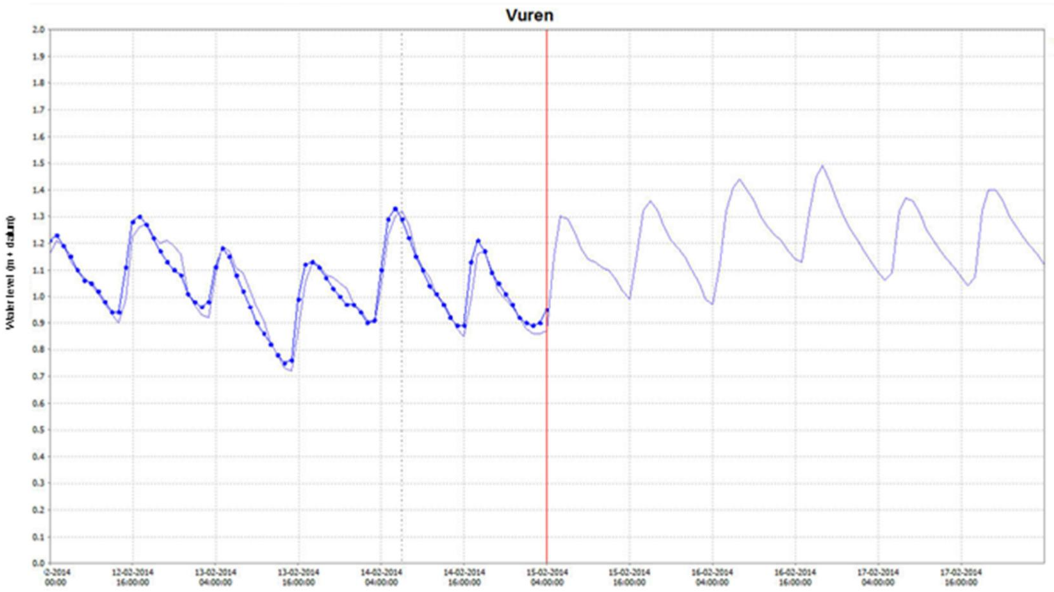

Figure 9. Water level at a certain location (Vuren) in the Rhine with respect to NAP-datum. Dots indicate measured water levels; solid line indicates modeled water levels (state and forecast run). The red line indicates the present time T0 (i.e., right of the red line means forecasted). Fluctuations are caused by the tide.

3.2.3 2DH morphodynamic model for bed levels

As explained in the previous section, a predictive model for water depth (= water level minus bed level) become essential if future forecasts are desired or if there are insufficient measured depths. Water levels can be derived from a 2DH hydrodynamic model. These forecasts are quite accurate, as long as the forecasted period (Y in Figure 7) is not that long. Making a prediction of future bed levels is a bit more complicated. This holds at least for the alluvial rivers in the Netherlands, where the river bed is changing continuously. For gravel bed rivers or rivers with an immobile bed, the bed level is just constant over time.

<u>Behavior of the river bed</u>
We should make a distinction between short term and long term bed level changes (see also Van der Mark et al, 2014). On the long term, the Dutch rivers do not show large variations (changes in the order of centimeters per year). This would suggest that the bed level at a certain location will change with only millimeters within a period of days. However, on the short term morphological processes take place that give rise to changes of the order of a meter. Bed forms (ripples and dunes) migrate with one to tens of meters each day, depending on the location in the river and the river discharge. Figure 10 shows dunes with ripples imposed in the Rhine River. Dunes may well have heights of about 1 m. Additional short term morphological changes are sedimentation and erosion processes due to periods of low flow and high flow (flood plains that start to overflow cause sedimentation and downstream erosion; and disturbances migrate towards downstream) and dredging and dumping activities to keep the river navigable.

Because of these short term bed level changes, the echo sounder depth measurements may show large differences. It is realistic that situations occur in which a ship measures the depth at the crest of a bed form, and that a second ship, at more or less the same location but one day later, measures the depth at the trough of the bed form, so that a difference of about 1 m in bed level arises (illustrated schematically in Figure 11).

<u>Calibrated morphological models of the Dutch river branches</u>
In the Netherlands, we have developed morphological models of the main river branches to be able to assess the effects of any measure on the river bed. The models calculate (and are calibrated on)

large-scale ("bed form averaged") bed level changes. This means that the models are capable of calculating the long term morphological changes (the earlier-mentioned bed erosion or sedimentation of centimeters per year). Besides, heights of bed forms are calculated based on an empirical relationship (bed form heights depend on flow conditions, sediment size). The model is not able to predict where the crest of a bed form is located, but calculates an envelope; within the envelope the bed forms migrate (Figure 12). Bed forms may grow if the discharge increases, then the envelope becomes wider.

Possible approaches to determine forecasted water depths

Now with the availability of morphological models and echo sounder water depth data, there are a couple of possibilities to determine forecasted future water depths:

- Derive future water levels from 2DH hydrodynamic model. Use echo sounder data from participating ships for the bed levels.
- Derive future water levels from 2DH hydrodynamic model. Derive future bed levels from 2DH morphodynamic models. Use echo sounder data to verify the results.
- Derive future water levels from 2DH hydrodynamic model. Update the 2DH morphodynamic models using the echo sounder data from participating ships. Derive future bed levels from updated 2DH morphodynamic models.

For now, we have set up the FEWS-Waterways system for the second option, as we feel that this is the best solution. Again, the boundary conditions are taken from Matroos. The model calculates bed-form-averaged future bed levels, which can be subtracted from the calculated future water levels. The obtained water depth may locally be larger or smaller because of present bed forms. The envelope of bed forms is calculated by the model as well. The echo sounder data show a lot of fluctuations due to the short term morphological processes, but are very suitable to verify the results. The measured data should fall within the envelope. Figure 13 shows the sedimentation-erosion pattern during a period of high discharge of 3 days, and the envelope of the dunes.

The first option has two difficulties: (1) extrapolation of the bed level to future bed levels and (2) data includes fluctuations due to bed forms that need to be filtered. The third option seems an attractive one: if the model is updated with the most recent measured bed levels, it should give reliable results. However, again the data needs to be filtered, as the model needs a bed form-averaged bed level. Besides, the computational grid is quite coarse, so that rules need to be developed that define the amount of tracks or data points that are needed before a computational cell is updated.

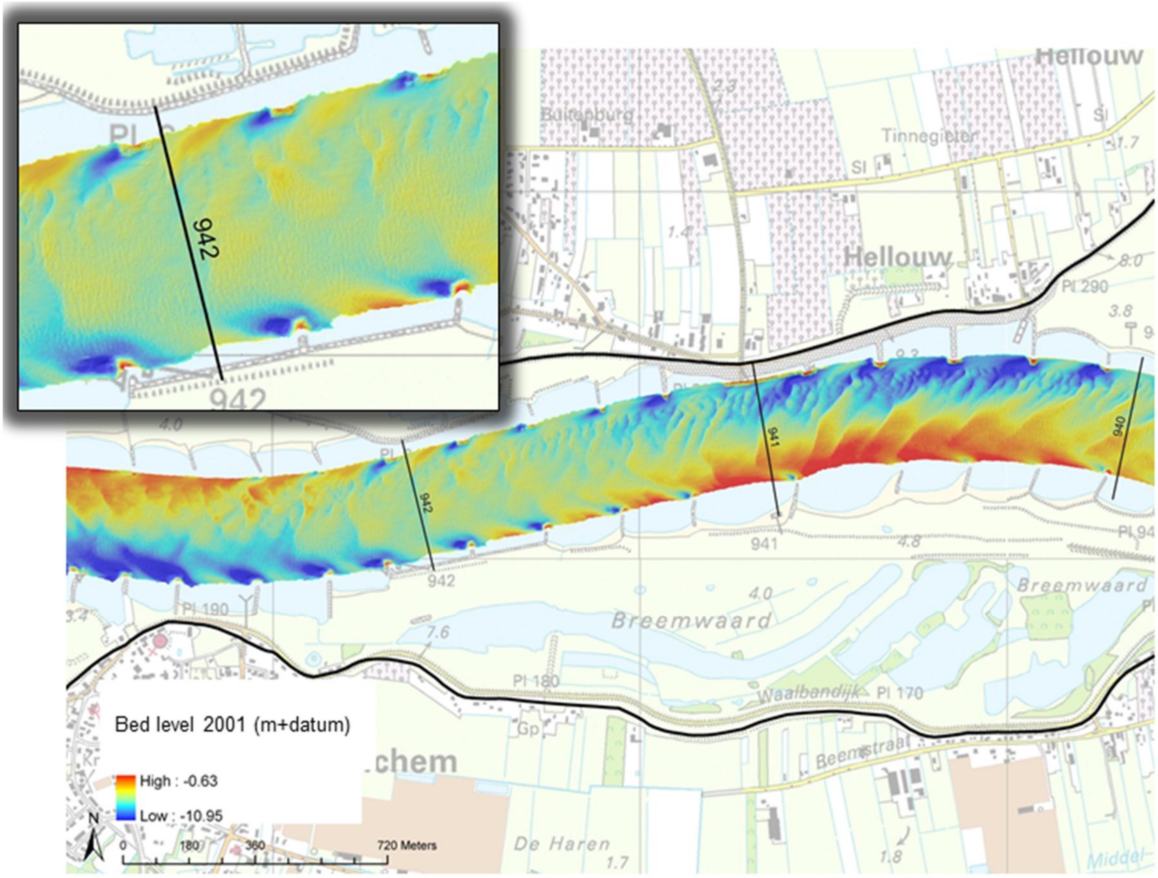

Figure 10. Bed level in one of the Rhine River branches. Dunes with a length of hundred meters can be seen, on top of the dunes smaller-scale ripples are visible (zoomed inset).

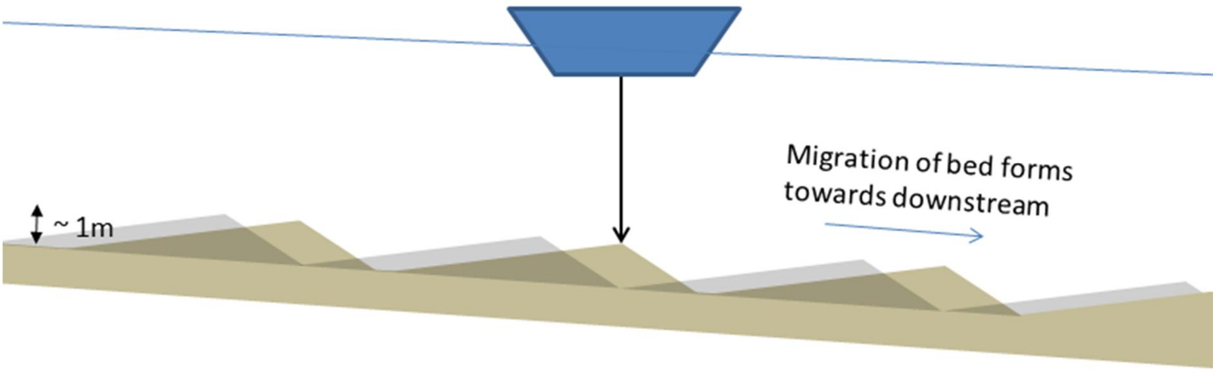

Figure 11. Short term morphological processes (such as migration of bed forms) may give rise to large differences in measured water depth (measured at same location but few hours or days later).

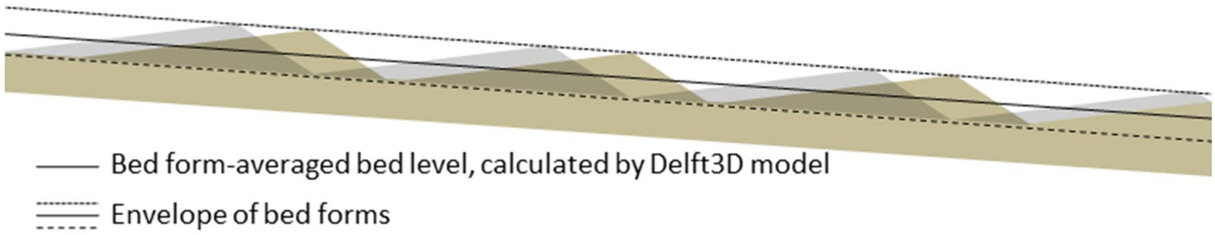

Figure 12. Bed level as calculated by morphological Delft3D-model, together with the envelope of bed forms.

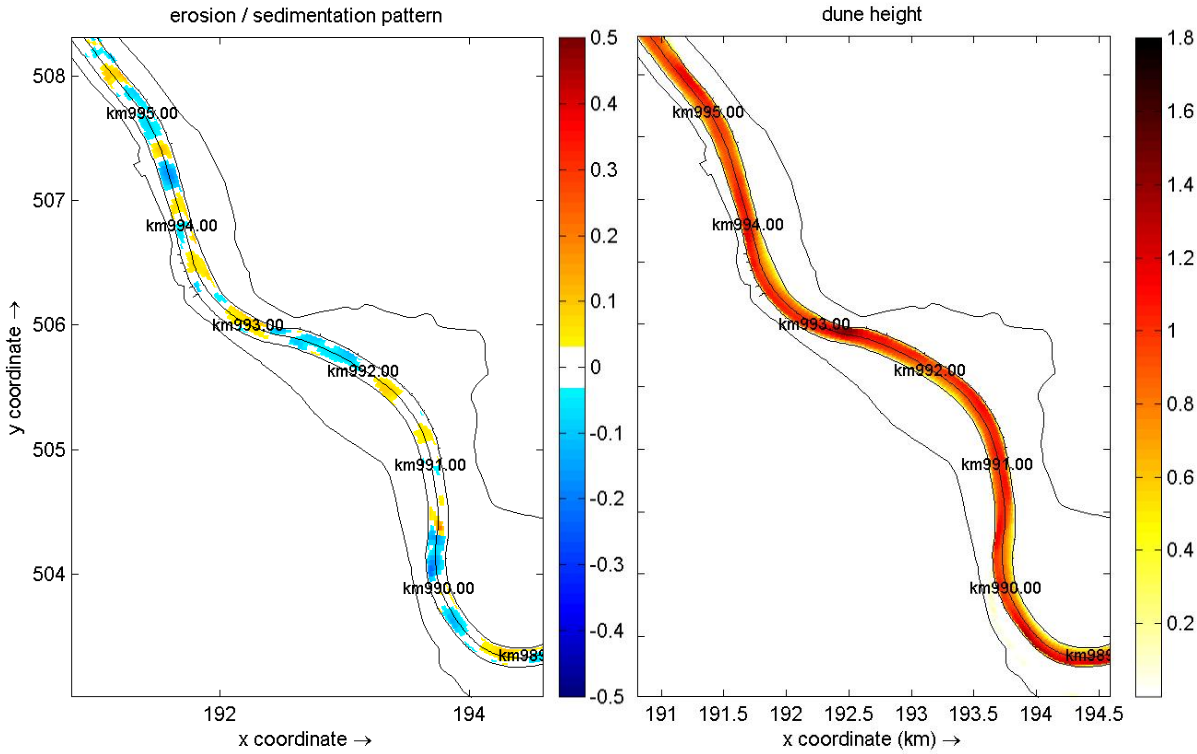

Figure 13. [left] Erosion (blue) and sedimentation (red) pattern (color scale in m) over a 3-day period of high flow as calculated by morphological Delft3D-model in one of the Dutch Rhine branches. [right] Dune height at the end of the 3-day period (distance from crest to trough in m). Black lines indicate the main river bed, river axis and the flood plains.

3.2.4 1D hydrodynamic model for air clearances below bridges

The wish for transporting more layers of containers is rising, which makes optimization on the available air clearance below bridges on the route profitable. An existing one-dimensional hydrodynamic model is applied to calculate water levels in the main Dutch canals and rivers. This model has been developed within the SOBEK software package. The SOBEK model is chosen because it comprises of the main navigation network in the Netherlands (Figure 14). Especially in canals, the calculation of air clearance is important. There are much more bridges over canals than over rivers, and also the bridge height is more critical at canals than rivers, as the space to build a bridge is often scarce.

The clearance is determined as the vertical distance between the bottom of the bridge and the predicted water level (again both state and forecast run) at the location of the bridge. The database of bridges in the Netherlands is usually defined with respect to a local reference level, and had to be converted to the Dutch NAP datum. Just as for the 2DH models, every four hours a new simulation starts automatically using the most up-to-date forecasted boundary conditions, which are taken from Matroos.

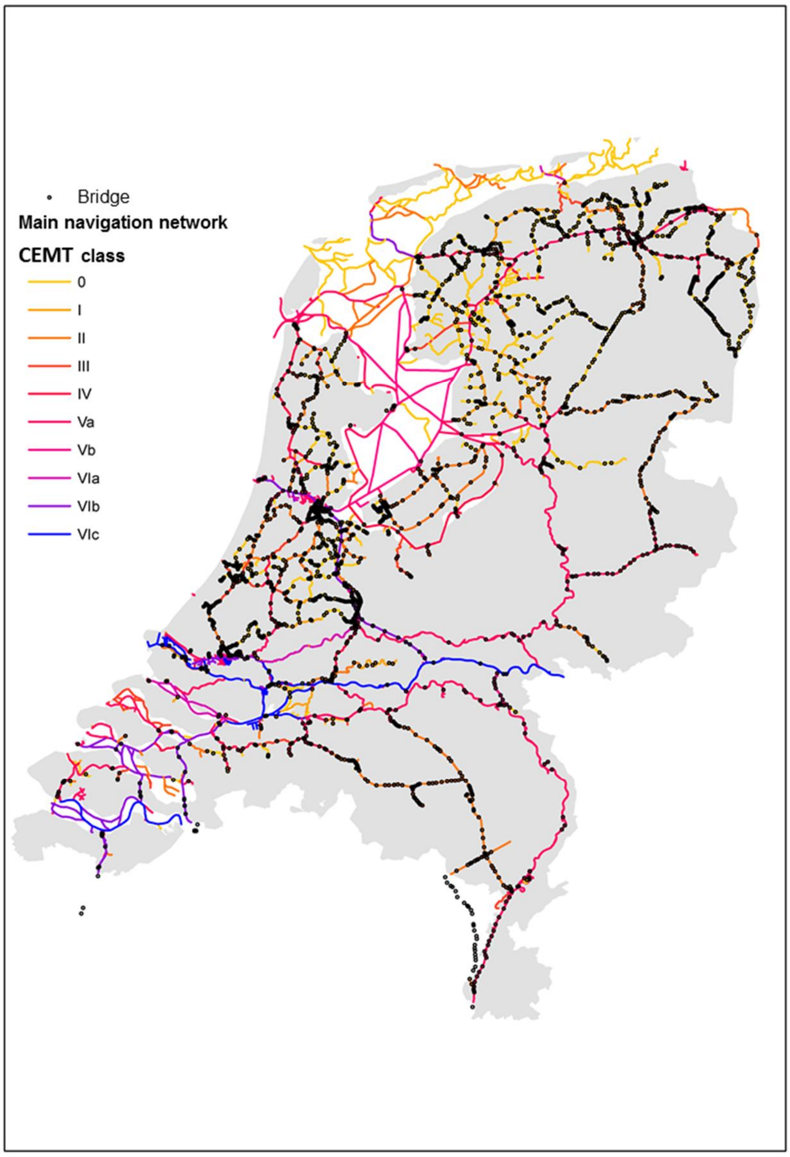

Figure 14. Main navigation network within the Netherlands, together with the database of bridges (black dots).

3. DISCUSSION

At the moment, as a first step the system only consists of models for rivers and navigation canals in the Netherlands. Lots of ships sail from the harbor of Rotterdam to Belgium or Germany and further. In order to let the system function more profitable, it is desirable to add models from the other countries as well.

A prototype of the FEWS-Waterways system consisting of the hydrodynamic and morphodynamic models, import and export possibilities and bridge database has been built. This means, the configuration has been made, but it has not been tested extensively yet. The system is automatically updated and simulations start every four hours. As mentioned, a couple of ships are now participating in a pilot project. The ships collect and export data to a server. The squat and trim correction takes place automatically.

The FEWS-Waterway system has been prepared to import measured echo sounder data. However, the verification between measured depth and calculated depth is still work in progress. The FEWS-Waterway system consists of existing calibrated models. The morphological models are calibrated on long term morphological behavior (large scale yearly bed level changes). The operational system is meant for short term computations (order of days rather than years). Until now, detailed bed level data measured with a frequency of days, were not available. The pilot project, in which participating ships share their data, are a perfect opportunity to calibrate and validate the models on short term processes as well.

4. CONCLUSION

A prototype of a so-called FEWS-Waterways system for navigation has been built. The operational system computes actual and future water depths, flow velocities, and air clearances below bridges. These data are input for a trip advisor (Economy Planner) that can be used to optimize inland water transport in two ways:

1. Water depths and air clearances below bridges during the trip and along the route are calculated so that the critical depth and critical height can be determined before a ship starts its trip. The critical values determine the capacity of a vessel on its trip.
2. Actual and forecasted future water depths and flow velocities in two dimensions (width and length of the waterway) are calculated so that an optimal track in the river and ship speed advice in relation to the desired arrival time can be determined for which fuel consumption is minimal.

The system consists of hydrodynamic and morphodynamic models that run automatically using measured and predicted boundary conditions (water levels and discharges at the open boundaries of the models). At the moment, as a starting point only Dutch models are incorporated. The system is especially useful if other countries are added.

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REFERENCES

Van der Mark C.F., K. Sloff, and M. Yossef (2014). Development of a sediment management tool for navigation channel maintenance. Paper prepared for the PIANC World Congress San Francisco, USA 2014.

Van Wirdum M., et al (2014). Pilot water depth measurements by the commercial fleet. Paper prepared for the PIANC World Congress San Francisco, USA 2014.

Werner M., J. Schellekens, P. Gijsbers, M. van Dijk, O. van den Akker, K. Heynert (2013). The Delft-FEWS flow forecasting system. Environmental Modelling & Software, 40, pp. 65-77.