Data-assimilation in flood forecasting for the river Rhine between Andernach and Düsseldorf

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Abstract

Precise and accurate flood forecasting is essential to decision making with regard to flood management. Untimely or premature flood warning results in millions of Euros in unnecessary damages or claims. To improve flood forecast accuracy actual measured data is combined with estimates using a mathematical flood model, a procedure called data-assimilation. Additionally data-assimilation provides an estimate of the forecast error, which is an useful addition to decision making in flood management. This paper discusses the benefits in using data-assimilation in on-line flood forecasting and the possible use of satellite images, based on a pilot study for the River Rhine between Andernach and Dusseldorf.

Keywords

Data-assimilation, flood forecasting, flood management, hydraulic model instrumentation

1 Introduction

In Europe there is an average of 20 severe floods each year costing the European society billions of Euro annually. Each year huge investments are made into flood prevention, flood early warning, flood mitigation measures and flood management. In flood management precise and accurate flood forecasts are essential. The forecasts are primarily used to alarm crisis management teams and to prepare for high water and floods. Before critical levels are reached preventive actions are taken, e.g. closing of barriers and inspection of dikes. During the high water period the water levels are continuously monitored and the threat of flooding is evaluated on a regular basis. In this evaluation the accuracy and timing of the flood forecasts are essential to the decision making process.

For example the Dutch Centre for Water Management is responsible for the forecast of water levels in the Rhine River at Lobith. The user requirements specify forecasts up to seven days ahead, with an accuracy of 10 centimeter in water level for the first day, up to 40 centimeter four days ahead.

Data-assimilation procedures provide us with a technique to combine model estimates and actual measured data. Starting with the model estimate, measured data is combined with this estimate, resulting in a better, more precise, flood forecast and a reduction in forecast uncertainty. Figure 1 illustrates the data-assimilation process: The blue model estimate and its accuracy (represented by the standard deviation) and red measured estimate combine to the green estimate, a more accurate (smaller standard deviation) and in between model estimate and measurement.

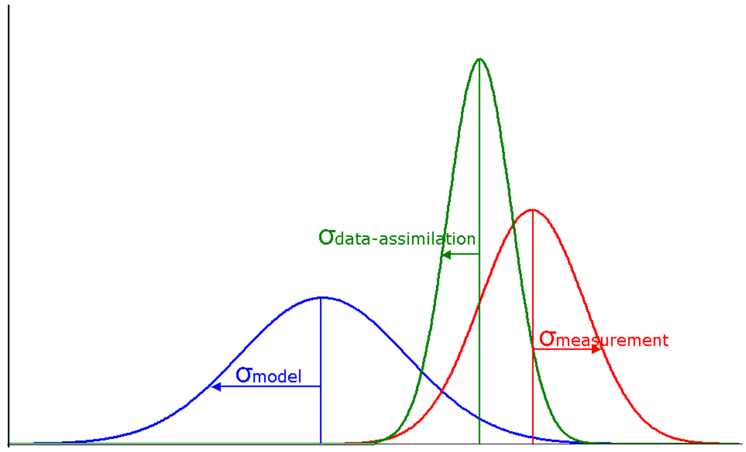

Figure 1
Illustration of the data-assimilation procedure.

In flood forecasting two approaches for data-assimilation are distinguished:
1. Optimization of the actual state of the mathematical model; a more accurate initial model state; or
2. Optimization of the underlying mathematical model; in effect calibrating the model on-line.

The later approach holds the assumption of a well calibrated model. The model produces reliable results but is applied to new situations, e.g. floods. It is expected the model will perform correctly, but slight modifications to model parameter are plausible.

2 Data-assimilation and forecasting

In flood forecasting two aspects are important:
1. a timely forecast of water levels above critical levels; and
2. accurate forecast of the water levels.

Timely water levels forecasts above critical levels provide the water manager with enough lead-time to prepare for floods (i.e. preparation of flood defenses, activating crisis management teams, etc.). In extreme situations when flooding seems unavoidable flood management involves evacuation of flooding-prone areas. Evacuations decisions are complex and costly decisions and require reliable and accurate forecasts of lead-time to flooding.

Data-assimilation is a technique to combine estimates to one forecast, usually combining model estimates with measured data. In the EU research project FloodMan data-assimilation techniques are developed and tested on the stretch of the River Rhine between Andernach and Düsseldorf, including its tributary the River Sieg. The test involved a model instrumentation comprising a hydrological model for the Sieg tributary and a hydraulic model for the River Rhine. It's measurements comprised water levels at Bonn and Cologne, and flood maps derived from satellite data.

The data-assimilation procedure is illustrated in Figure 2. The left column is the prediction: the estimation of flow and water levels starting from the last estimate up to the present time (at which measurements are available). The right column is the data-assimilation of the models.

- Prediction
  We start with de hydrological model and predict the flow into the Rhine tributaries. These inflows are used to compute the total inflow of each tributary into the Rhine. These total flows, together with the measured discharge at Andernach and measured water level at Düsseldorf are used in the hydraulic model to compute water levels and flows. Predictions are made using the mathematical model in real-time.
- Data-assimilation
  The data-assimilation starts with the hydraulic model, using actual measured water levels, resulting in better estimates for water levels and flows. The newly estimated flows are used as 'measurements' for the hydrological model. The new estimated parameters for both models are used in next calculation cycle (e.g. next day).
- Forecast
  Based on the actual situation, e.g. the newly estimated parameters in the hydrological and hydraulic model, a flood forecast is made using weather forecast and forecast flow.

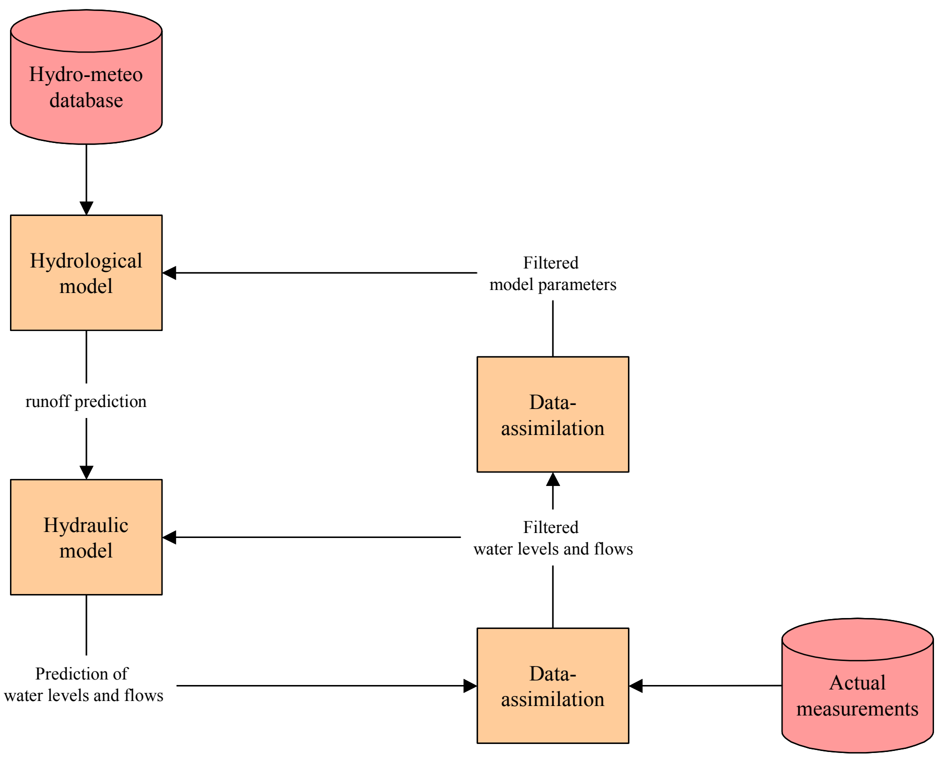

Figure 2
Schematic layout of data-assimilation procedure.

Data-assimilation comes with a price; it increases calculation time of the model instrumentation significantly and makes the flood forecast procedure much more complex (e.g. requiring special expertise and additional maintenance to the model instrumentation).

For the flood management system existing models for the River Rhine basin were used. The data-assimilation procedure is additional to the existing models, using the standard input and output options of the models. The hydrological and hydraulic models are thus regarded as black-boxes. Although the overhead in computer handling is a burden, the advantage is that the underlying model is easily replaced with another model. For example replacing the Sobek model with a Mike 11 model.

For the pilot of the Rhine River from gauging station Andernach to gauging station Düsseldorf (130 km) a model instrumentation is developed for operational flood forecasting. New forecasts are made on a regular basis, e.g. once a day.

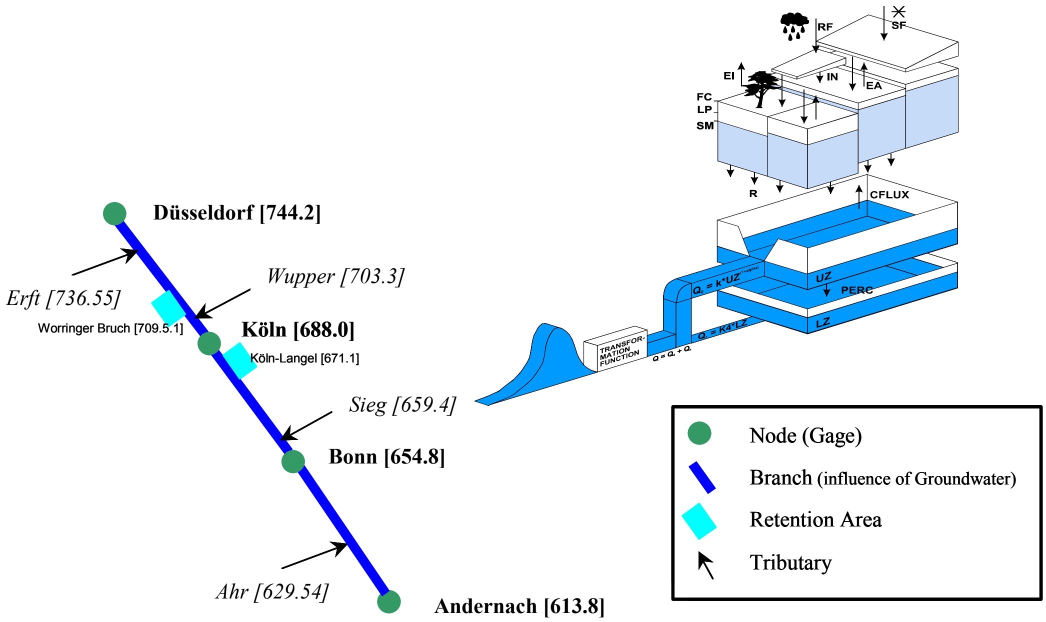

Figure 3 Schematic layout of model instrumentation

2.1 Hydrological model (HBV)

The Sieg catchment is divided into four sub basins: Obere Sieg, Mittlere Sieg, Untere Sieg and Agger. Each sub basin is simulated separately in HBV and their discharges are used as input for the flood routing routine. HBV is a conceptual rainfall-runoff model that simulates discharge using precipitation, reference evaporation and temperature as input. Per sub basin different types of land use and areas with different altitudes may be distinguished. Air temperature data are used to calculate snow storage and melt. The model for the Sieg is run with daily values of reference evaporation and hourly data for precipitation and temperature.

2.2 Hydraulic model (Sobek)

The hydraulic model of the River Rhine consists of a calibrated and verified one-dimensional model (Sobek). The model uses boundary conditions at Andernach (flow) and Düsseldorf (water level). The lateral discharge from the Sieg is calculated with HBV, the lateral discharges from the other tributaries Ahr, Wupper and Erft are specified by measured discharges or by measured water levels and stage discharge relations.

3 Data-assimilation

In developing the data-assimilation procedure a sensitivity analysis was performed to determine the key-elements in both the hydrological and hydraulic model.

3.1 Sensitivity anaysis on the hydrological model

Two types of parameters are investigated in the HBV model: model parameters and state parameters.

A change in model parameters for field capacity, the recession coefficient and lag causes the discharge of 'Obere Sieg' to differ from the reference situation. They have a large influence on the model output. A negative change in the field capacity results in a higher peak and a time displacement of 2 hours. The recession is slower than in the reference situation. A negative change in the recession coefficient also results in a higher peak and a time displacement of two hours, but the recession is now faster than in the reference situation. A negative change in the lag results in a faster history, a higher peak, which arrives earlier, and a faster recession.

In case of the model sensitivity to the initial values of the state variables, especially soil moisture content and upper zone turn out to be important. Lowering the initial storage of the upper zone and soil moisture content results in a lower discharge during the whole high-water period. The effect of changing the upper zone is more obvious than the effect of changing the soil moisture content, nevertheless their influence on the discharge extinguishes within ten days. For data assimilation has been chosen for the parameters field capacity and the fast runoff component because they are the most sensitive and uncertain parameters. The results show that adapting these parameters give not the desired results. Apparently the fast components in the catchment are not modelled accurate enough. Changing the initial state or the input in the model is an alternative.

Since the soil moisture content and the upper zone have such a significant effect it was decided to apply the data-assimilation on the state parameters. The procedure itself is not operational yet.

3.2 Sensitivity anaysis on the hydraulic model

A sensitivity analysis has been carried out for roughness, discharge of river Sieg and ground water parameters. The bed roughness of the main channel shows the largest effects. The discharge of the river Sieg is also important. The effects of roughness of the bank section, the roughness of the floodplain and the ground water parameters are less important.

Parameter	Influence	Uncertainty
Roughness main channel	Large	Moderate
Roughness bank section	Moderate	Moderate
Roughness floodplain	Moderate	Moderate
Discharge Sieg	Moderate	Large
Groundwater	Small	Moderate/Large

Table 1
Sensitivity analysis results for the hydraulic model.

The effect of roughness changes in the main channel on the water levels is calculated at the locations (stations) Andernach, Bonn, Cologne and Düsseldorf. Also backwater curves that affect the water levels upstream are calculated. A change of 1% in the roughness leads to water level changes at the upstream location of the branch of around 5 cm. The effects are quite constant for each branch and its upstream location.

The behavior of the river Sieg on the top water levels in the Rhine river is linear; a factor two in the discharge of the river Sieg leads to water level difference of around 20-25 cm. The effect is almost constant along the river stretch. A linear interpolation gives an accuracy of around 2 cm. Time effects however should not be ignored: two days before the peak discharge of the Rhine occurs the effect is about 50% stronger. Two days after the peak, the effect is reduced with a factor two. The effects in between the stations can be calculated with formulas that are derived from the Bresse approach for backwater curves. The used formulas have accuracy in the water levels of around 5 cm. The total found minimum accuracy after calibration is around 15 cm.

Based on influence and uncertainty of the parameters involved the bottom roughness in the main channel and the lateral discharges are selected as parameters for the data-assimilation. The sensitivity analysis provides information on the relative changes in the parameters needed to minimize the differences between model and measurements.

3.3 Data-assimilation

The data-assimilation algorithm is applied tot the flood of December 1993. In Figure 4 the forecast for location Cologne (Köln) is given for December 23 up to December 31, using measured data up to December 23. The blue line depicts the difference between forecast and measured water levels without data-assimilation, the red line the differences with data-assimilation (data-assimilation on measured data up to December 23 of course).

The data-assimilation improves the water level forecast. Since Andernach to Bonn is a relatively short stretch, the data-assimilation accounts only for the improved results in the first two days. The small differences between forecast and measured data thereafter are due to the perfect forecast for the input at Andernach

The adaptations by the data-assimilation on the model parameters were small indication a well calibrated hydraulic model for 1993 flood and that robust data assimilation procedure.

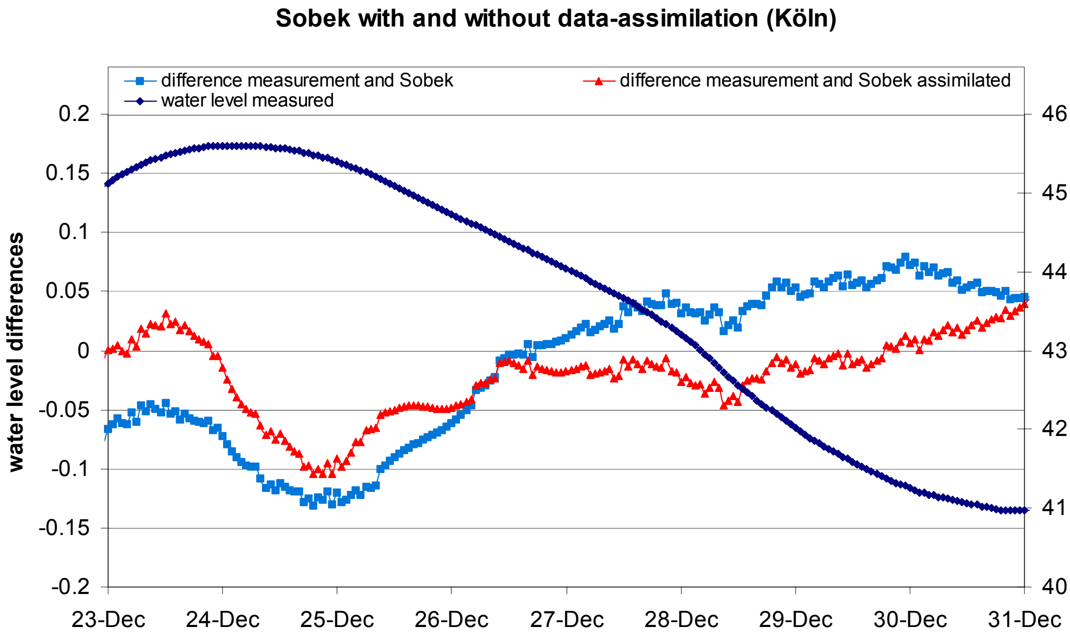

Figure 4
Result of data-assimilation on forecast water levels at Bonn.

4 Role of satellite data in flood forecasting

Flood maps from satellite data could play an important role for improved flood forecasting. Flood extent as well as flood levels (calculated from combining flood maps and digital elevation model (DEM)) could be additional sources of information. For the Rhine river there are no suitable satellite data available for historic flood periods. Therefore synthetic flood maps were used to study the possible role of satellite data for improved flood forecasting. These synthetic flood maps are generated using calculated water levels and a DEM.

The synthetic flood maps give a perfect fit to the model representation of the flooded area. To incorporate model errors two modifications were made: a shift in the data, representing an error in georeferencing and random disturbances on grid cells representing classification errors.

A transformation from flood extent to the river cross-sections gives poor results: the inaccuracies in the flood maps dominate the process. Better results were derived when cross-sections were combined (area-method).

Further research showed that the area-method requires a careful selection of river stretches:

- The selected areas comprise sufficient river length to reduce to errors of georeferencing (about 10 km)
- The stretches have to be more or less straight to reduce the errors of georeferencing, so no curved river stretches should be selected.

- The flooded area and water level in a stretch need to be correlated within the whole range of water levels; i.e. the areas have gentle valley slopes and no steep banks.

The quality of the satellite data has great influence on the accuracy in flood forecasting. First, the resolution of the satellite image. Second, the noise in the image, because it greatly influences the quality of the derived water levels. The noise in the image is why no real radar images were used. With the tested real radar images large differences appeared between the water levels from the Sobek-model and radar image (Figure 5). This implies that the quality of the currently available classified radar images is insufficient.

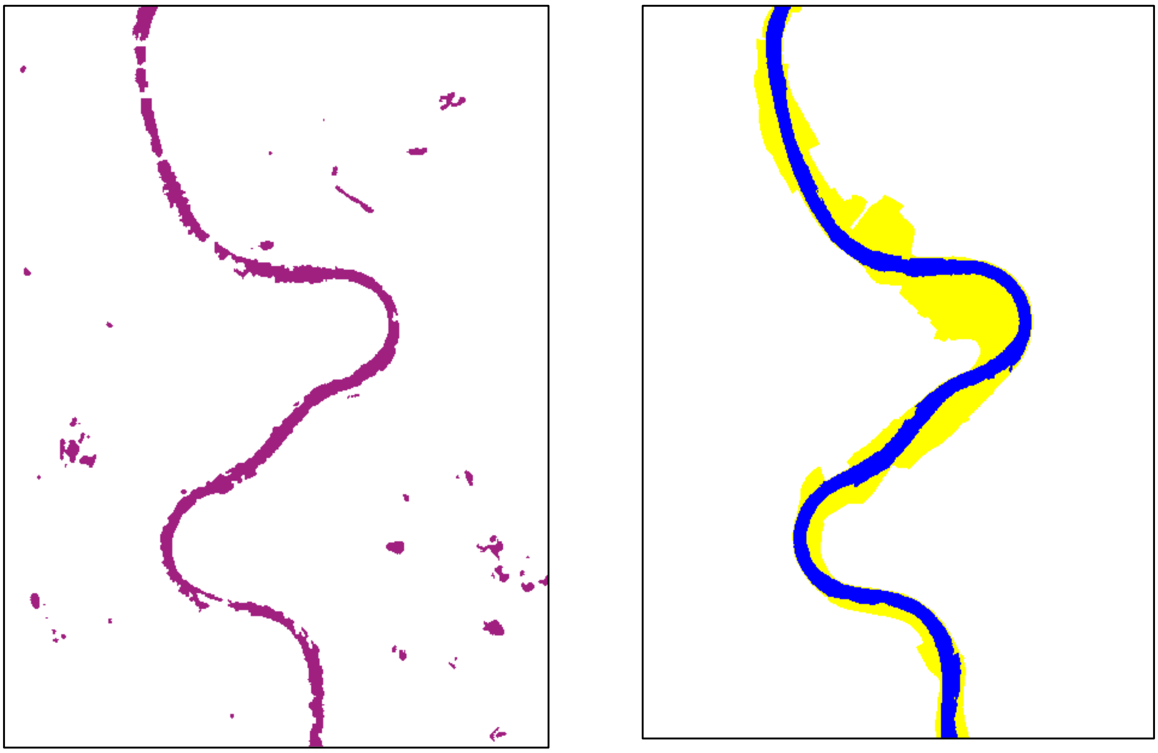

Figure 5
Part of the classified radar image (left) and modelled flood map (right) of 7 November 2004.

5 Conclusion and further research

The forecast system developed uses data assimilation techniques to optimize forecast water levels. The forecast system comprises a hydrological model (HBV) and a hydraulic model (Sobek). Based on a sensitivity analysis on these models, a selection of parameters for data-assimilation has been made.

The data-assimilation procedure is based on the accuracies in the model estimate and the measurement, represented by the specified standard deviation. In this way the uncertainty of the data is taken into account in the forecast water levels. For example if the water levels from the satellite images are uncertain, the deviation will be higher. This implies that the satellite info will be less important to the solution.

Data-assimilation changes model parameters as bed roughness and the lateral discharges in such a way that calculations agree as good as possible with all measurements (both from gauging stations and the satellite images). We observe how much the roughness changes or how much the discharge in one of the tributaries is adapted. This information gives us insight how realistic the solution is.

The model instrumentation also incorporates a model that derives water levels from satellite images. The satellite images provide flood maps that are related to actual water levels using a digital elevation data. Data-assimilation using flood maps from satellite images is most promising in areas where field measurements are scarce and having gentle transverse bed slopes in the floodplains. If we use the system in a densely measured river basin, the advantages are small, because the data-assimilation will follow the more accurate field measurements.

The advantages of flood forecasting models using data-assimilation techniques are well-known. The FloodMan project has shown that satellites can not only provide information on flood extent to illustrate the actual situation, but can also provide additional information to be used in these flood forecasting systems. Flood maps can be used as an indication of water level. However, at present both the frequency of the satellite data and the spatial accuracy of the flood extent maps is insufficient. Also the short term ordering of satellite images proved to be difficult.
The satellite information will definitely be of high value in remote areas where field data is scarce. In addition satellite information may also be of importance for well monitored river system, for example when gauging stations fail or uncontrolled inundations (dike breaches) occur.

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