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APPLICATION OF SATELLITE DATA FOR IMPROVED FLOOD FORECASTING AND MAPPING

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ABSTRACT: Reliable and timely information is essential for appropriate flood management. The EU research project FloodMan (Near real time flood forecasting, warning and management) focussed on the possible role of satellite information for improved flood forecasting. The project, which started in 2003 and was finalised in 2006, addressed the topic of near real-time flood forecasting, warning and management. The overall objective of the 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 (Synthetic Aperture Radar) data, hydrological and hydraulic models, and in-situ data. 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. This paper reviews the final results of the project. In addition we present the results of a follow-up study in Finland on the value of satellite images for flood mapping and detection of potential water detention areas.

The major challenge of FloodMan 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.

In Germany a model instrumentation was developed and applied in a pilot study of the river Rhine. The model combines a hydraulic model representing the Rhine River between Andernach and Düsseldorf with a hydrological model for the Sieg tributary. To increase the accuracy of flood forecasts, data assimilation is applied, using temporal data (time series of water level measurements) as well as spatial data (flood maps derived from satellite data). Due to the restricted availability of satellite images in the project period, synthetic flood maps were applied to test the approach.

In Finland the existing hydrological flood forecasting system was extended in FloodMan so as to apply satellite information on soil moisture and flood extent. The satellite information was later on also used for floodplain mapping and evaluated for its potential use for detection and quantification (volume assessment) of water detention areas intended for floodwater storage.

Key Words: remote sensing; hydrological modelling; flood mapping; water detention.

1. BACKGROUND

The FloodMan-project (2003-2006) addressed the topic of near real-time flood forecasting, warning and management. The overall objective 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 for flood extent and soil moisture, in-situ data, hydrological and hydraulic models. Later on data have been used to detect possible detention basins in Finland, which supports implementation of the new EU Flood Directive of the European Parliament (October 2007).

Satellite data may provide near real-time information on the flood event, better flood predictions, a tool to detect flood detention areas and improve management of rivers and their catchments, including hydropower production planning.

In FloodMan two pilot cases have been studied. The first case is a river basin in a part of the Rhine in Germany between Andernach and the Düsseldorf. The second case is a river basin in the Kemijoki River basin 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.

2. 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.

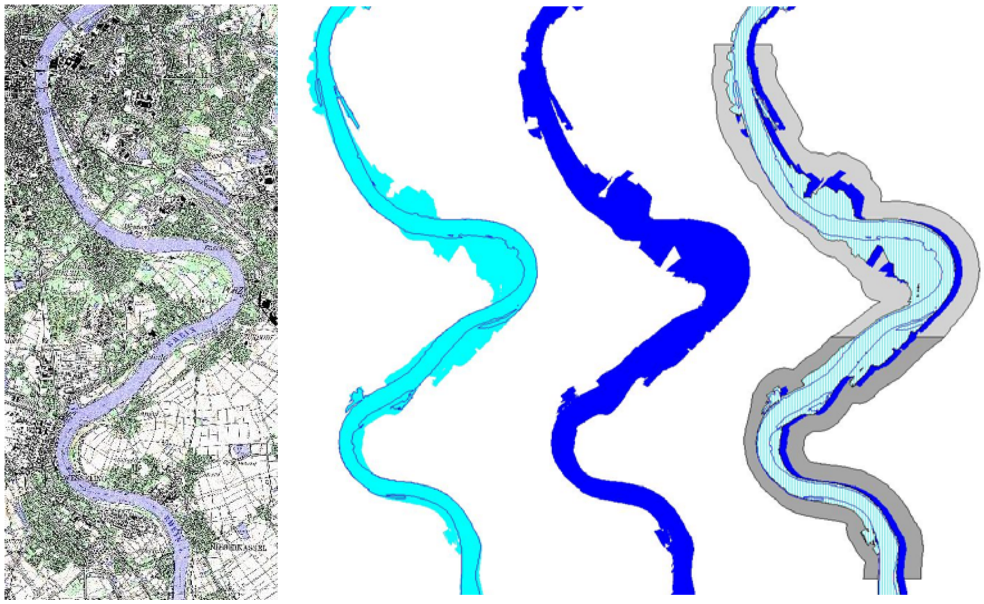
Soil moisture information proves to be valuable for describing the initial situation in a hydrological model.

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 for large flooded areas.

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 the water level directly from combining observed flood maps and digital elevation maps (DEM), are very sensitive for small errors in georeferencing of the maps and local errors in the inundation.

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 (see Section 3). This so-called 'area method' is illustrated in Figure 1. The figure shows that georeferencing errors do not influence the total flooded area in a reach as long as the boundaries of the reach are selected properly.

In addition to soil moisture and flood extent maps from SAR-images, a short survey on available techniques for direct measurement of river water levels from space was carried out. At that time (and apparently to date) altimeter measurements from satellites were not feasible for rivers, but only for very wide water bodies.



calculated satellite image comparison ‘Area method’

Figure 1: Illustration of ‘area method’

3. GERMANY

3.1 Pilot reach

For the Rhine River pilot a reach of about 130 km between the gauging stations Andernach and Düsseldorf was selected (Figure 2). 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 other tributaries of the Rhine River have been included in the model as lateral inflows.

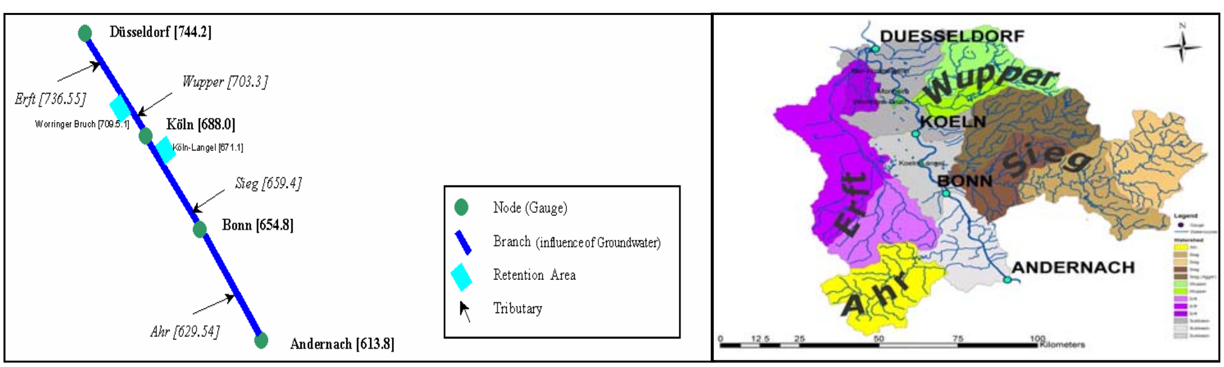


Figure 2: Schematic layout of the model for the Rhine river and its tributaries.

The coupled modelling system forms the core of the flood forecasting system described under *“Flood forecasting”*.

3.2 In situ data and satellite 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. These data are used as boundary conditions for the flood forecasting system and also as information for the on-line updating of the model as described under *"Flood forecasting"*.

In the Rhine-case pilot flood maps based on 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 3. Unfortunately usable SAR-images were sparse during the project period due to conflicts with a calibration site for the satellite in Flevoland (NL) nearby. The project had thus little success in acquiring data over the Rhine area.

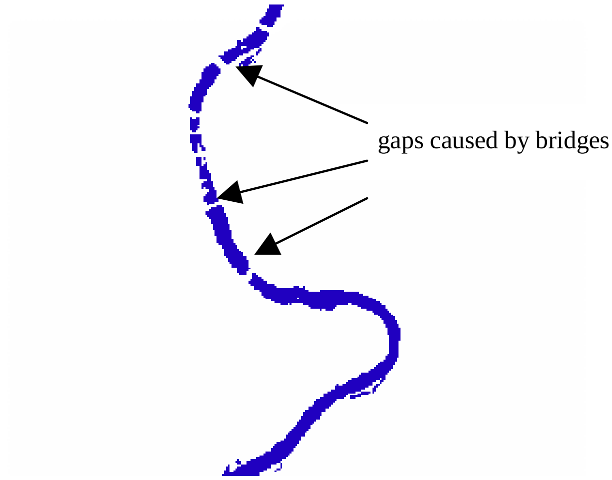


Figure 3: SAR-derived flood map on February 15th 2002 near Cologne

3.3 Flood forecasting

A 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:
    a. Use measured precipitation, temperature and evaporation to calculate the discharges in the sub-basins of the Rhine catchment.
    b. 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
    a. 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
    a. Use forecasted precipitation, temperature and evaporation to forecast the discharges in the sub-basins of the Rhine catchment.
    b. 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.

3.4 Results

An Operational test was carried out with the developed system in co-operation with the Bundesanstalt für Gewässerkunde (BfG) in Germany on the 9th and 10th of February. It proved to be possible to produce and disseminate water level, discharge and flood extent forecasts for 10 days ahead to the BfG.

For the flood events of 1993 and 1995 forecasts were made using the hydraulic and hydrological models and data-assimilation on measurements. This test showed that the forecasts could be improved only slightly. Main reason is, that the base model for this river is already well calibrated. Unfortunately no satellite images were available for this flood, so the implemented algorithm for the ‘area method’ could not be tested.

4. FINLAND

4.1 Pilot reach

The Kemijoki river basin (65 000 km^2) 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 where 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 regulation 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 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.

4.2 In situ data and satellite

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 meters) is around 1.8 meters. 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.

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.

4.3 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.

4.4 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 of 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.

The assimilation of the satellite flood extent data into the hydrological model the WSFS was demonstrated in the spring 2005 by making hydrological forecasts every day during 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 (Paloscia & Huttunen et al., 2006).

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 snow melt period is up to 20 mm. With high precipitation during the snowmelt period the uncertainty can be remarkably higher.

The flood extent product and flood mapping in near real time. The city of Ivalo, May 27th, 2005: The flood was due to snowmelt and heavy rainfall prior to the flood. About 25 people were evacuated. A high resolution (10 meter) RADARSAT-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/). Around 80 % of the flooded area was detected with a 10-meter image resolution. End users such as the regional environment centres saw that the method rather to complete air photos than substitute them.

4.5 Detecting water detention areas

World wide (and also in Finland) the floodplain area has been reduced considerably during the last century due to increased human activities and man-made structures. The smaller available flood conveyance areas have resulted in higher flood levels. In several situations flood risks are already considered to be too high and in other situations climate change effects may erode the required flood safety levels. Temporal storage of floodwater in detention areas is a possible measure to reduce flood discharges, water levels and risks. The available digital elevation model in remote areas of Finland has a vertical resolution of about 2 metres, and proved to be non-applicable for identification of possible detention areas. Flood maps from ERS and RADARSAT proved to be valuable information for detection of potential flood areas. These areas, which are flooded naturally in the existing situation, can be surrounded by small embankments to create delayed detention. Using these areas may not require new permissions for changed land use.

The raw images were filtered for false water detections (slopes, airports, roads) and non-realistic flood detention areas (densely populated, too far from river). For the Rovaniemi area 0.05% of the total area proved to be feasible for flood detention. 90% of identified areas were smaller than 1000 m^2. By storing 2 m of water in these areas a flood storage capacity of 1 million m^3 per each 1000 km^2 of land would be generated. For the Kittilä region (see Figure 4) similarly around 3000 potential detention basins were detected.

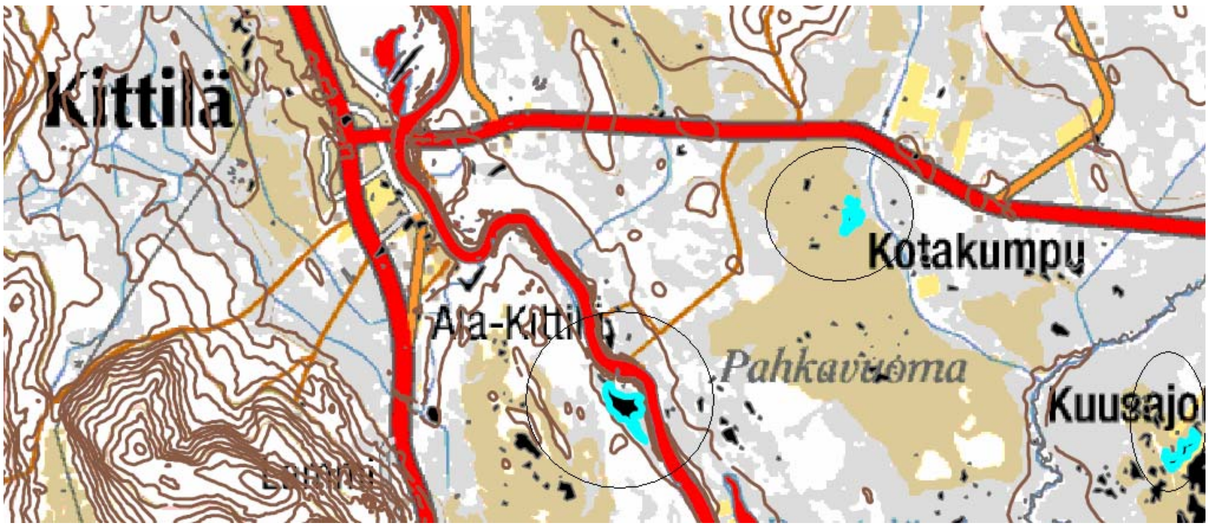


Figure 4 Potential flood detention basins detected (black spots) from the RADARSAT image acquired on 30.5.2005 during a flood in the city of Kittilä: without a field survey, the black areas within circles were defined as the most appropriate. Areas identified are outside of typically water-covered areas (red colour).

5. 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-images) in the data-assimilation process of these flood-forecasting tools. It was demonstrated that raw satellite information can be processed within 3 hours into usable information (i.e. flood extent and soil moisture maps).

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 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.

In addition high-resolution satellite data is quite usable for flood mapping and detection of water detention areas. Combining the method with a snow detection algorithm would further improve it.

Concerning the availability and accuracy of flood and soil moisture information from satellites, the following developments are expected:

1. increase in availability of SAR-images. Several new research and commercial satellites have been launched during the last years (e.g. ALOS Palsar, TerraSAR-X, Cosmo-Skymed and Radarsat-2) and will be in the nearby future (e.g. Sentinel-1);

2. the accuracy of flood maps will increase mainly due to higher spatial resolution, but also due to improved properties of the radars (e.g. other wave-lengths, polarization) and processing methods.

3. nearly on line availability of high-resolution flood maps is within reach with processes such as GMES, GEO and GEOSS.

4. The International Charter on Space and Major Disasters (http://www.disasterscharter.org/, joint effort by space agencies worldwide to put space technology at the service of rescue authorities in the event of a major disaster) may order all satellites to monitor certain areas and parameters.

5. Direct and frequent measurement of water levels in relatively narrow water bodies such as rivers with altimeters on satellites is not expected in the near future. An interesting initiative appears to be WATER HM (The Water And Terrestrial Elevation Recovery Hydrosphere Mapper). Using interferometric SAR altimeters, accurate, frequent (repetition < 30 days) and good coverage (wide swath) water level measurements can be obtained. The base accuracy of ± 50 cm for individual 'pixels' may be improved to even ± 1 cm by averaging over areas less than 1 km^2 e.g for river stretches or lakes (see also http://www.legos.obs-mip.fr/recherches/missions/water/).

6. For soil moisture maps deep penetration into the soil is desirable. Instead of the often-used C-band SAR, L-band SAR (ALOS Palsar), L-band passive instruments (e.g. SMOS) and even P-band SAR will become available in the future.

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