DATA-ASSIMILATION IN FLOOD FORECASTING USING TIME SERIES AND SATELLITE DATA

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Abstract
Fast and precise flood forecasting is essential to decision making with regard to flood management. As part of the EU research project FloodMan (Near real time flood forecasting, warning and management) data-assimilation techniques are developed, demonstrated and validated for integrated hydrological and hydraulic computer models.

A model instrumentation is developed and applied in a pilot study of the river Rhine. The model combines a hydraulic model (SOBEK) representing the Rhine River between Andernach and Düsseldorf with a hydrological model (HBV) for the Sieg tributary. To increase the accuracy of flood forecasts, data assimilation is applied, using temporal data (time series, like water level measurements) as well as spatial data (flood maps derived from satellite data).

In co-operation with Bundesanstalt fur Gewässerkunde (BfG) an operational test has been carried out. The model instrumentation is also demonstrated for the flood periods of 1993 and 1995. Flood forecasts were made for Bonn and Cologne on a daily basis. Results of these tests are discussed in the paper.

Information from satellite data is less accurate compared to in-situ water level measurements. The hypothesis is that the images provide additional information because the data is spatially distributed. In the research synthetic flood maps, generated from calculated water levels in combination with a DTM, were used. Several methods were applied to deduce hydraulic information (water levels and flood extent) from the flood maps. Results are presented and analysed in this paper.

Key words: data-assimilation, flood forecasting, satellite images

INTRODUCTION
FloodMan is a project for near real-time flood forecasting, warning and management. The overall goal of the FloodMan project is to develop, demonstrate, and validate an information system for cost effective flood forecasting and management using EO data, in particular spaceborne SAR data, hydrological and hydraulic models, and in-situ data. The prototype system will provide near real-time information on the flood event, better flood predictions, and improve best practices for management of rivers and their catchments, including hydropower production planning.

In Work Programme 2 of FloodMan possibilities are assessed to improve flood forecasts in river basins using field data and satellite information. Hydrological and hydraulic models are further improved and coupled. In addition data-assimilation routines are developed and implemented.

A model instrumentation is developed to demonstrate the flood forecasting procedure and applied to a selected stretch of the river Rhine from gauging station Andernach to gauging station Düsseldorf (130 km). This river reach is modelled with a one-dimensional hydro dynamical model (SOBEK). For the inflow of the Sieg River (downstream of Bonn) a hydrological model (HBV) of the basin (2862 km²) has been analysed and coupled to the one-dimensional Rhine model. The rainfall-runoff model consists of four sub basins. For flood routing of the discharge of these four basins through the river Sieg a water transport model (WTM) is used.

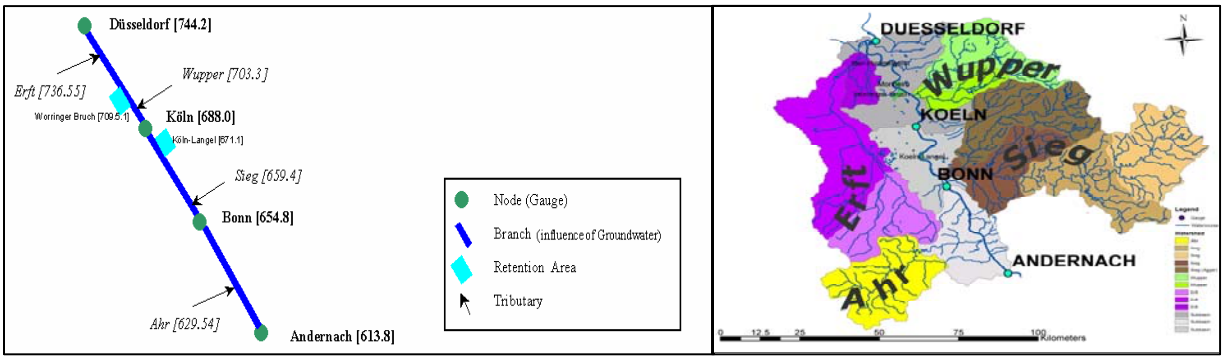


Figure 1: Schematic layout of the model for the Rhine river and its tributaries.

For the other tributaries the distance between the gauges of the tributaries and the confluence into the river Rhine has been taken into account (measured hydrographs of the tributaries are extended by area weighted factors and shifted by a time lag).

DATA ASSIMILATION AND FORECASTING

The flood forecasting procedure consists of three phases: actualisation, data-assimilation and forecast.

1. Actualisation:
   i. Use measured precipitation, temperature and evaporation to calculate the discharges in the sub basins of the Rhine catchment.
   ii. Use the calculated discharges from the sub basins with measured discharge at Andernach to calculate the water levels and the discharges in the river Rhine.
2. Data-assimilation
   i. Use measured water levels at Bonn and Cologne to adapt bed roughness and lateral discharges until the calculated water levels agree with the measured water levels.
3. Forecast
   i. Use forecasted precipitation, temperature and evaporation to forecast the discharges in the sub basins of the Rhine catchment.
   ii. Use the forecasted discharges from the sub basins with the forecasted discharge at Andernach and the forecasted bed roughness to forecast the water levels in the river Rhine.

The model calculations are made with a one-hour time step; data-assimilation is performed once a day.

Data assimilation procedure

The data-assimilation technique applied, computes model corrections based on the assumption that the uncertainties in model output and observations are known. The model uncertainty is assumed to be represented by the parameters selected for data-assimilation only. Furthermore, it is assumed that the uncertainties are normal distributed. The parameters that are adapted in the data-assimilation technique are based on an extensive sensitivity analysis. From this analysis it was concluded that the lateral discharges to the Rhine and the bed roughness are the most uncertain parameters and have a large effect on the water levels. Formulas that represent the effects of these parameters on the water levels have been used in the data assimilation technique.

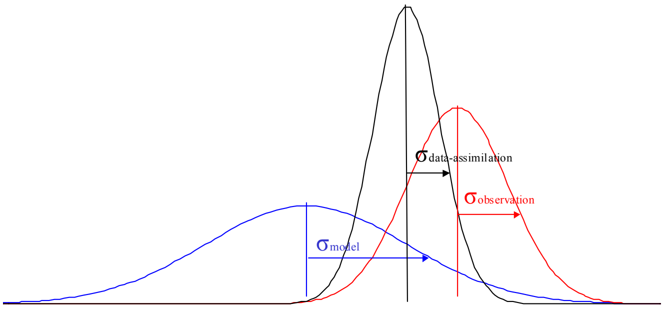


Figure 2: Illustration of data-assimilation technique.

The data-assimilation procedure implemented takes into account the uncertainty of the parameters involved and the measurement uncertainty. The data-assimilation algorithm compares the observed value with the calculated value. Based on this difference (small) changes are made to the parameters. The changes are made taking into consideration the uncertainty of the parameters and measured data. For example, a mean water level measurement is accurate compared to calculated water levels. Therefore the water level calculated with data-assimilation will be closer to the measured water level than the calculated without data-assimilation (see Figure 2).

During the data-assimilation the adaptation factors have been calculated. These adaptation factors are relative multiplication factors.

The data-assimilation procedure uses so-called adaptation factors: multiplying the original value with the adaptation factor and substituting this value into the model leads to new parameter values. Therefore the data-assimilation procedure requires no changes in the computer code of SOBEK and HBV and could be applied to any modelling system.

Flood maps

Flood maps derived from satellite images data can play an important role for improved flood modelling and forecasting. For example when no gauging stations are available, gauging stations fail or unforeseen events (such as dike breaches) happen. Geo-referenced and classified satellite data is used to determine flood extent (area) as well as flood levels.

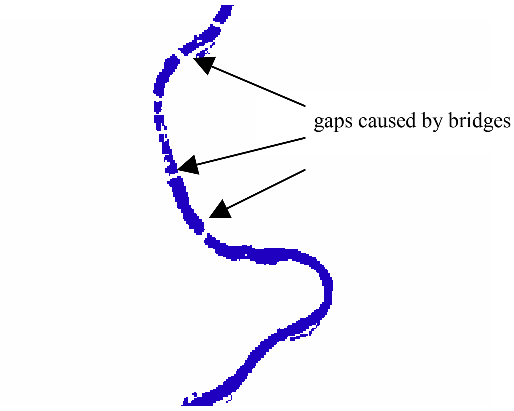


Figure 3: SAR floodmap on feb 15th 2002 near Cologne.

Besides water levels, SOBEK also calculates the cross-sectional data and the mean river width per section. Knowing the length of each section, we can calculate the corresponding flooded area according to SOBEK. If we compare these calculated flooding areas per section with the perfect synthetic flood maps, we find (as expected) an extremely strong relation. The values obtained from satellite images might therefore be used as independent ‘measurements’ for data-assimilation purposes. Because of the lack of suitable (historic flood) data for the river Rhine synthetic (simulated) flood maps were used to study the possible role of EO-data for improved flood forecasting. Four different methods were investigated for comparing flood maps from satellites with calculated flood areas or related water levels. It was proved (Huizinga et al, 2004) that methods for deriving directly the water level from combining observed flood maps and digital elevation maps (DEM) (see Figure 4) are very sensitive for small errors in georeferencing of the maps and local errors in the inundation. Therefore it was proposed to use differences in observed and calculated flood areas for river stretches of several kilometres in the data-assimilation procedure.

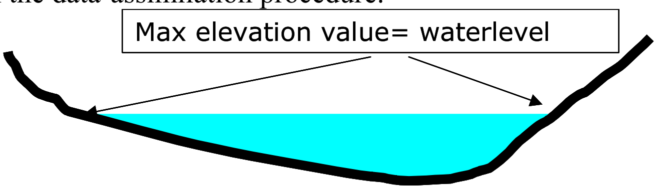


Figure 4: Determination of water levels by masking a DTM by means of a flooding area.

RESULTS

Operational test

In co-operation with the Bundesanstalt fur Gewässerkunde (BfG) an operational test has been carried out with the developed system on the 9th and 10th of February.
The test had three main objectives:
1. Verify the flood forecasting methodology
2. Verify the data-flow for flood forecasting
3. Verification of flood-forecasts

As input for the model the BfG delivered:
- Measured values of precipitation and temperature for 4 sub basins of the Sieg catchment from 1 September 2004 – 9 February 2005;
- Measured water levels from 1 December 2004 until 9 February 2005;
- Forecasted values of precipitation and temperature for 4 sub basins of the Sieg catchment from 8 February 2005 – 14 February 2005;
- Monthly-mean-daily-evaporation to be used as forecast;
- Forecasted water levels from 9 February 2005 until 15 February 2005 for the boundary conditions;
- Forecasted discharges from 9 February 2005 until 15 February 2005 for the boundary conditions.

Before the model could make a forecast the data had to be corrected and completed. These actions had to be done because of:
- Missing data;
- Data at different time intervals than the database expected;
- Differences in reference levels;

The same day, HKV Consultants could deliver the forecast for 10 days ahead to the BfG. This forecast consisted of:
- Discharges at locations in the Rhine
- Discharges at locations in the Sieg
- Water levels at locations in the Rhine
- Actual and forecasted flood maps for the river Rhine

The results of the test have lead to a model update and procedures describing how to deal with the data in case of operational flood forecasting. Further the results have been used to improve the flood forecasting tool.

Flood events of 1993 and 1995

For the flood events of 1993 and 1995 forecasts were made using the hydraulic and hydrological models and data-assimilation on measurements. The uncertainties of the assimilation parameters have been chosen in agreement with BfG that uses prescribed values from the Ministry (Länderarbeitsgemeinschaft Wasser (LAWA) und Bundesminister für Verkehr (BMV), 2000):

- Standard deviation measuring error: 0.01 m. water level
- Variation coefficient discharge: 0.20 [-]
- Variation coefficient bed roughness: 0.02 [-]

From figure 4, in which the adaptation of the bed roughness is plotted for the 1995 flood, we observe that:

- The adaptation has an average around the same order as the standard deviation;
- The adaptation changes in time;
- The two branches show different behaviour;
- The adaptation is almost zero at the high water peak;
- At the moment of a large increase of the water level, the adaptation is relatively large and negative.

Similar results have been found for the flood of 1993.

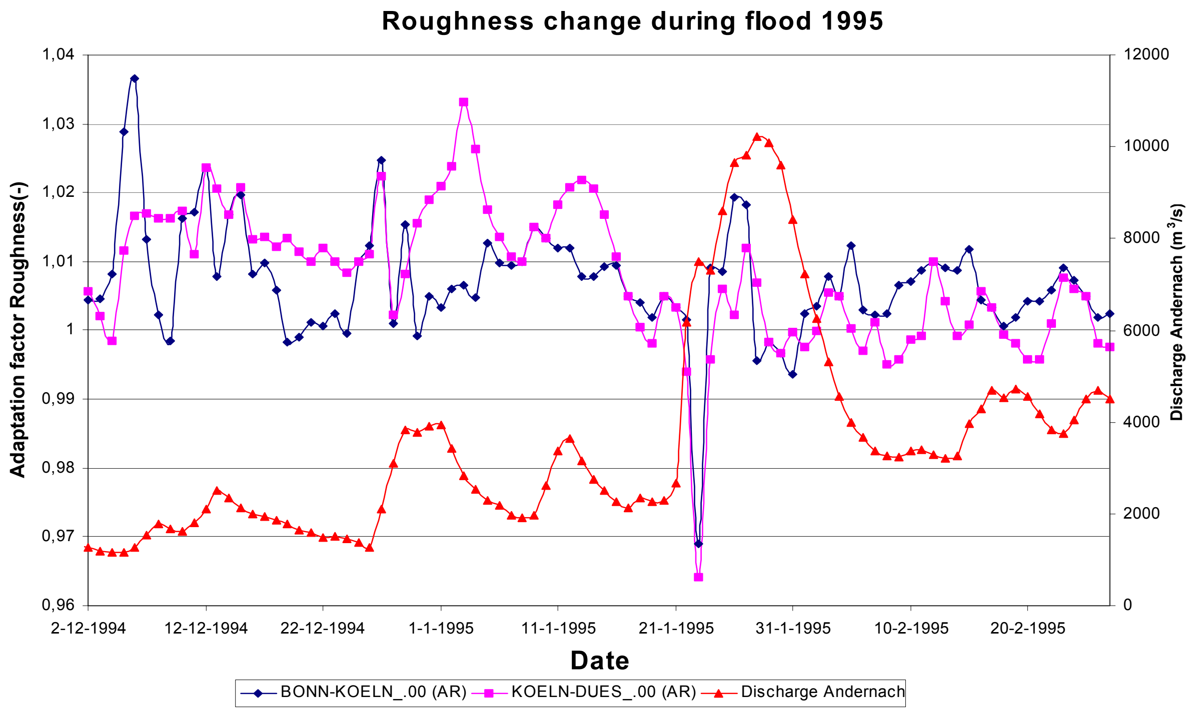


Figure 5: Bed roughness change (left axis) and the discharge at Andernach (right axis)

In Verboeket-Klavers and Vermeulen (1994) the same phenomenon was observed in the downstream part of the river Rhine.

From Figure 6, in which the differences between the model computations and the water level measurements at Cologne for the floods of 1993 and 1995 are presented, we observe that:

- The maximum difference is around 15 cm for 1995 and around 20 cm for 1993;
- The average difference is around 5 cm for both periods;
- The pattern in the forecast is similar for both periods;
- The differences in the forecast have a maximum at the peak for 1995 (31 January);

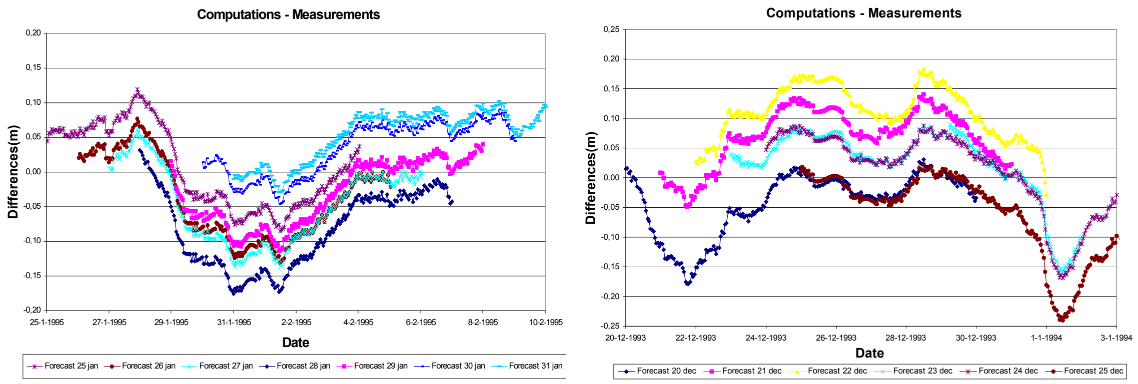


Figure 6: Forecast performance for the flood of 1995 and 1993 (Cologne)

Role of flood maps

The synthetic flood maps are generated based on the calculated water levels with SOBEK in combination with a digital terrain model (DTM). If the flood maps are used to deduce the water levels we expect a perfect match. However due to steep banks or levees there is not always an unambiguous relation between river width and water levels (Figure 7).

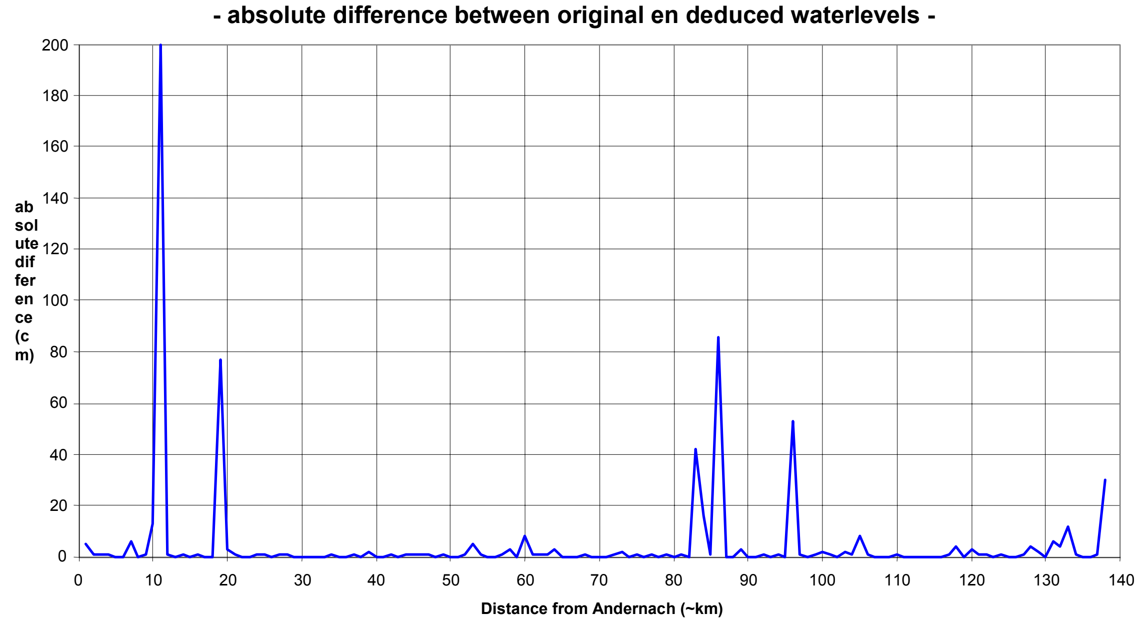
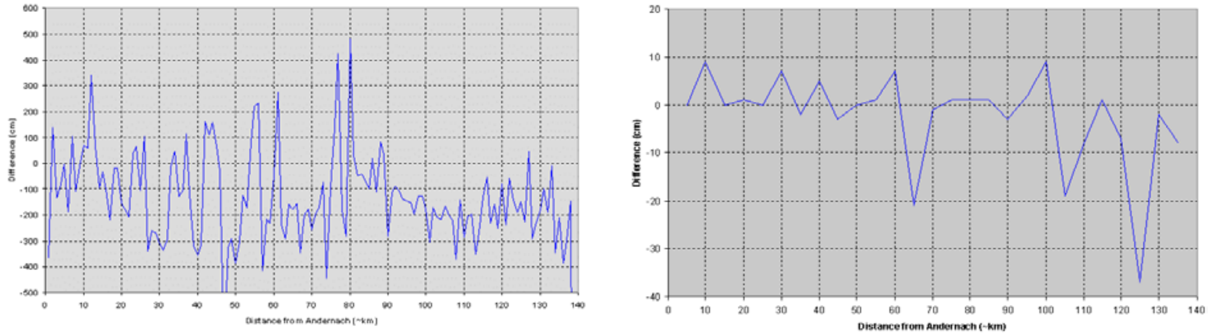


Figure 7: Absolute difference between original and deduced water levels for December 24, 1993, using a ‘perfect’ flood map.

To study realistic situations noise is added to the synthetic flood maps in two different ways: a shift in the co-ordinates representing a flawed geo-referencing method and adding random flooded cells adjacent to the ‘perfect’ flood map. In case of a shift in the flood maps the water levels resulting from intersecting flood maps and the DEM are highly unreliable. This demonstrates the importance of accurate geo-referencing of satellite images. For noise added flood maps we got far better results, but still large errors remain. For both cases the results are unsatisfactory and un-usable for practical application. The method in which calculated and measured (flood map shifted and noise added) flood areas over river reaches of several (7-12) kilometres are compared, proved to give far better results. However, the reaches should be selected with great care.



a) b)

Figure 8: Differences in water level from the calculation and from a 'disturbed' flood map based on a) intersection of flood map and DTM, and b) comparing 'observed' and calculated flood areas for river reaches (Note the enormous differences in vertical scale).

Discussion

From the operational test and the demonstrations for 1993 and 1995 it is concluded that the model is robust, it works well during operation and as an analytical tool in which behaviour of parameters can be studied. Further we observed that the adaptation factors, and thus the corrections, are relatively small. That the adaptation factors are small implies that the model is calibrated with a high accuracy. As a consequence, it implies that the benefits by using data-assimilation techniques are small. The benefits will be higher in rivers of which the behaviour is less known or if the parameters may change more in flood situations.

From flume and river measurements it is known that during high water river dunes can develop. Especially in the flood of 1995 this phenomena has been observed. The model results could have shown a relation between the discharge and the bed roughness. For 1995 we found a correlation that is however too low to confirm this assumption. To study this behaviour we must have an almost perfect model, what is at this moment still not the case. If we look at the negative peak during the strong increase of the water levels, we find that the differences are caused by a time lag between measurement and computation. Due to the fact that the computation is just one hour behind, we force the model to correct this water level difference by changing the lateral discharges and the bed roughness. This example illustrates that the adaptation in this case is not caused by possible river dunes but possibly by an error in the wave celerity. Therefore it can be concluded that not only the discharges and the bed roughness are important, but also the wave celerity and the wave volume.

The flood forecast tool

The flood forecast tool is independent of the hydraulic and hydrological models. The tool is also equipped with a graphical user interface (GUI) in which the results can be easily compared with measurements. Besides actual and forecasted water levels at the desired locations, the interface will also generate actual and forecasted flood maps. These flood maps can be used to verify the actual situation and in case of flood warning. An example of the user interface is presented in Figure 9.

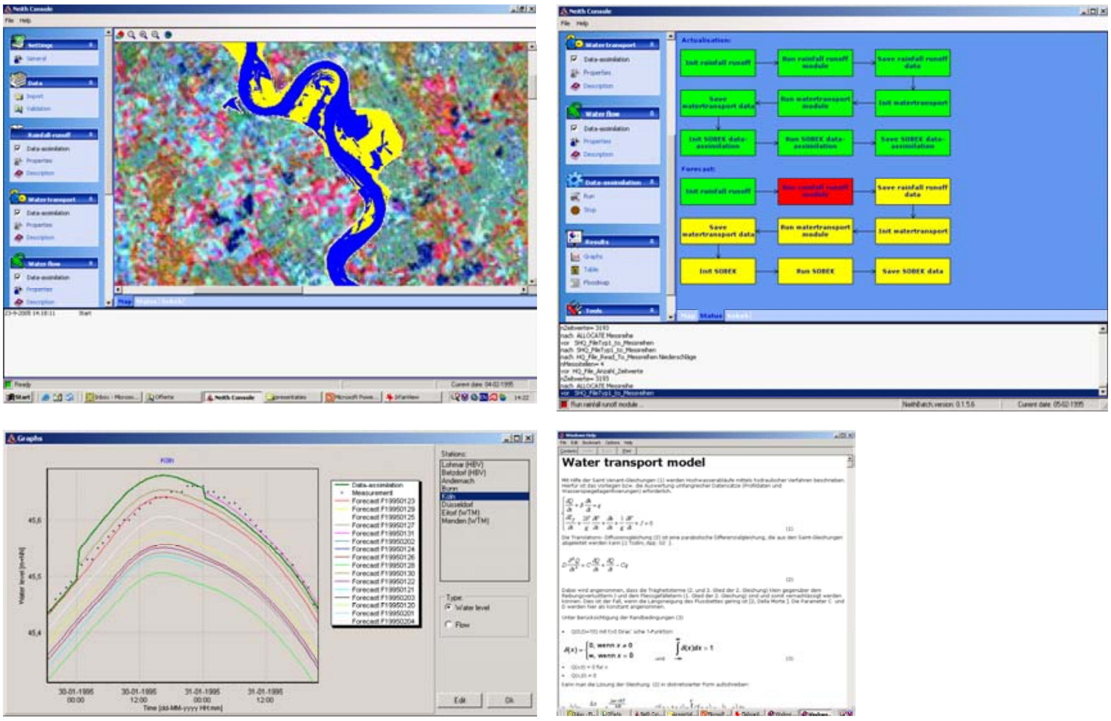


Figure 9: GUI of flood forecast tool; flood maps, status computation, water levels and help files.

4 CONCLUSIONS

Using actual measured water levels to improve the calculation of the actual state of the water system improves the average forecast accuracy to two days ahead. To increase the forecast horizon a longer stretch of the river Rhine must be used since up to 90% of the water flow is determined by the upstream boundary at Andernach.

The operational test and the demonstrations indicate that the tool works robust for the Rhine: the adaptations are small and the tool works under operational conditions. As a consequence of these small adaptations, the improvement of the accuracy is small as well. The benefits are expected to be higher in rivers of which the behaviour is less known.

Changes in the bottom roughness seem to have a weak correlation with the change in discharge in the river Rhine. An increase in the discharge leads to an increase in roughness changes. For further analysis of this assumption, the wave celerity and the wave volume should be studied and taken into account in the data-assimilation.

The results using the synthetic flood maps indicate that the area method is the most promising for applying in the data-assimilation procedure. This could be based on water levels derived using the area method wherein areas are translated to water levels using tables giving area and water level relations that are established using GIS flooding simulations. Another possibility is to compare observed flooding areas to calculated flooding areas in the data-assimilation process.

For both methods it holds that stretches with steep banks (e.g. levees) do not give relevant information above certain flood levels because potential flooding areas are limited and increasing water levels does not result in area increase.
For determination of water levels with a desired accuracy of approximately 10 centimetres the spatial resolution and horizontal accuracy of EO flood maps as well as the vertical accuracy and spatial resolution of DTM's should be high.

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REFERENCES

Huizinga H.J., H.J. Barneveld, C.J.M. Vermeulen, I. Solheim and S. Solbø, 2005: On-line flood mapping using spaceborne SAR-images, waterlevel de-duction techniques and GIS-based flooding models in the river Rhine. ISFD-Conference, Nijmegen, the Netherlands, May 2005.

Länderarbeitsgemeinschaft Wasser (LAWA) und Bundesminister für Verkehr (BMV) 2000: “Pegelvorschrift, Anlage D”, 1991,
Verlag Paul Parey, Spitalstr. 12, Hamburg.

Verboeket-Klavers, H.C. and C.J.M. Vermeulen, 1994: Application of Kalman filtering for calibration of a large one-dimensional flow model.
Second Conference on Advances in Water Resources Technology and Management, Lisbon, Portugal, June 14-18, 1994.
In: Tsakiris, G and M.A. Santos (eds): Advances in Water Resources Technology and Management, Balkema, Rotterdam, pp. 71-76.

Vermeulen, C.J.M., Huizinga, H.J., Barneveld H.J. & J. Silander 2004. Improved flood forecasting and the possible role of satellite images.
Paper presented during the ACTIF conference in Delft, the Netherlands, November 2004.