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Use of weather radar for combined control of an urban drainage system and a sewage treatment plant

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Abstract In present practice, the design and operation of urban drainage systems, and the corresponding sewage treatment plants, are usually independent. In this paper an approach is presented, the aim of which is joint operation of an urban drainage system and the corresponding sewage treatment plant. This operation will be based on real-time flood forecasts, which are computed with the aid of radar rainfall measurements. The goal of this control is to minimize the combined negative effects of the hydraulic load (water quantity) and the pollution load (water quality) in the receiving waters during floods. In growing urban areas, higher imperviousness is the cause for increased flood peaks and volumes in the receiving water. In the test basin used, an industrial area with a high imperviousness strongly effects the control of the total system.

INTRODUCTION

An interdisciplinary research project (involving three institutes of environmental engineering and hydrology) has been carried out to control complex urban drainage systems in real-time. To improve the water quality of the receiving water, an optimal control of the two components, the sewerage system and the sewage treatment plant, has to be achieved. The control goal is to minimize simultaneously the hydraulic load and the pollution load in the receiving water. In order to make the control of the sewer network and sewage treatment plant more efficient, a precipitation forecast is required. This requires a high resolution in space and time since the variability of rainfall distribution is highly significant for the control potential of the sewerage because even small differences of precipitation lead to large differences in runoff. This situation is reflected in rainfall-runoff modelling (Faurès *et al.*, 1995). Besides detailed information on precipitation, detailed information concerning the drainage basin (land use data, soil maps, data from a Digital Elevation Model) is also used and incorporated into a Geographic Information System (ARC/INFO) and thus into the hydrological model. Industrial areas with high imperviousness and a high pollution load on the surface play an important role.

RESEARCH PROJECT AND TEST BASIN

Research project

To achieve the goal of minimizing the contamination in the receiving water, future oriented techniques of the three branches (a) measurement and forecast of precipitation, (b) control of sewage network and (c) control of sewage treatment plant are combined. These efforts are mainly focused on the following topics:

(a) Measurement and forecasting of precipitation by weather radar (active microwave sensor):
- measurement of precipitation with a high resolution in space and time, by C-band radar;
- quantitative forecast of precipitation up to 30 minutes in advance, to control the sewerage system with the aid of these high resolution radar data;
- qualitative forecast of precipitation up to four hours ahead using international composit images of several radars and METEOSAT satellite data.

(b) Water quality based management of available storage capacity in the sewerage system:
- development of imission based criteria for planning and operating storage capacity in the sewerage system;
- quantification of the dependence between rainfall rate and pollution load at different sites in the drainage basin and effects on the runoff.

(c) Development of control strategies for the sewage treatment plant taking into consideration the situation of the system:
- off-line simulation of control measures at the sewage treatment plant by using the Activated Sludge Model No. 1 (Henze *et al.*, 1986);
- realization of control measures at a pilot sewage treatment plant.

Test basin

An urban drainage system in the city of Bochum, Germany, was chosen as a test basin. The area of the test basin "Schattbach" is 3.6 km^2 and drains completely into the sewerage system. The storage reservoir "Markstraße" is located at the outlet of this area. Because of its high imperviousness, a large industrial area located close to the storage reservoir, is of particular relevance.

RAINFALL MEASUREMENT AND FORECASTING BY C-BAND WEATHER RADAR DATA FOR CONTROL OF THE SEWERAGE SYSTEM AND THE SEWAGE TREATMENT PLANT

For hydrological modelling purposes in small drainage basins it is very important to have available rainfall information with high resolution in space and time. Therefore a C-Band-Radar of the regional office of the German Weather Service (DWD) in the city of Essen, located about 20 km away from the Schattbach test basin was used. Of a variety of different radar products of the DWD (DWD, 1995) the so-called DX product is most suitable for urban hydrological purposes because it has a high resolution in space ($1° \times 1$ km), time ($\Delta t = 5$ min) and radar reflectivities (0.5 dBZ). Furthermore the control of the sewage treatment plant needs—besides short-term quantitative forecasting—a qualitative forecast of inflows of several hours, and thus also satellite data (METEOSAT) or international composit pictures of several radar (PI product) are taken into consideration.

Rainfall measurement

Measuring precipitation by radar is unlike the conventional method (raingauges) being an indirect method, which uses that, part of the electromagnetic radiation (emitted by the radar) which is reflected by the raindrops. The radar reflectivity Z depends on the sixth power of the rain drop diameter D:

$$Z = \int n(D) D^6 \mathrm{d}D \tag{1}$$

The rain intensity R is a function of Z. The standard Z-R relationship of the DWD (DWD, 1995) used for the test basin is:

$$Z = 256 \cdot R^{1.42} \tag{2}$$

Since the radar reflectivity is strongly depending on the drop size distribution and therefore on the type of precipitation (stratiform or convective), larger mistakes in the calculation of rain intensities, using the standard Z-R relationship, are likely to occur. In order to reduce the error in the calculation of the rain intensities R, two different methods were investigated in the research project. In both methods convective rain was studied because it has a high variability of precipitation intensities in small areas. This is of special interest for the control of urban sewerage systems.

In the first method, radar data was adjusted to the precipitation measured at the ground by raingauges (Collier, 1996). The best results were achieved by using different adjustment factors for high, medium and low rain intensities. This is due to the fact that high rain intensities are better represented by the Z-R relationship.

The second method uses the Window Probability Matching Method, WPMM (Rosenfeld *et al.*, 1994) to calculate a better matching Z-R relationship for convective rain. This method connects conditional probability density functions of rain intensities measured by radar and raingauges. The highly deviating form of the exponential Z-R relationship of the DWD, compared to the one generated by the WPMM (from six convective rain events), can be seen in Fig. 1.

Rainfall forecast

For the control of the sewerage system a short-term quantitative rainfall forecast of the next 30 minutes is computed with high space and time resolution radar data. As stated above, the control of the sewage treatment plant needs a quantitative forecast of up to 4 h. This is achieved by using radar and satellite data with a lower resolution in space and time. The calculation of the velocity vector of storm cell movement is done by

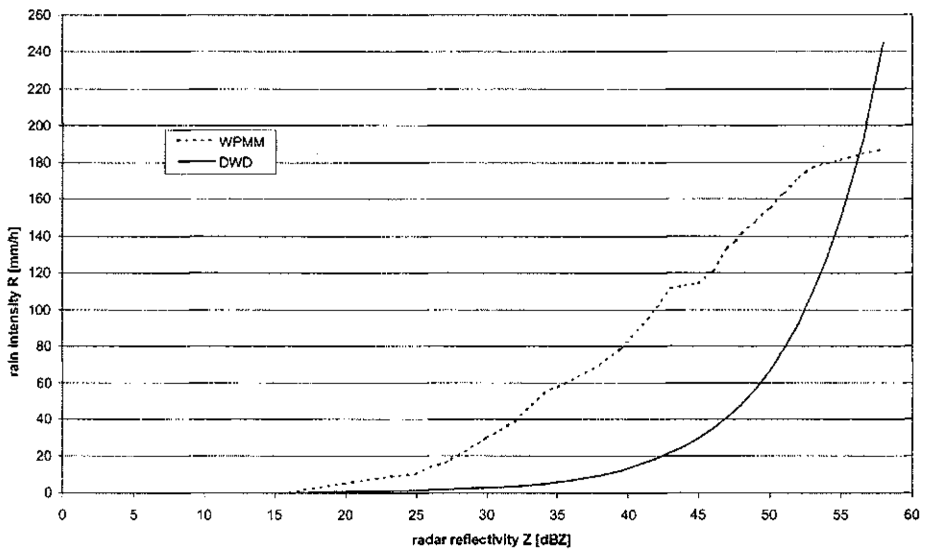

Fig. 1 Comparison between the *Z-R* relationship generated by the WPMM and the exponential *Z-R* relationship of the DWD.

cross-correlation techniques for separate storm cells of two successive radar images. The separate calculation of a velocity vector for each of the cells produces better results than a joint velocity vector for all cells of the radar image because the single cells can have very different directions of movement (Fig. 2).

IMPACT OF SPATIALLY DISTRIBUTED RAINFALL INFORMATION ON THE RUNOFF AND THE POLLUTION LOAD

At first the rainfall data from a single raingauge was used to calibrate the hydrological urban simulation model HYDRO (Rödder, 1997). The calibration for several storms was only moderately successful. The irregular distribution of rainfall over the drainage basin is the main reason for differences between measured and simulated flow. Therefore rainfall data from three different raingauges were used for the calibration and simulation. The data from these raingauges were related to three different sub-basins by the Thiessen-Polygon method. Figure 3 shows the storage content of the Markstraße storage reservoir as a function of time during the storm event of the 29 April 1997. It can be seen that spatial rain data lead to better agreement between observed and computed runoff data. A quantitative comparison between measured and simulated hydrographs is possible with the aid of the dimensionless hydrological deviation DV by Schultz (1968).

$$DV = 200 \cdot \frac{\sum_{i=1}^{n} \left| Q_{ri} - Q_{mi} \right| \cdot Q_{mi}}{n \cdot Q_{m,\max}^{2}} \tag{3}$$

Comparing the data in Fig. 3 shows that both results can be regarded as good ($DV <$ 10%), but that the simulation with detailed precipitation ($DV = 3.259$) is significantly

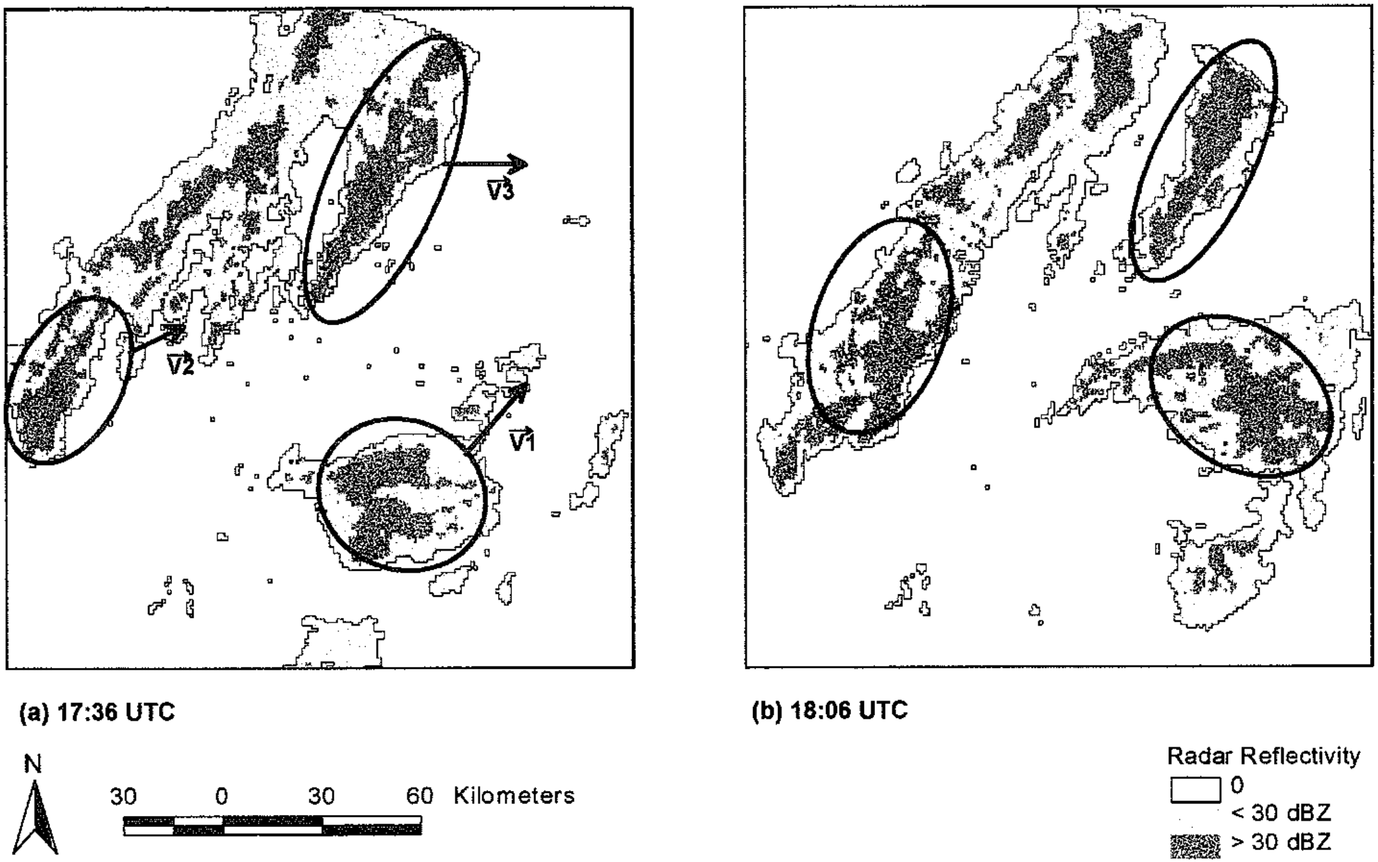

Fig. 2 Velocity vectors of various rain cells during a convective rainstorm on 9 April 1998; courtesy German Weather Service (DWD).

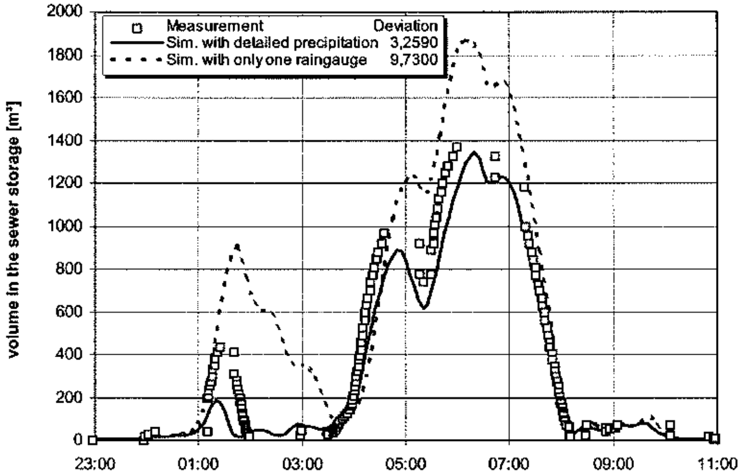

Fig. 3 Comparison between measured and simulated reservoir storage using detailed precipitation information (three raingauges) and using only one raingauge.

better. In the industrial area especially, high rainfall rates result in a very high hydraulic and pollution load to the Markstraße storage reservoir and—in the case of the storm water overflow—to the receiving water. Use of spatially distributed radar data allows forecasting of such high rainfall rates for the industrial area. Thus storage capacity can be made available in the upper drainage basin to enable the Markstraße storage reservoir to cope with this kind of fast runoff.

The effect of spatially variable rainfall intensities in the test basin on the pollution load should also be recognized. The difference between the measured pollution, and simulation without detailed rainfall data, might be up to 100% (e.g. for the COD), whereas this difference amounts to an average of only 10% for simulations with distributed rainfall data, especially for convective rain events

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