IMPROVED FLOOD FORECASTING USING IN SITU 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 European Union (EU) research project FloodMan (Near real time flood forecasting, warning and management), data-assimilation techniques have been developed, demonstrated and validated for integrated hydrological and hydraulic computer models. The developed tools have been applied to two pilot sites in Germany and Finland.

Major challenge was to assess the feasibility of using satellite images as an additional spatially distributed source of information for on-line updating of modelling systems. Algorithms were developed to assess soil moisture and flood extent from radar images (Synthetic Aperture Radar - SAR).

In Germany model instrumentation was 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). Due to the restricted availability of satellite images synthetic flood maps were applied to test the approach.

In Finland the existing hydrological flood forecasting system was extended so as to apply satellite information on soil moisture and flood extent. Although the frequency of the satellite images is not sufficient yet, the information on the surface water storage situation in remote upstream peat land areas showed the potential to improve the accuracy of flood forecasts downstream.

BACKGROUND

The FloodMan-project (2003 - 2006) addressed the topic of near real time flood forecasting, warning and management. The overall goal of the FloodMan project was to develop, demonstrate, and validate an information system for cost effective flood forecasting and management using Earth Observation (EO) data, in particular space borne SAR data, hydrological and hydraulic models, and in-situ data. The prototype system provides near real time information on the flood event, better flood predictions, and may improve best practices for management of rivers and their catchments, including hydropower production planning.

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

In the project two pilot basins have been studied. The first pilot basin is a part of the Rhine in Germany between Andernach and the Düsseldorf. The second pilot is the Kemijoki River in northern Finland. After a discussion on the possible role of satellite images for flood forecasting these two pilots will be discussed in this paper.

ROLE OF SATELLITE DATA FOR FLOOD FORECASTING

In the FloodMan project possibilities were investigated to assess the hydrological state in a river basin using SAR (Synthetic Aperture Radar) images. Independent of cloud cover these radar images can provide information on flood extent and soil moisture conditions in the basin. Algorithms have been developed for this purpose.

Soil moisture information proves to be valuable for describing the initial situation in a hydrological model.

Flood maps derived from satellite imagery 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 can provide information on flood extent (area) as well as water levels in large flooded areas.

For the study on 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. Huizinga, et al. (2004) proved that methods for deriving directly the water level from combining observed flood maps and digital elevation maps (DEM) (Figure 1) are very sensitive for small errors in georeferencing of the maps and local errors in the inundation.

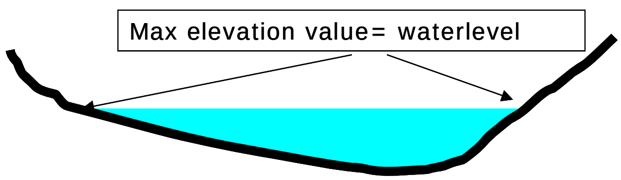


Figure 1. Determination of water levels by masking a DEM by means of a flooded area.

The method in which differences in observed and calculated flood areas for river stretches of several kilometres are compared proved to be more robust. This method was therefore implemented in the data-assimilation procedure of the flood-forecasting model of the Rhine River. This so-called ‘area method’ is illustrated in Figure 2. The figure shows that georeferencing errors will not influence the total flooded area in a reach as long as the boundaries of the reach are selected properly.

Figure 3 shows the difference between two methods. In Figure 3-a the ‘measured water’ level is derived from combining flood extent with DEM (Figure 1). Figure 3-b presents the results when the differences between measured and computed flood area for longer river stretches are translated in a mean water level difference for each reach. Figure 3 shows that the latter method is much less sensitive for errors in the measured flood map.

RHINE

Pilot reach

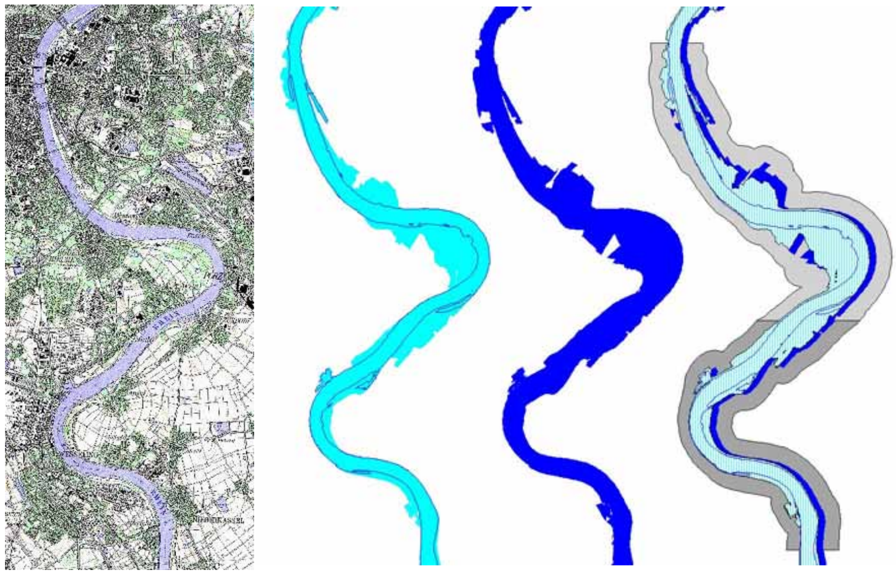
For the Rhine River pilot a reach of about 130 km between gauging station Andernach and gauging station Düsseldorf was selected (Figure 4). This river reach is modelled with a one-dimensional hydro-dynamical model (SOBEK). For the inflow of the Sieg River (downstream of Bonn) a hydrological model (HBV) of the basin (2,862 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. The other tributaries of the Rhine River have been included in the model as lateral inflows.

The coupled modelling system forms the core of the flood forecasting system described under *‘Flood forecasting’*.

In situ data

From the German measuring systems information is online available on precipitation, temperature, evaporation as well as water levels and discharges at the gauging stations (Figure 1). These data are used as boundary conditions for flood forecasting system, but also as information for on-line updating of the model as described under *‘Flood forecasting’*.



calculated satellite image comparison ‘Area method’

Figure 2. Illustration of ‘area method’

a)

b)

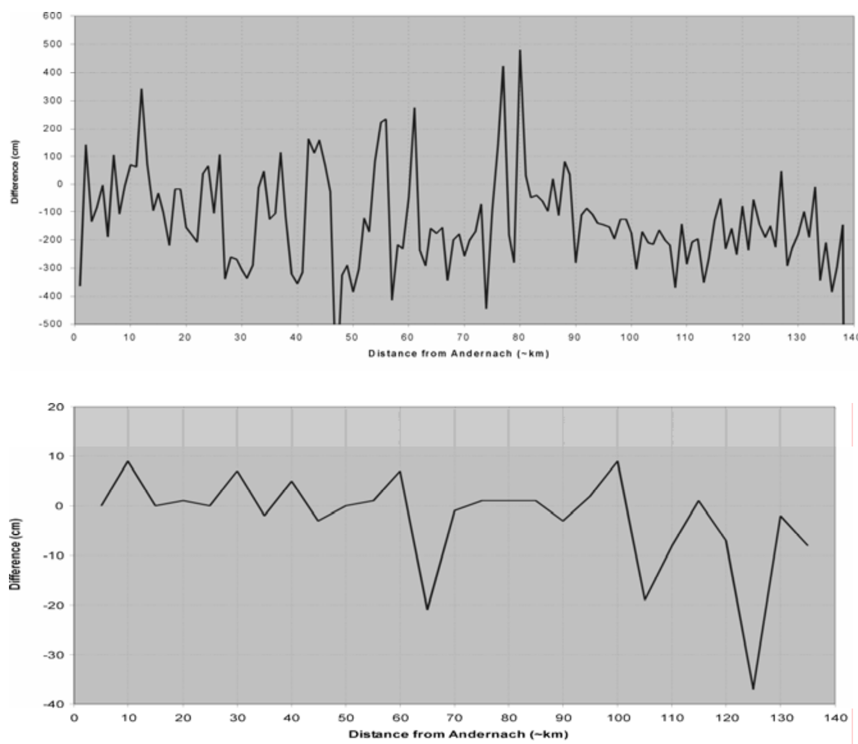


Figure 3. Differences in water level from the calculation and from a ‘disturbed’ flood map based on a) intersection of flood map and DEM, and b) comparing ‘observed’ and calculated flood areas for river reaches (Note the enormous differences in vertical scale).

Satellite data

In case of the Rhine pilot flood maps from SAR-images have been considered as a possible additional source of information for flood forecasting. An example of an image during normal flow conditions is presented in Figure 5. Unfortunately usable SAR-images were sparse during the project period because of calibration activities for the satellite every time it passes this part of the world.

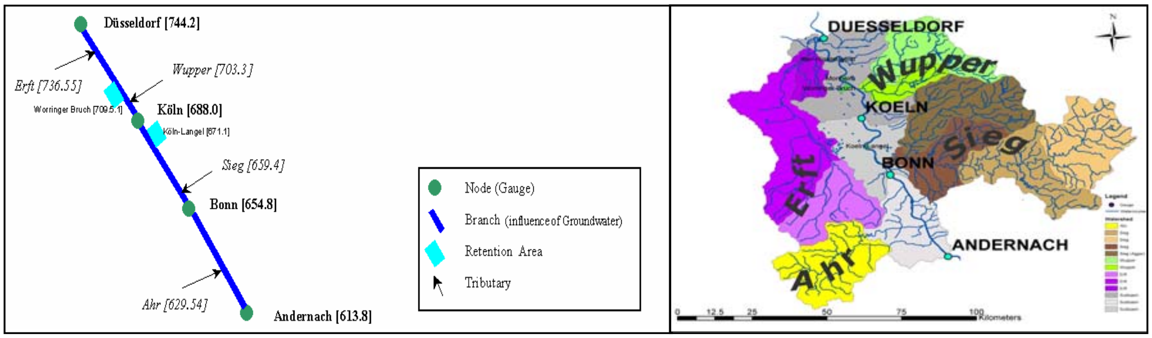


Figure 4. Schematic layout of the model for the Rhine River and its tributaries.

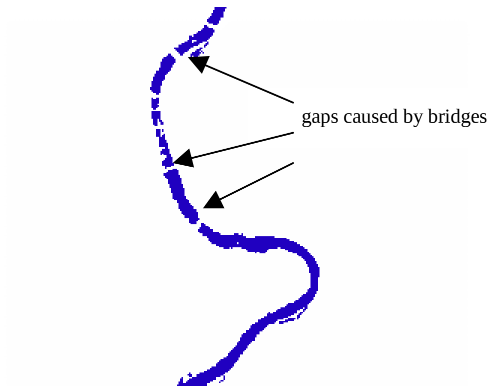


Figure 5. SAR flood map on 15 February 2002 near Cologne

Flood forecasting

Model instrumentation has been developed including a flood forecasting procedure consisting of three phases: actualisation, data-assimilation and forecast. In the situation with only in-situ data these phases comprise:

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.

When also flood extent maps are taken into account, these will form an additional source of information in the phase of data-assimilation.

The flood forecasting system is called Neith and has been embedded in a Graphical User Interface. The model calculations are made with a one-hour time step; data-assimilation is performed once a day. The data-assimilation technique applied is described in more detail in Vermeulen, et al. (2005) and requires no changes in the computer code of SOBEK and HBV. It can therefore be applied to any modelling system.

Results

An operational test was carried out with the developed system in co-operation with the Bundesanstalt fur Gewässerkunde (BfG) in Germany on the 9th and 10th of February. The test had three main objectives:

1. verify the flood forecasting methodology;
2. verify the data-flow and validation process for flood forecasting;
3. verification of flood-forecasts.

It proved to be possible to produce and disseminate forecasts for 10 days ahead to the BfG consisting of:

- discharges at several locations in the Rhine;
- discharges at several locations in the Sieg;
- water levels at several locations in the Rhine;
- actual and forecasted flood maps for the river Rhine.

For the flood events of 1993 and 1995 forecasts were made using the hydraulic and hydrological models and data-assimilation on measurements.

Figure 6 shows for two branches of the SOBEK-model the adaptation of the bed roughness (one of the changed model parameters during data-assimilation) for the 1995 flood. It can be observed that:

- the adaptation changes in time;
- the adaptation is almost zero at the high water peak (note: original model was calibrated on this period of the flood);
- 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.

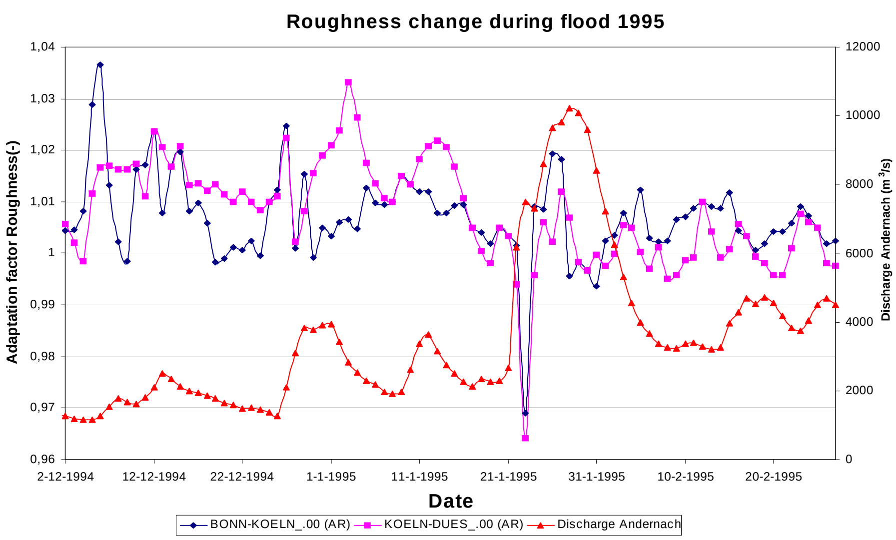


Figure 6. Bed roughness change (left axis) and the discharge at Andernach (right axis)

The test showed that the forecasts could be improved only slightly. Main reason is, that the base model for this river is well calibrated. Unfortunately no satellite images were available for this flood, so the implemented algorithm for the 'area method' could not be tested.

KEMIJOKI

Pilot reach

The Kemijoki river basin in Northern Finland consists of several large peat land areas in the upstream part of the water basin, which is sparsely populated. Water flows from peat lands to the sea within 2 to 7 days. It passes Lake Kemijärvi and continuous through several cities amongst which the main city of Rovaniemi. Main floods are generated in these large peat land areas, from which only poor digital elevation model exists. This means that the water volume is difficult to estimate in those areas. With information on the flood extents better estimates of water volumes can be made to improve hydrological forecasts. In addition this information helps to optimise operation of the Kemijärvi Lake for flood management downstream and hydropower production.

The Finnish Environment Institute operates a watershed simulation and forecasting system (WSFS), which covers over 85% of the land surface. The model development has started from a rainfall-runoff model having the same structure as the widely used HBV-model in Scandinavia (SYKE, 2007). The model simulates snow cover, soil moisture, soil evaporation, ground water, runoff, rivers and lakes. The simulation is on sub-basin level. The mean size of sub-basins is 60 - 100 km^2.

In situ data

In the Kemijoki, there are around 40 water level and discharge stations transmitting data on daily basis. Additionally, snow line measurements are done in 15 places on average five times a year to predict flooding due to snowmelt. There is basically no soil moisture data available from the area. Standard error of the digital elevation model (grid size 25 m) is around 1.7 m.

Although a fair amount of gauging stations is in place, in sparsely populated areas there are still some points in the water basin, which are over 100 km away from the nearest gauging station.

Satellite data

The satellite coverage for the area is good and radar data can be received almost every day. Existing land use data is mainly based on satellite observations. Barren soil and large swamp areas with sparse small trees hamper accurate assessment of the soil moisture. Flood extent in those flat flood plains is simpler to detect.

Flood forecasting

In the adapted forecasting system WSFS information on flood extent from satellite images is applied in the following way:

1. the hydrological model simulates the rainfall-runoff process and discharges in the river;
2. in addition the wetted area is simulated;
3. the wetted area simulation is corrected to agree with the observed flood extent by correcting the input runoff and discharge data;
4. the hydrological model simulation is corrected to agree with the corrected runoff and discharge data.

Results

Satellite soil moisture data in the WSFS was available for the Kemijoki basin for two days in years 2004 and 2005. This was not enough for testing the data assimilation using soil moisture data, because for proper data assimilation the comparison of the observed and simulated data in several historical situations is needed. However, a system was developed for presenting the soil moisture data from satellite images on detailed maps for the users of the hydrological forecasts. These maps are a valuable source of local information on the soil moisture and provide additional information for the hydrological forecasts if the satellite data is available in real time.

The assimilation of the satellite flood extent data into the hydrological model the WSFS was demonstrated in the spring 2005 by making every day hydrological forecasts over the spring flood period with and without the satellite data. The discharge forecasts without additional satellite data proved to be accurate already. The error of the forecasted maximum discharge was less than 5% even one week before the flood. Therefore no significant improvement in the accuracy of the forecasts was achieved by adding satellite information for this period.

However, it is likely that satellite information will improve the forecasts in other periods. The accuracy of snow simulation in the Kemijoki basin is such that the estimated uncertainty in the surface water volume at the end of the snowmelt period is up to 20 mm. If there is high precipitation during the snow melt period the uncertainty can be remarkably higher. Figure 5 shows the effect of 20 mm uncertainty in the surface water volume on the accuracy of the discharge forecast. The Figure shows that when satellite images can correct the error in water volume at the beginning of the forecast (14 May in Figure 7), the error in the predicted maximum discharge 4 days later can be reduced by 10 - 20%.

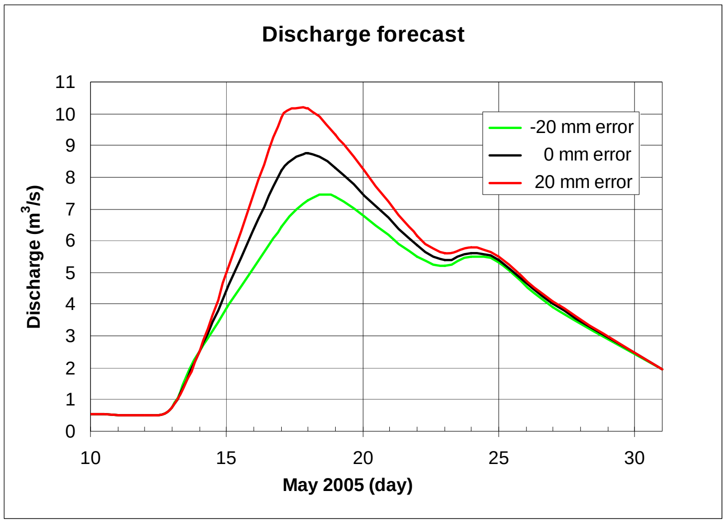


Figure 7. A test case for showing the effect of 20 mm uncertainty in the surface water volume on the accuracy of the discharge forecast.

The flood extent product and flood mapping in near real time. The city of Ivalo, 27 May 2005: The flood was due to snowmelt and heavy rains prior to the flood. About 25 people were evacuated. A high resolution (10 m) RSAT-1 scene was ordered two days prior to the flood. The Flood Extent product was delivered via the FloodMan system within 3-hours after the data acquisition. Flood forecasts and flood hazard maps were shown on the Internet page with flood forecasts (see also http://wwwi9.ymparisto.fi/i9/en/).

DISCUSSION

The flood forecasting systems for the Rhine and Kemijoki Rivers prove to be robust and accurate tools for predictions up to 10 days ahead. Algorithms have been added to include information from satellites (SAR-mages) in the data-assimilation process of these flood-forecasting tools.

The possible improvement of the flood forecasts using satellite images could only be illustrated using theoretical test cases because:

1. the existing models are already well calibrated;
2. during the FloodMan project period insufficient usable satellite images were available.

However, the analyses showed, that when information from satellite images on soil moisture, flood extent or water level can be made available nearly online, this information can be valuable for improving accuracy and lead-time of forecasts. During the FloodMan project it was demonstrated that raw satellite information could be processed within 3 hours into usable information (i.e. flood extent and soil moisture maps).

Developments in acquisition and processing of satellite images go fast. Frappart, et al. (2006) show an interesting application of satellite information for the lower Mekong. The paper shows that direct water level measurements using a radar altimeter is promising, also for inland waters. It is expected that in the coming years satellite information will provide an important additional source of information for improved flood forecasting. This will specifically be the case for river basins were in situ on-line data is scarce.

ACKNOWLEDGEMENTS

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REFERENCES

Frappart F., K. Do Minh, J. L'Hermitte, A. Cazenave, G. Ramillien, T. Le Toan and N. Mognard-Campbell, 2006. *Water volume change in the lower Mekong from satellite altimetry and imagery data*. Geophys. J. int. (2006) 167, pp 570-584.

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

SYKE, 2007. *Basic information about Watershed Simulation and Forecasting System in Finland*. www.environment.fi > State of the environment > Surface waters > Current hydrological... > Hydrological forecast... > Basic information of WSFS.

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

Vermeulen C.J.M., H.J. Barneveld, H.J. Huizinga and F.J. Havinga, 2005. *Data-assimilation in flood forecasting using time series and satellite data*. International conference on innovation, advances and implementation of flood forecasting technology, Tromsø, Norway, October 2005