SOME GENERAL COMMENTS ON FLOOD FORECASTING

Michael Bruen
Centre for Water Resources Research,
Civil Engineering Department
University College Dublin
Earlsfort Terrace, Dublin 2, Ireland.

E-mail: michael.bruen@ucd.ie

Abstract:

The paper addresses the question of forecasting rainfall-generated severe floods so that people who may be affected can be warned. The forecasts must be timely so that those warned have time to respond and of sufficient reliability that they will decide to respond. Depending on the type of catchment and river network different tools may be used in a real-time forecasting system. The paper discusses the capabilities and current limitations of these tools, which include meteorological models, radar, hydrological and hydraulic models. High resolution limited area models with horizontal spatial resolutions below 5 km are available and are being run operationally with resolutions in the order of 20 km. These use ECMWF information as boundary conditions. Quantitative precipitation forecasts of usable quality can be obtained for areas in which the precipitation has a strong orographic character. Radar cannot forecast rainfall but it can give a good representation of its spatial distribution and can track the movement of rain storms. Considerable technical difficulties remain before reliable quantitative estimates of precipitation can be had from radar. The catchment response, converting precipitation into runoff and the channel response in modifying the flood wave are both highly nonlinear but have been modelled with varying degrees of accuracy. Telemetry is the glue linking the information and models and is a key element of any warning system.

The paper presents results from the EU-funded TELFLOOD project, coordinated by CWRR, and also discusses briefly possible options for flood control and damage mitigation.

Key Words:

Flash flood; Flood forecasting; Telematics; High Resolution Limited Area Meteorological Models; catchment Models; TELFLOOD-EU

1. Introduction

These comments fall naturally into two main categories. In the first category the topics of flood forecasting and telematics are discussed in general terms and some important ideas and technology are introduced. In the second, some results of the EU-funded TELFLOOD project relating to flood forecasting are described.

In the period 1986 to 1995, floods caused approximately 32% of the 5370 recorded major natural catastrophes, but were responsible for 55% of the associated fatalities. Floods caused 31% of the total estimated economic losses of US$ 630 Billion but only 8% of the total insured losses of US$ 120 Billion, Figure 1. These figures, produced by Munich Reinsurance, indicate the seriousness of flooding as a major natural hazard and worldwide threat to life. A detailed analysis of figures for the major flood events shows that developing countries have a much higher ratio of fatalities to economic loss associated with flooding, Figure 2. This indicates both their greater vulnerability and their less developed economy.

The purpose of forecasting floods is to minimise loss of life and injuries to people, loss and damage to property and disruption of normal activities caused by flooding. While it is desirable to completely prevent all of these outcomes, this is not always possible and the objective becomes to reduce the flood magnitude and/or mitigate the negative effects of flooding. The desirable characteristics of a good flood forecast are

- Timeliness
- Accuracy
- Reliability

The exact requirements under each heading will depend on the individual circumstances and are influenced by a large number of factors, which include the range of practical responses, the size and response time of the catchment and river system and the type of precipitation.

1.1 Timeliness

The time between making a forecast of an event and its occurrence is called the lead-time. Naturally the longer the lead-time is the more are the opportunities for flood control or modification and for damage mitigation. If sufficient time is available and accurate predictions of the area to be affected are available then evacuation, even of relatively large numbers of people may be possible. This was done in 1993 In Holland during the flooding of the Maas when, with approximately three days warning, the Dutch evacuated approximately 100,000 people from the danger region. For smaller catchments and river systems such a relatively long lead time may not be possible and response may vary from people moving themselves and their valuables to upper stories in their houses, to building sandbag defenses. Attempts have been made to quantify the reduction in losses afforded by increasing the lead-time, e.g. Figure 3 which is for an urban area in the US. Increasing the lead-time does reduce losses but up to a limit of approx. 40% and with diminishing returns.

1.2 Accuracy

Accuracy usually relates to the correctness of the forecasts of the magnitude and time of the flood peak and of the resulting water levels. In exceptional circumstances it may relate to the forecasts of the complete hydrograph of the flood. The more accurate the forecast the better flood control/modification and damage mitigation measures can be implemented. These measures have a cost both financial and in physical and psychological injury. For instance if part of the response is to evacuate certain areas then there are financial costs, both direct and indirect, incurred in doing this. If large numbers of people are involved there may be injuries caused by the evacuation. For some people, the psychological effects of the evacuation may last longer than any physical injury or financial loss. Decisions are taken about what response measures are required at any given time. For instance, whether or not to evacuate and which areas to evacuate. A particularly difficult decision is whether, with a flood in a large embanked river, to deliberately breach the embankments in some places and allow the flood access to less densely populated rural land and villages in order to protect the more densely populated areas. This dilemma occurred with the Mississippi flood in 1993 and with the Oder flood in Poland in 1997. Better forecast allows more confident decision making in such circumstances.

1.3 Reliability

Reliability can be associated with accuracy, but I want to distinguish between the accuracy of a forecast of a particular flood and the overall long-term reliability of the flood forecasting system. The long-term reliability of the system can be assessed by its performance in two respects. It should always forecast a flood when one occurs and it should not forecast floods when one doesn't occur. The reliability, like accuracy, affects the confidence in deciding on response measures. Public perception of its reliability, or lack of reliability, may be very important in determining whether or not its warnings are heeded.

1.4 Conflict in requirements

Forecasts require both data collection and modeling. The amounts of data and the complexity of the modelling necessary to achieve specific targets of lead-time, accuracy and reliability vary from catchment to catchment. There is a natural conflict between the desire for greater forecast lead times and greater accuracy and reliability. Generally the longer the lead times the less accurate and reliable are the forecasts of flood magnitude, location and timing.

2. Space and time scales

2. 1 *Types of precipitation*

It is important to understand the mechanisms which produce flood-causing precipitation in a given catchment. This usually determines the maximum forecast lead-time for headwater catchments and dictates the data collection and modelling requirements necessary to achieve it. It is important to take account of the many different types of precipitation which can occur. Convective precipitation can be very intense and localised. It can cause flash flooding in very short times. Frontal precipitation, as its name suggests, is associated with of large air masses. The precipitation can be prolonged but is usually not very intense. Large volumes of water are produced but over a period of days. This is associated with large floods in large river basins, such as the Odra, Nysa and Morava flood in July/August 1997. Orographic precipitation, unlike the others, is associated with the influence of mountains and moisture-laden wind and is thus relatively fixed in space. However, unusual wind directions can sometimes spring surprises, such as in the case of the Hurricane Charlie floods in the Dodder and Dargle.

The type of precipitation determines the amounts of rain and the speed of development and movement of the storm thus the scale of modelling required for forecasting. The second part of these comments deals with specific techniques used for flash flood forecasting in small basins, arguably the most difficult type of flood to forecast. First, by way of contrast, forecasting performances for some very large scale recent floods are described.

2.2 *Examples*

2.2.1 Rhine (Wilke, K, 1997)

The river Rhine is 1320 km long and drains a catchment of 185,000 km^2 involving 9 states, Fig 4. It has a number of major tributaries, Aare, Ill, Necker, Main, Nahe, Lohn, Moselle, Ruhr and Liffe. There are 25 different centers in 5 different countries with responsibilities for flood warning or forecasting. A number of different types of model are used, including relationships between gauges, linear and nonlinear flood routing models, rainfall/runoff models and multiple regression models. For the upper Rhine, the Swiss National Hydrological and Geological Survey forecast discharges down to the Rheinfelden gauge for up to 66 hours in advance using multiple regression, rainfall runoff and flood routing models. As well as water level data from the river gauges, they use hourly data from 42 automatic weather stations as well as precipitation and temperature forecasts from the Swiss Meteorological Institute. Forecasts are faxed to centers downstream. A sample of their forecasts, up to 48 hours ahead, for the Rheinfelden gauge for the 1995 flood is shown in Figure 5. Each forecast trace starts with the measured water level. Further downstream forecasts can rely on measurements at (and forecasts for) the upstream gauges and becomes more reliable, Fig. 6. However the tributaries contribute significantly to the flood and also must be well gauged and modelled. For the upper Rhine accurate forecasts are available for up to 12 hours in advance and in the lower Rhine for up to 24 hours in advance. However, forecasts for longer lead-time are made.

2.2.2 Mississippi – 1993 (NOAA 1994)

The US Midwest flood of 1993 was the worst recorded flood in the US in terms of precipitation amounts, water levels, extent and duration of flooding, number of people displaced and damage to property and crops. Damages totaled $15 billion, 50 people died, hundreds of levees failed, and thousands of people were evacuated, some for months. The flood was unusual in the magnitude of the crests, the number of record crests. An extended wet period in the autumn and winter of 1992 saturated the soils and filled the reservoirs so that, when the spring thaw came, the accumulated snow melted on either frozen or saturated ground. Some flooding occurred as early as March 1993. Normally summer precipitation in the mid-west US is light with some localised severe convective rainstorms which can cause flash flooding over relatively small areas but rarely causes large scale river flooding. However in June, July and August of 1993 an unusual weather system established itself over the entire Midwest. A front remained stationary over the Mississippi basin, there was a low-pressure trough to the Northwest and warm moist air from the Gulf of Mexico and Caribbean met and overran cool dry air from the Northwest. Preliminary tests with a numerical climate model have shown that most of the unusual meteorological patterns which occurred during this period could be lined to the unusually persistent EL Nino/Southern oscillation phenomenon in the southern Pacific, which affected the entire Northern Hemisphere.

At that time the National Weather Service's River Forecasting System (NWSRFS) had been operational since the mid 1980s. Effective rainfall was calculated at 6 hourly intervals by an empirical model using an antecedent precipitation index (API), reported precipitation amounts and duration and time of year. From these, river discharge inputs were calculated using a unit hydrograph and by adding baseflow. A storage routing algorithm is used to route the discharges downstream and the corresponding water levels at established gauging locations are forecast using a previously established rating curve. The precipitation inputs were from both manual and there were some automatic (tipping bucket gauges and water level measurements) data collection platforms. However, the latter were programmed to transmit accumulated data at pre-set times (typically 6-hour intervals) and were not able to report significant events as they happened.

The 1993 flood exposed some of the shortcomings of that forecasting system and a subsequent analysis of the flood identified the major issues NOAA (1994). Most notable were the delays in reporting and verifying precipitation measurements and the inadequacy of the flood routing models. Two interesting findings are

"FINDING 4.2: The number of sites where backwater or loops in ratings affected forecasts was unprecedented"
"FINDING 4.3: In many of the flooded areas on the Missouri and Mississippi Rivers, the stages exceeded those of prior records while the corresponding discharges often did not."

Because the floods reached record levels the pre-existing rating curves had to be extrapolated when making water level forecasts. This is one possible source of inaccuracy. However, from gaugings taken during the flood substantial changes and loops in rating were observed even over short time periods at the same site. Figures 7 show the actual forecasting performance for water levels at St. Louis. 1,2 and 3-day in advance forecasts compare well with the measured levels. However, the forecasts at longer lead times are poor. The increase in bias and uncertainly is shown in Figure 8.

The National Weather Service's flood forecasting service has been modernised to address some of the shortcomings identified during the 1993 flood. Doppler Weather Surveillance

Radar (WSR-88D) is integrated with the pre-existing surface monitoring system. This will provide more frequent “nowcasting” of precipitation and its spatial distribution. GIS-based distributed catchment models are replacing the lumped unit-hydrograph based models for estimating runoff and hydrodynamic models (e.g. DWOPER) are being introduced for flood routing. The changes are expected to substantially improve flood-forecasting performance.

3. Elements of a flood forecasting system

A flood-forecasting organisation may have some or all of the following components:

- *The technology to make quantitative forecasts*
- *A system to evaluate the forecasts and decide on a course of action (e.g. warnings., reservoir releases, evacuations etc.)*
- *A system for implementing the actions (e.g. distributing the warnings etc.)*
- *A system for providing information or managing operations during the flood.*
- *A system for evaluating all the above after a flood.*

While all of these deserve serious attention, this paper concentrates on the first element, the technology for making flood forecasts.

3.1 Flood Forecasting System

The technical requirements of a flood forecasting system are :

- *A real-time data collection system for meteorological information, water levels in rivers, reservoirs and lakes and for soil moisture. This may involve manually read gauges, terrestrial data collection platforms, ground-based radar, satellite or airborne sensors.*
- *A numerical forecasting system for meteorological inputs. These are generally called Numerical Weather Prediction models (NWP). Some European countries operate their own models, but many use the European Centre for Medium Range Weather Forecasting (ECMWF).*
- *A system for optimally combining the data from the many sources and for providing feedback for recalibration of sensors and for initialisation or error correction of models.*
- *A catchment model to estimate runoff. This may be a single lumped model, semi-distributed or GIS-based distributed catchment model.*
- *A hydrodynamic river routing model to estimate the movement of the flood, water levels and the effects of dyke breaches, reservoir operation and the interaction with the floodplain and flooded areas. This will gives water levels as well as discharges. Special models may be necessary to model the progression of a flood through large urban areas.*
- *An error correction algorithm for improving the estimates of discharge based on feedback from river gauge data.*
- *A tide/estuary model if there are likely to be backwater effects.*

3.2 Telematics

Telematics is the use of electronic equipment to collect and transmit data over some distances. It includes all types of electromagnetic radiation, radio, radar, visible and infrared light, microwave, telephone, television, digital data link (and the World Wide Web). In this paper I assume that the technology for transmitting information via radiowaves, telephone etc. is available and is well understood, if not always well implemented. I will concentrate on the use of telematics in the gathering of information as input for numerical models. These models and their data sources must be considered together and the ultimate performance of the forecast system depends critically on the matching of both. This paper thus concentrates on the role of telematics at the interface between data and model.

3.3 Effects of scale on forecasts

In the US, the National Weather Service now uses the Sacramento soil moisture accounting rainfall/runoff model for catchments with response times greater than 12 hours. It requires mean areal precipitation and potential evapotranspiration. Its parameters can be calibrated manually or optimised with historic data.

Finnerty, B.D. et al (1997) tested the sensitivity of the model to the scale of the precipitation input, which was derived from the NEXRAD radar network. They found that as the spatial scale of the precipitation increased the model forecasts of surface runoff, interflow and supplemental baseflow decreased, Figure 9. As the time scale decreased from 6 hours to 1 hour surface runoff predictions and interflow increased while baseflow decreased. Evaporation changed to maintain the long-term water balance. These changes are attributed to better modelling of the short intensity intense precipitation events which cause a lot of the surface runoff. This was a modelling exercise only and did not compare with actual flows and so did not need to consider the general question of underestimation of precipitation by radar.

4. Remote sensing

4.1 Satellite

Satellites can provide useful information for flood forecasting and for flood management during the event. They can be classified by the type of orbit they occupy:

- Polar Orbit : Earth Resources Satellites tend to be placed in low (e.g. 200 km) polar orbits so that as the earth rotates beneath the orbit the satellites sensors can, over a number of orbits, cover the entire globe. The sensors typically see a swath up to 200 km wide. The Landsat series with horizontal resolution in the visible of 30 m and the SPOT satellites with a resolution of 10 m are examples of this type for satellite. They are not routinely used as part of an operational flood forecasting system. The principle disadvantages are that they do not give continuous coverage of all locations and their visible light and infrared sensors cannot penetrate cloud cover, although their radar can.

- Geostationary Orbits: Weather satellites tend to be placed in geostationary orbits because it allows them obtain continuous coverage of a region of interest. These are much higher than polar orbiting satellites and so the horizontal resolution is much coarser, of the order of 2 km in the visible spectrum. They provide large-scale weather information, the images can cover entire continents, and also can be used to map the extent of snow cover in colder areas, which is an important factor in determining the magnitude of the spring thaw floods.

Some interest has been shown in active radar measurements, by a satellite, of rainfall. Cloud-top temperature and cloud extent were correlated, by the GAMP project, with ground-based measurements of rainfall amounts, but no useful relationship was obtained. However it was noticed that rain only fell from clouds which had a cloud-top temperature of lower than

230ºK. Using only these clouds produced rainfall estimates in Niger with a RMS error of 30%, and these were used as one of the inputs to an agricultural model, Rosema(1986).

A number of countries are investigating the integration of information from ground-based radar and satellite imagery to achieve small-area forecasts of rainfall, e.g. the "FRONTIERS" project in the U.K., "ARAMIS" in France and the "HRAP" in the U.S.

4.2 Meteosat

There are a number of different weather satellite systems operated by different organisations, e.g. the GOES system in the US. The European Meteorological Satellite Organisation (EUMETSAT) is an inter governmental organisation intended to support the national meteorological services of member countries. It produces satellite data to help forecast weather, as an input to Numerical Weather Prediction (NWP) systems and for long term climate research. Ireland is a member of EUMETSAT. It operates the Meteosat series of satellites which monitor the earth continuously from geostationary orbits 36,000 km high. These provide images of the earth and atmosphere in the visible, infrared and water vapour channels every 30 minutes. They also receive and retransmit data from remote terrestrial data collection platforms. Meteosat is located over the equator and on the Greenwich meridian, which allows it to monitor almost all of Europe, Africa and the Atlantic Ocean. The current horizontal resolution of Meteosat is 2.5 km in the visible and 5 km in the infrared. The second generation Meteosat (to be launched in 2000) will have 1.4 km horizontal resolution in the visible, 4.8 km in the other bands and will produce images every 15 minutes.

The information provided by Meteosat are of most use as for manual forecasting and as input to Numerical Weather Prediction models. The types of information are:

- Wind vectors at various heights derived from cloud movement and from other tracers.
- Extent, height and type of clouds.
- Relative humidity in troposphere
- Sea surface temperatures
- Clear sky radiance
- Air mass instability
- Solar and longwave radiation fluxes.
- Precipitation index
- Total Ozone
- Identification of clouds likely to produce precipitation and calculation of precipitation intensity for convective clouds.
- Identification of thunderstorms
- Calculation of precipitable water in clear air.

Many of these quantities are of direct use for initialising Numerical Weather Prediction Systems, for nowcasting precipitation and for projecting forward over short lead times. The second generation Meteosats will to be able to distinguish between ice and water clouds and to detect low cloud and fog as well as giving information about the vertical structure of the atmosphere.

4.3 Flood Mapping using ERS-1 SAR imagery (German space agency)

Useful for Disaster management rather than flood forecasting:
SARs use special algorithms to process reflections from a continuous swath to produce images with enhanced resolution. The main advantages of radar over the visible spectrum is that it can see through clouds and does not depend on the position of the sun. The SAR imagery from the ERS-1 satellite (polar orbiting) is good for manually delineating the flooded areas along the river. Accurate interpretation is possible in flat terrain. However, there are

some interpretation problems with different land uses which have similar backscatters. Some progress has been made with automatic delineation of flood areas. The automatic classification correctly classifies most of the obviously (from a visual inspection) inundated areas, but it incorrectly includes some forests and one-family-housing areas and steep slopes. ERS-1 SAR imagery is of more use in agricultural terrain than for urban areas and is, of course not as accurate as aerial photography when the latter is possible. It has the advantage of covering large areas quickly and its 1 m vertical accuracy can be of some use in flood management.

4.2 Terrestrial Radar

Radar

Radar is an instrument which emits a regular series of pulses of electromagnetic radiation, each of approximately 1 microsecond duration, at a rate of approximately 1000 pulses per second. The amount of energy reflected by a target and returned to the radar station, together with the time-delay involved allow the position and magnitude of the target to be inferred.

Wavelengths used in hydrometry are:

- X-Band : approx. 3 cm. wavelength. (10000 MHz) High attenuation, high sensitivity, low cost. Good for temperate climate with frontal rain and showers

- C-Band : approx. 5 to 6 cm(5600 MHz) Medium attenuation, Medium sensitivity, Medium cost Severe attenuation in heavy rain, best for light rain.

- S-Band : approx. 10 cm. (: 3000 MHz) Low attenuation, Low sensitivity, High Cost. Widely used in the US, good for detecting thunderstorms and hail showers.

The shorter wavelengths are attenuated more by clouds and precipitation, but the longer wavelengths are responsive to medium to large drops only. Thus, the choice of band depends on the purpose of the radar. The method has proved useful as a storm detector and tracker, over distances of from 150 up to 200 km.

Because radar beams are only slightly refracted in the earth's atmosphere, low level precipitation, especially far from the radar installation, may not be detected. Data from the radar is processed by computer and there are many operations required to produce a precipitation field of accumulated precipitation.

Early work on radar measurement techniques suggested it had considerable promise for short-term flood forecasting applications, but are not yet sufficiently reliable to be widely used for this (Collier & Knowles, 1986). Estimates suggested that, for a 25% accuracy in mean hourly rainfall, a calibrated radar system is more cost-effective than a telemetering raingauge network for short-term forecasting for areas exceeding 3000 km^2(Farnsworth et al., 1984).

4.2.2 Advantages and Problems

The main advantages of radar are:

- High spatial resolution
- Real-time data availability
- Ability to track a moving storm

In particular where gauges are sparse and/or storms are small then radar is useful, however if storms are of large extent (covering many gauges) then the gauges give a more accurate estimate of the rainfall amounts while the radar still gives a better indication of the spatial distribution.

The principle sources of error in radar estimation of precipitation

- Variability of the reflectivity in the vertical
- Assumptions of standard radar equation not valid
- Variability in rainfall drop size (coalescence, break-up and evaporation)
- Advection of precipitation
- Undetected orographic precipitation enhancement beneath the radar beam.
- Bright-band due to melting of snow and ice.
- Blocking and shielding by mountains and high buildings
- Rising and widening of the beam with distance from transmitter. The beam samples at greater altitudes as the range increases.

Multi-parameter radars are being increasingly used, for instance

- Dual-polarisation systems to give better information about raindrop size distributions. They emit radiation at two different polarisations and use the difference between the energy returned from each polarisation.

- Dual wavelength systems: less sensitive to fluctuations raindrop size distributions and more independent of the radar calibration constant. They reduce some of the uncertainties in calibration and inaccuracies due to attenuation, by nearer rainfall, of reflections from distant rainfall, Fujita·(1983).

4.2.3 Examples

Some sample hydrological radar Programmes are :

(a) NEXRAD (USA): A network of approx 175 S-band high power doppler weather radars.

The US National Weather Service now have the NEXRAD radar system which provides precipitation inputs to their river forecasting system (NWSRFS). NEXRAD includes:

- Doppler Weather Surveillance Radar (WSR-88D)

- Advanced Weather Interactive Processing System (AWIPS)

Apart from making the forecast system interactive, the National Weather Service developed a set of post processing algorithms for NEXRAD precipitation estimates . Hourly radar rainfall estimates are combined with raingauge observations at a 4 km grid scale out to a radius of 230 km from the radar. The estimation uses an optimal estimation technique to account for "local biases" in the vicinity of individual raingauges in addition to the mean field bias. The data from overlapping radars are then combined to produce hourly estimates of rainfall covering the entire area of responsibility. The user can interaction with the radar and gage data for manual quality control purposes.

(b) FRONTIERS (UK): Uses the UK weather radar network combined with METEOSAT. Meteorological and Water authority offices receive rainfall analyses and forecasts up to 6 hours ahead in a half-hourly cycle. Viner, D et al. (1990, 1991),

(c) Japan: Network of 15 C-Band radar data combined with raingauge and satellite data.

(d) MARS radar for Urban hydrology: In order to adequately model flows in large urban drainage systems, high temporal and spatial resolution rainfall data are required. A C-band (5.4 cm, 5400 Mhz), low power (35 kW) radar was developed at Bristol University. It is one component in a real-time Multiple Attribute Radar System (MARS) which also includes information from vertically pointing radars, automatic weather stations and regional weather radars. The MARS radar Is intended to provide coverage of large urban drainage areas such as Greater Manchester. It provides estimates of rainfall at 2 minute intervals up to a radius of 50 km with a minimum grid size of 250m

(e) Met Eireann operate two radars, one in Dublin airport and the other in Shannon. They are C-Band (5640MHz) radars with a maximum range of 600 km and a useful range 250 km. The Dublin radar collects 10 elevations of rainfall intensity every 15 minutes at 240 km and 10 elevations of Doppler rainfall and wind every 15 minutes at 120 km and 1 elevation of rainfall intensity at 480 km. The Shannon radar operates on the S-Band (2950MHz) and collects 4 elevations of rainfall intensity every 15 minutes at 210 km

4.2.4 Assessment of Radar

The are a number of ways in which the performance of radar system may be evaluated. The important elements are (I) the detection of the occurrence of rainfall, (ii) accuracy in the position of the rainstorm and (iii) accuracy in estimating the quantity of rainfall.

Radar is not good at detecting rainfall at long range, i.e. > 160 km. Depending on the radar it also may not be good at detecting rain close to the radar, i. E. < 35 km.

There may be individual systematic biases in the calibration of individual radars leading to different estimates of the amount of rainfall in the same area by two radars with overlapping coverages.

When compared with rainfall measured in gauges, radar underestimates the rainfall. The most pronounced underestimation occurs at near and at far ranges. For example the data in Table 1 was reported by Smith et al (1996) for the WSR-88D radars of the USA's NEXRAD system. He concluded that radar can provide an accurate delineation of the no-rain area, e.g. Smith et al (1996) report up to 98% accuracy up to a range of 200 km.

Radar can also provide a more accurate assessment of extremely heavy rainfall. For example Smith et al. (1996) report radar giving heavy rainfall intensitiesto to 75 mm per hour in a storm in which the maximum recorded by a rain gauge was 22 mm.

5. TELFLOOD : Forecasting floods in urban areas downstream of steep catchments

The objectives and some of the results of the TELFLOOD research project are described. To forecast flash floods in steep catchments in time to warn an urban population requires forecasts of precipitation. High resolution limited area models must be linked to hydrology catchment models and there are a number of scientific and technical difficulties involved. Good overall performance can be achieved by refining the meteorological grid down to 22 km. Further refinement improves the precipitation forecast fields, when compared with analysis, and the time distribution of precipitation but does not improve the quantitative estimates of total precipitation with hydrostatic LAMs. To achieve this, careful consideration must be given to nesting procedures, boundary conditions, smoothing orography and specifying horizontal diffusion. The HBV model is the best of the catchment models tested.

5. 1 Partners and personnel

The work reported here is a very short summary of a large corpus of research done by a large group of people at the partner institutions. The credit for this work, which is fully described in the various project technical reports, belongs to this group. I take full responsibility for any shortcomings of this short and, of necessity, selective summary. The partners and personnel involved are:

- Centre for Water Resources Research (CWRR), Civil Engineering Dept., UCD, Ireland.
  Dr. Michael Bruen, team leader, Prof. J.C.I. Dooge, Mr. Benoit Parmentier, Mr. John Turner, Mr. Fechin O'Reilly

- Met Eireann (ME), Ireland.
  Dr. Tom Keane, team leader, Dr. Peter Lynch, Dr. Cisco de Bruin, Mr. Tom Larkin

- Swedish Meteorological and Hydrological Institute (SMHI), Sweden
  Dr. Sven Bergstrom, team leader, Dr. Stefan Gollvik, Dr. Bengt Carlsson

- Dept. of Earth and Geo-Environmental Sciences (DISTGA), University of Bologna, Italy

  together with the Dept. Of Physics (ADGB), University of Bologna, Italy

  Prof. Ezio Todini, team leader, Prof . Stefano Tibaldi, Dr. Paolina Bongioannini Cerlini, Eng. Rosa Vignoli, Eng. Margot Van Soetendael, Mr Enrico Minguzzi (SMR- Regional Meterological Service), Dr. Tiziana Paccagnella (SMR), Mr Sandro Nanni (SMR), Mr Tommaso Diomede, Ms Giuseppina Melchiorre

5.2 Motivation for Project

The idea for this project arose from the following observations

- There are a number of countries in the European Union which have large urban areas subject to episodic flooding by rivers draining relatively small but steep mountainous catchments. Many of these urban areas are situated on a narrow coastal plain and tidal effects, particularly backwater influences on water levels in the rivers also contribute to the severity of flooding. For example, in Ireland a number of short rivers flow eastwards from the Dublin and Wicklow mountains through parts of Dublin and Bray and into the Irish Sea. Much of the central spine of Italy and parts of Norway, Sweden and Spain have similar situations.

- Much of the upper parts of these catchments have high runoff potential and the rivers draining them can be subject to sudden and severe flooding. This causes severe economic damage and is a major threat to both health and life in the large urban areas downstream.

- There is a very short time lag between any extreme precipitation event and the resulting flood so that traditional flood warning systems based only on measurements of actual precipitation or river water levels cannot be expected to give adequate advance warning. A practical flood warning system must be based on forecasts of precipitation followed by rapid simulation of flood runoff and assessment of flooding risk.

Until recently, the spatial resolution, typically from 1.5 ° to 0.6° of the routinely used meteorological models was not sufficient to adequately forecast precipitation amounts at the catchment scale. Recently, however, Limited Area Numerical Weather Prediction Models, such as HIRLAM (High Resolution Limited Area Model) and LAMBO, with spatial resolutions of from 0.5° down to 0.05° and finer have become available and are routinely run in a number of European Union countries. HIRLAM, for instance, operates in Denmark and Sweden with a resolution of 22 km. This extra resolution allows a better representation of topography and gives a much improved forecast of precipitation amounts. To date, this improvement in quality of meteorological information has not been exploited for flood warning or other hydrological purposes. It is also possible that further improvements can be achieved by increasing the HIRLAM spatial resolution even further.

5.3 Project Objectives

5.3.1 General

The main objectives of the proposed research were:

- To develop and evaluate the components of a modelling system to forecast floods in rivers draining steep mountainous catchments into flat plains where they flood large urban areas. Traditional flood warning systems are inadequate because of the fast response time of the catchments. Accurate forecasts of precipitation are essential for successful flood warnings. The system developed by this project consists of a high-resolution limited area meteorological model together with a hydrological catchment model and an hydraulic channel network model.

- To investigate the factors affecting the accuracy and reliability of flooding forecasts from such a system and to determine the nature of the trade-off between forecast lead-time, spatial resolution and forecast accuracy.

These general objectives can be broken up into a number of more specific subsidiary objectives, each of which must be satisfied in order to achieve the major objective.

5.3.2 Meteorological Models

The high resolution limited area meteorological models are used to forecast precipitation. The basic models were HIRLAM and LAMBO and the project addressed the following detailed objectives.

- To develop adequate parameterisation schemes for clouds and precipitation,

- To investigate the sensitivity of the resulting high resolution limited area meteorological models to (i) orography steepness, and (ii) the formulation of the horizontal diffusion.

- To determine the spatial resolution required in a meteorological model for precipitation forecasts adequate for a flood warning system.

- To quantify the trade-off between forecast lead-time, resolution of the meteorological model and accuracy of the precipitation forecasts.

- To investigate the possible role of weather radar in verifying and updating the meteorological model forecasts in real time.

- To develop an algorithm for triggering high resolution modelling for more detailed forecasts

5.3.3 Hydrological models

In relation to the catchment and channel models, the project addressed the questions;

- What type and complexity of catchment model is required for (i) adequate discharge forecasts and (ii) for adequate flood warnings ?

- What type of hydraulic channel model is required for accurate forecasts ?

- To determine the effect of backwater from a tidal estuary on water levels in one of the catchments tested.

5.4 Outline of Project tools

5.4.1 The Study Catchments

The study catchments were in Ireland, Sweden and Italy and varied in area from a few hundreds of square kilometers to a few thousands, Table 3.

5.4.2 The LAMs studied

- HIRLAM (for Sweden and Ireland)
- LAMBO (for Italy).

5.4.3 The catchment models studied

- Unit hydrograph with prior information;
- SMAR (conceptual, quasi-physical, lumped, Soil Moisture Accounting);
- HYRROM (conceptual, lumped);
- HBV (conceptual, semi-distributed);
- ARNO

6. TELFLOOD Results – Meteorological

6.1 Preliminaries

From a meteorological point of view, there are a number of reasons why it is difficult both to measure and to forecast precipitation. It is characterised by small scales both is time and space, and, except for specialised research catchments, rain gauging stations are normally too sparse. Precipitation measurements with radar are also available but are associated with serious uncertainties. The problem of mesoscale analysis, to produce gridded precipitation fields which are consistent on a typical spatial scale, has been treated by Häggmark et al., 1997. The most suitable tool for estimating the precipitation in forecast mode is a complete three-dimensional numerical weather prediction model system. Therefore, we have here concentrated on the precipitation forecasts produced by the two limited area numerical weather prediction models described above, HIRLAM (Källen, 1996) and LAMBO. Before such models can be effectively used in a flood warning system a number of important questions have to be addressed. The main ones are summarised below:

6.2 Changes in parameterisation of clouds and condensation process

The study concentrated on the precipitation producing mechanisms within the LAMs. For instance, in HIRLAM, the condensation parameterization utilises the cloud water as a prognostic variable (Sundqvist et al., 1989, Sundqvist, 1993). This implies that the condensation scheme first produces cloud water, and this is then converted into precipitation, the process of which is modelled by using cloud physical assumptions. The cloud cover is diagnostically computed within the condensation scheme. The precipitation is either produced by convection, or by stratiform clouds, and it is assumed that convection is dominant, i.e. if the conditions for convection are fulfilled at a gridpoint, no stratiform clouds can be produced, except for convective anvils. The convection is based on the formulation of KUO, 1974, which means that its intensity is a function of the convergence of water vapour.

To make the condensation processes somewhat smoother in HIRLAM, some small changes in the parameterisation of clouds and condensation processes were introduced which allow to model to take account of both stratiform and convective clouds in a region at the same time, and this should produce a more continuous cloud cover.

6.3 Refinement of grid resolution

The project tested a number of different methods of achieving very high grid resolution. This was tested with HIRLAM over Swedish and Irish catchments. The model has been run with 24 vertical levels and three different horizontal resolutions, 22, 11, and 5.5 kms.
When the meteorology is strongly influenced by orography, the results indicate that we are able to forecast average 12-hour or 24-hour precipitation over a reasonable large drainage basin. In any of the periods, no sensible improvement could be seen in accuracy of precipitation forecasts by decreasing the horizontal grid size below 22 km. An important complication is that the resulting precipitation pattern is strongly dependent on the magnitude of the horizontal diffusion, which must be tuned for each grid resolution.

6.4 Effects of strong/weak orography

In catchments with weak orography, HIRLAM model is capable of estimating the broad features of the precipitation, but has difficulties in estimating the correct amounts over relatively small drainage basins. When the flow is strongly influenced by the orography, the results look much better, and the results indicate that we are able to forecast the average precipitation over a reasonable large drainage basin.

6.5 Horizontal diffusion

The effect of the horizontal diffusion, which is included in the HIRLAM model, is discussed in Gustafsson and Mc Donald, 1996. In the case study of the first period, we found that a strongly damped 11 kms run was slightly better than the version which produces a more realistic kinetic energy spectrum. The 5 kms forecasts should also be subject to large horizontal diffusion in order to control the noise in the precipitation pattern. It is not clear how the horizontal diffusion should be treated for an optimum performance.

6.6 Smoothed orography

The 5.5 km grid results produced noisy precipitation fields. Smoothing the orography prior to running the model controlled this. This produced acceptable precipitation fields.

6.7 Nesting strategy / Lateral boundary conditions

A large amount of work has been implemented in the design of a NESTED system allowing HIRLAM to run experiments at fine-resolution in the meso-beta and meso-gamma scale.
In particular, the results for the Hurricane Charlie (25-08-1986) case have proved of particular interest. and demonstrate that the NESTED system, summarised in Table 3 works.

The results at 0.0625 degree resolution are sensitive to the parameterization scheme being used. The forecasted precipitation fields improve considerably as the grid size decreases. However for a small catchment area, in this case the Dodder, the forecasts seem to predict the starting time of the storm quite well, but the estimate of precipitation amounts grid points varies considerably between neighbouring grid points and in the case show all underestimate the measured precipitation, Fig. 10

7 Issues and Results – Hydrological

7.1 General

The first hydrological question is to establish the most appropriate hydrological catchment model to use in a flash flood forecasting system. The problem is not straightforward since there are a large number of possible models. All models are simplifications of reality and developed with specific purposes in mind. The simplifications and assumptions made in one application may not be appropriate for another and so the best model for one application may not be the best for another. In addition there is the very real problem of model calibration. A model which has a detailed representation of many components/process will have a large number of parameters, many of which must be calibrated for each catchment in which the model is applied. The more parameters which require calibration the more difficult and unreliable is the calibration. In extreme cases we may have a complex and comprehensive catchment model which cannot be reliably calibrated and at the other extreme we may have a model with fewer parameters which can be calibrated but with too poor a representation of the catchment to be useful. The ideal model achieves a compromise between having sufficient detail/complexity for the purpose in hand but also with reliable calibration with the data available.

A number of catchment models were studied and assessed in this study, including the HBV, HYRROM, SMAR and UH models. As the HBV model performed best in the comparisons (see comparison results below), only it and the improvements made to it will be described here.

7.2 Semi-distributed Conceptual Model HBV

HBV was originally developed in the 1970s by the Swedish Meteorological and Hydrological institute (SMHI) and has been improved and upgraded many times over the years (Bergström and Forsman, 1973; Bergström and Lindström, 1992; Bergström 1992, 1995; Gardelin and Lindström, 1996). The latest version, HBV-96, was used in the project (Lindström et. al. 1997). A schematic outline of HBV-96 can be found in Figure 11. It can be classified as a semi-distributed conceptual model and uses subbasins as primary hydrological units. Within these an area-elevation distribution and a crude classification of land use – forest, open and lake – is made.

Input data are precipitation, temperature and potential evapotranspiration. The principal output is discharge. Normally, monthly standard values of potential evapotranspiration are sufficient, but daily values can also be used as input or even calculated within the model from air temperatures (Lindström et. al. 1994). The model has a number of free parameters, values of which are found by calibration. There are also parameters describing the geographical characteristics of the basin.

7.3 A new approach to catchment response in the HBV model

When developing the HBV model in the early 1970s the statistically distributed model was the only practical approach to the problem of soil moisture accounting in an operational runoff model in basins with as poor data coverage as in northern Sweden. It was shown that the dynamics and basin-wide variability of the soil could be satisfactorily described by a few simple equations representing how the ground responds to snowmelt and rain, and how evapotranspiration is reduced as the soil dries out. (Bergström and Forsman, 1973). A very similar approach is the cumulative distribution function later used for soil moisture simulation in the ARNO rainfall-runoff model (Todini, 1995). The approach has also found its way into climate modelling (Dümenil and Todini, 1992).

SMHI improved of the HBV model for this project by applying a similar concept to the wet area contributing to the flood recessions. This improved the soil moisture modelling so critical to flash flood forecasting. The overall behaviour of the proposed new routine is schematically described in Figure 12.

The improvement in modelling performance of the new model is shown in Fig. 13. Note the improved modelling of the recession.

7.4 Overall Comparison of catchment models

7.4.1 Comparison Criteria R^2 - Efficiency

For comparing hydrological models, a non dimensional measure was suggested by Nash and Sutcliffe (1970) which is an expression of the relative improvement of the model over the performance an naive model. It is expressed as a percentage, given by the formula

$$R^2 = 100\left(1 - \frac{MSE}{F_O}\right) \tag{1}$$

Here:

$$F_o = \frac{1}{N}\sum\left[(Q_o)_i - \overline{Q_c}\right]^2 \tag{2}$$

and Q_c is the long-term average of the observed flow over the calibration period.

The R^2 efficiency criterion is non-dimensional, has an upper limit of 100, but may have values less than zero in calibration. Past experience suggests that an R^2 value over 90% is very good, that values in the range of 80%-90% is fairly good, but that values below 80% indicate an unsatisfactory model fit. The calibration results are summarised in Tables 4 and 5 Note that:

- Overall: all models appear to underestimate the peak flows.
- HBV is best, particularly for peak flows
- HYRROM is slightly worse than HBV but better than SMAR
- SMAR performed poorly on the Dodder catchment (R^2 under 80%), possibly because it concentrates on soil and evaporation process which is not predominant for extreme events in the Dodder basin.
-

The results of verification tests are not yet available and will be included in the final report.

7.5 Runoff simulations and forecasting experiments

Runoff simulations and discharge forecasting trials were conducted over all study catchments. Only one set of results are reported here.

The HBV model was first set up for the Pepparforsen catchment with the time steps of 24 h and 12 h. From the climate stations data were available only every 24 h which means that for the 12 h time step the data from the climate stations had to be proportioned according to the synoptic observations south of the area. HIRLAM precipitation forecasts, climate station data and HIRLAM/MESAN data for the period 1996-05-20--24 were prepared and used in the forecasting tests. With MESAN (mesoscale analysis) is understood data prepared from both HIRLAM forecasts and observed data. (Häggmark et. al. 1997).

In Figure 14 the HBV model forecasting routines were tested with precipitation input from climate stations, HIRLAM 22 km precipitation forecasts and mesoscale analysis of HIRLAM data and synoptic stations. The totals for the period show a lower number for the HIRLAM-runoff forecasts, mainly due to the low precipitation forecasts on May 24 and 25 (Gollvik, 1997).

Comments on HBV simulation

One advantage of the HBV model has always been its ease of calibration and use. One reason for this is that subroutines and parameters are relatively independent. The new routine introduces one complexity as the response function is now dependent on parameters of the soil moisture routine. This has to be considered during the calibration process. Although the new routine is seemingly more complex it does not introduce more empirical parameters. On the contrary there seems to be a possibility to reduce by one by avoiding the use of a parameter for capillary flux, which is introduced in some applications to adjust for the problems discussed above.

The precision of a runoff forecast is basically depending on the original calibration of the model. A bad simulation can, to some degree, be compensated by a good updating routine. The routine used in the HBV model, updating of observed precipitation and temperature, has shown some limitations at events with poor simulations.

When adding a new updating routine to the HBV model we choose between error prediction and updating the state and. Both Refsgaard (1997) and Moore et. al. (1993) have reported that updating the state is the most advisable method. Tests of this method has shown improvements also on difficult events. However, at very high flows the updating method needs improvements and here error prediction will be tested in the future. An additional problem that needs further improvements is how to handle the phase errors that can occur both at updating and forecasting.

7.6 Postprocessing

Postprocessing of gridded precipitation fields shows considerable promise for improving the use of the spatial information in both LAM forecasts and radar estimates of precipitation. There are a large number of possible techniques. There are now three possible sources of spatial precipitation information, (I) telemetering raingauges, (ii) radar and (iii) forecasts from a Limited Area Model. The important question is how much useful information is in each source and how best to combine the information. In the Reno catchment in Italy, which is the largest of the study catchments and has a large proportion of convective rainfall, the LAM and the telemetering raingauges agreed quite well in terms of rainfall amounts and locations. However, fields produced from radar and from telemetering raingauges did not show high correlations (Todini et al 1999). Comparison of predicted with measured discharges shows the raingauge information to be more reliable. However in this case only a single radar is operational when the size of this catchment would ideally require a number of overlapping weather radars. For the Reno catchment the best method for forecasting precipitation was a combination of a stochastic nearest neighbour model and the LAM forecasts. The stochastic model on its own was best for up to 3 hours lead time, but for unbiased estimation over longer lead times the addition of the LAM forecasts is required.

8 TELFLOOD Conclusions

High resolution limited area models can produce useable forecasts of precipitation in mountainous catchments where there is a strong orographic influence on heavy precipitation.

As expected, the method does not work well on flat catchments.

No further improvement in precipitation forecasts was shown for grid sizes smaller than 22 km with hydrostatic model used here.

However, care must be taken with the boundary conditions, grid nesting, orographic smoothing and parametrising the horizontal diffusion.

The HBV model, with the improvement mentioned above, performed best in our comparison of hydrological models.

The combination of LAM and hydrological model showed good performance in forecasting discharge for the steep catchments tested.

Since most meteorological services already run LAMs at resolutions close to 22 km (or will in the near future) there is now no requirement for a triggering algorithm.

Postprocessing algorithms can improve the forecasts of precipitation for lead times greater than 3 hours. It also provides a methodology for combining precipitaion estimates from a number of sources with forecasts to improved discharge forecasts.

References

AFORISM, (1996*). A Comprehensive Forecasting System for Flood Risk Mitigation and Control*. Commission of European Communities, Final Report. EPOC-CT90-0023.

Bergström, S. and Forsman, A. (1973). Development of a conceptual deterministic rainfall-runoff model. *Nordic Hydrology*, 4:147-170.

Bergström, S. (1992). *The HBV model - its structure and applications*. SMHI Reports RH, No. 4, Norrköping, Sweden.

Bergström, S and Lindström, G. (1992). Recharge and discharge areas in hydrological modelling - a new model approach. *Vannet i Norden No. 3.*

Bergström, S. (1995) The HBV model. In *Computer Models of Watershed Hydrology*, Water Resources Publications.

Briendenbach, J., Seo, D.J & Fulton, R. (1998) Stage II and III Post Processing of NEXRAD Precipitation Estimates in the Modernized Weather Service.
Proc. American Meteorological Society 78th Annual Meeting ,Phoenix, Arizona.

Bruen, M. & Dooge, J.C.I. (1992) Unit hydrograph estimation with multiple events and prior information, Theory and computer program, Evaluation of the method*. Hydrological Sciences 37, 5, 429-462.*

Carlsson, B & Bergstrom,S. (1998)
The TELFLOOD project : Rainfall-runoff modelling and forecasting.
Swedish meteorological and Hydrological Institute report no. 14, Norrköping, Sweden.

Collier,C.G., Accuracy of Rainfall Estimates by Radar, Part 1: Calibration by telemetering raingauges. *J.Hydrol.,* Vol.83, pps. 207 -223, 1986

Collier,C.G., Accuracy of Rainfall Estimates by Radar, Part 2: Comparison with Raingauge Network. *J.Hydrol*., Vol.83, pps. 225-235, 1986

Collier,C.G. & Knowles,J.M., Accuracy of Rainfall Estimates by Radar, Part 3: Application for short-term flood forecasting. *J.Hydrol*., Vol.83, pps. 237-249, 1986

Dümenil, L. and Todini, E. (1992). A rainfall-runoff scheme for use in the Hamburg climate model. In *Advances in theoretical hydrology*. J.P. O'Kane, Ed., Elsevier, 129-157.

Finnerty, B. & Johnson D. (1997)
Comparison of National Weather Service Operational Mean Areal Precipitation Estimates Derived from NEXRAD Radar vs. Rain Gage Networks. presented at International Association for Hydraulic Research (IAHR) XXVII Congress San Francisco, August, 1997

Finnerty ,B.D., Smith ,M.B., Seo ,D-J., Koren, V. & Moglen , G.
Sensitivity of the Sacramento Soil Moisture Accounting Model to Space-Time Scale Precipitation Inputs from NEXRAD. Office of Hydrology, NOAA/NWS USA.

Gardelin, M., & Lindström, G. (1996). Priestley-Taylor evapotranspiration in HBV-simulations. Contribution to the Nordic Hydrological Conference in Akureyri, Iceland, 13-15 August 1996, NHP-Report No. 40, 648-657

Gollvik, S (1997). *The TELFLOOD Project, estimation of precipitation over drainage basins*. SMHI RMK No. 77, June 1997. Norrköping, Sweden.

Gustafsson, N., Mc Donald, A., 1996: A Comparison of the HIRLAM Gridpoint and Spectral Semi-Lagrangian Models, *Mon. Wea. Rev*., 124, pp 2008-2022

Häggmark, L., Ivarsson, K-I,. Olofsson, P-O. (1997*). MESAN, Mesoskalig analys. (In Swedish with English abstract)*. SMHI RMK No. 75, Mars 1997. Norrköping, Sweden.

Huang, X.-Y., 1996: Initialization of cloud water content in a data assimilation system*. Mon. Wea. Rev*., 124, pp 478-486.

Källén, E., 1996 (editor): *HIRLAM Documentation Manual, system 2.5,* (Available from SMHI, Norrköping, Sweden)

Kuo,J.L., 1974: Further studies of the parameterization of the influence of cumulus convection on large-scale flow. J. Atmos. Sci., 31, 1232-1240.

Lander, J., Hoskins, B., 1997: Believable Scales and Parameterizations in a Spectral Transform Model, *Mon. Wea. Rev*. 125, 292-303.

Larson, L. W. (1996) *The Great USA Flood of 1993.* Presented at IAHS Conference Destructive Water: Water-Caused Natural Disasters - Their Abatement and Control.

NOAA (1994) *The great flood of 1993 : natural disaster report.* US Dept. of Commerce.

NOAA /National Weather Service (1997*) Automated Local Flood Warning Systems Handbook.* US Dept of Commerce

Lindström, G., Gardelin, M., & Persson, M. (1994). *Conceptual modelling of evapotranspiration for simulations of climate change effects*. SMHI RH No. 10, September 1994. Norrköping, Sweden.

Lindström, G., Johansson, B., Persson, M., Gardelin, M. and Bergström, S. (1997). Development and test of the distributed HBV-96 model*. J. Hydrology.*, 201: 272-288.

Lundberg, A, (1982). Combination of a Conceptual Model and an Autoregressive Error Model for Improving Short Time Forecasting. *Nordic Hydrology*, Vol. 13 No. 4 :233-246.

Moore, R.J., Austin, R. and Carrington, D.S. (1993). *Evaluation of FRONTIERS and local radar rainfall forecasts for use in flood forecasting models*, R&D Note 225. National Rivers Authority, UK.

Oberstadler, R., Hoensch, H. & Huth, D. (1996): Assessment of the mapping capabilities of ERS-1 SAR data for flood mapping: A case study in Germany*. Hydrological Processes.*

Page, D. (1996) *The Implementation of an Interactive River Forecast System for the National Weather Service.* Proc. 12th International Conference on Interactive Information and Processing System (IIPS) for Meteorology, Oceanography, and Hydrology, Atlanta, Georgia

Refsgaard, J. C., (1997*). Validation and Intercomparison of Different Updating Procedures for Real-Time Forecasting. Nordic Hydrology*, Vol. 28 No. 2 :65-84.

Smith, J. A., Seo, D. J., Baeck, M.L. & Hudlow, M.D. (1996) An intercomparison of NEXRAD precipitation estimates. *Water Resources Research* 32(7):2035-2045

Wilke,K. (1997) Forecast systems for large rivers – the river Rhine catchment.
In Casale,R., Havno,K & Samuels,P. "River basin modelling, management and flood mitigation Concerted action" European Communities.

Sundqvist, H., Berge, E. and Kristjansson, J. E., 1989: Condensation and cloud parameterization studies with a mesoscale numerical weather prediction. *Mon. Wea. Rev.* 117, 1641-1657.

Sundqvist, H., 1993: Parameterization of clouds in large scale numerical models, Aerosol-Cloud-Climate Interactions, edited by P.V. Hobbs, pp. 175-Academic Press, Inc.

Todini, E. (1995). The ARNO rainfall-runoff model. J. Hydrology., 175:339-382.

Todini, E., Bongioannini, P et al. (1999) *Forecasting floods in the Reno catchment.* TELFLOOD Technical Report, Univ. Bologna.

Viner, D., Cluckie, I.D., and Collier, C.G. (1991) A preliminary analysis of the hydrological analysis of FRONTIERS system, Proc. Weather Radar Networking, COST-73 Final Seminar, Ljubliana, Yugoslavia, CEC WD/73/186.

Viner, D., and Cluckie, I.D. (1990) The hydrological utilisation of FRONTIERS data. Proc. Int. Symp. on Remote Sensing of Precipitation and its Application to Hydrology, Sao Paulo,

Wilke,K. Forecast systems for large rivers – the river Rhine catchment
In Casale,R, Havno,K & Samuels,P. (eds.) River basin modelling management and flood mitigation Concerted Action : report of 1st expert meeting. European Commission, Brussels EUR 17456 EN.

WMO (1988). *Simulated real-time intercomparison of hydrological models*. Report from WMO workshop in Vancouver, Canada, 1987, WMO/TD no 255.

The TELFLOOD research was supported by the EU “Environment and Climate Programme” under contract ENV-CT96-0257

I gratefully acknowledge the input of all my TELFLOOD colleagues from CWRR at UCD, Met Eireann, SMHI and University of Bologna, mentioned above.

List of Figures

1. Worldwide statistics on natural catastrophes

2.Flood fatality / Economic losses

3. Reduction in flood damages from forecasts

4. Rhine catchment

5. Water level forecasts at Rheinfelden

6. Forecasts at Cologne

7. Forecasts at St. Louis

8. Bias and Error Bands

9. Effects of scale of precipitation fields on hydrological modelling

10. Example of Precipitation estimates for Dodder catchment

11. Structure of the HBV model.

12. Behaviour of the new response for the HBV model.

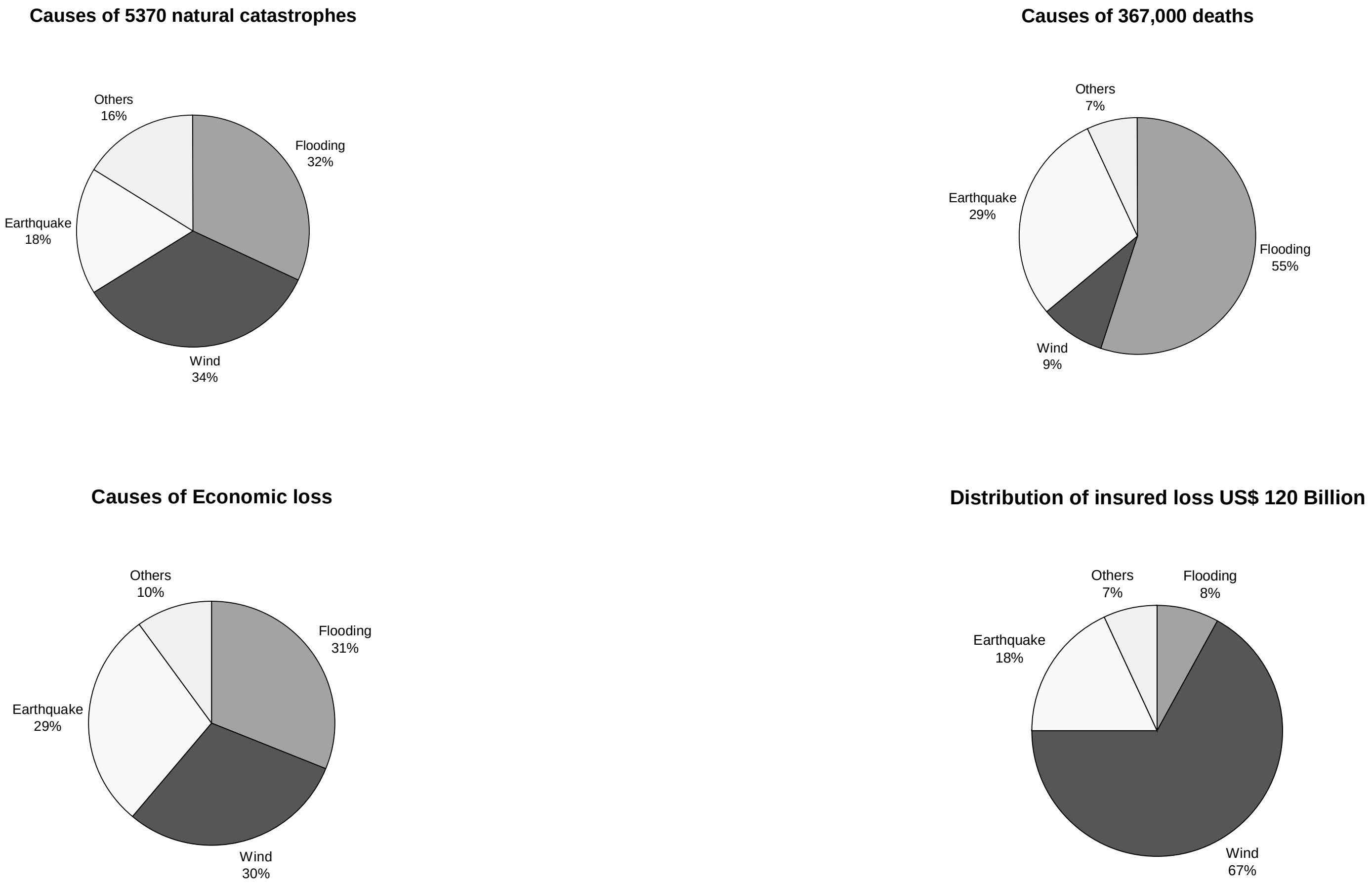
13. Differences between old and new HBV models.

14 Forecasting in Pepparforsen basin

List of Tables

1. Under-estimation of rainfall by radar.
2. Main TELFLOOD study catchments
3. Nested arrangements
4. Calibration performance over entire calibration period
5. Calibration performance over high flow events only

Figure 1 Worldwide statistics on natural catastrophes



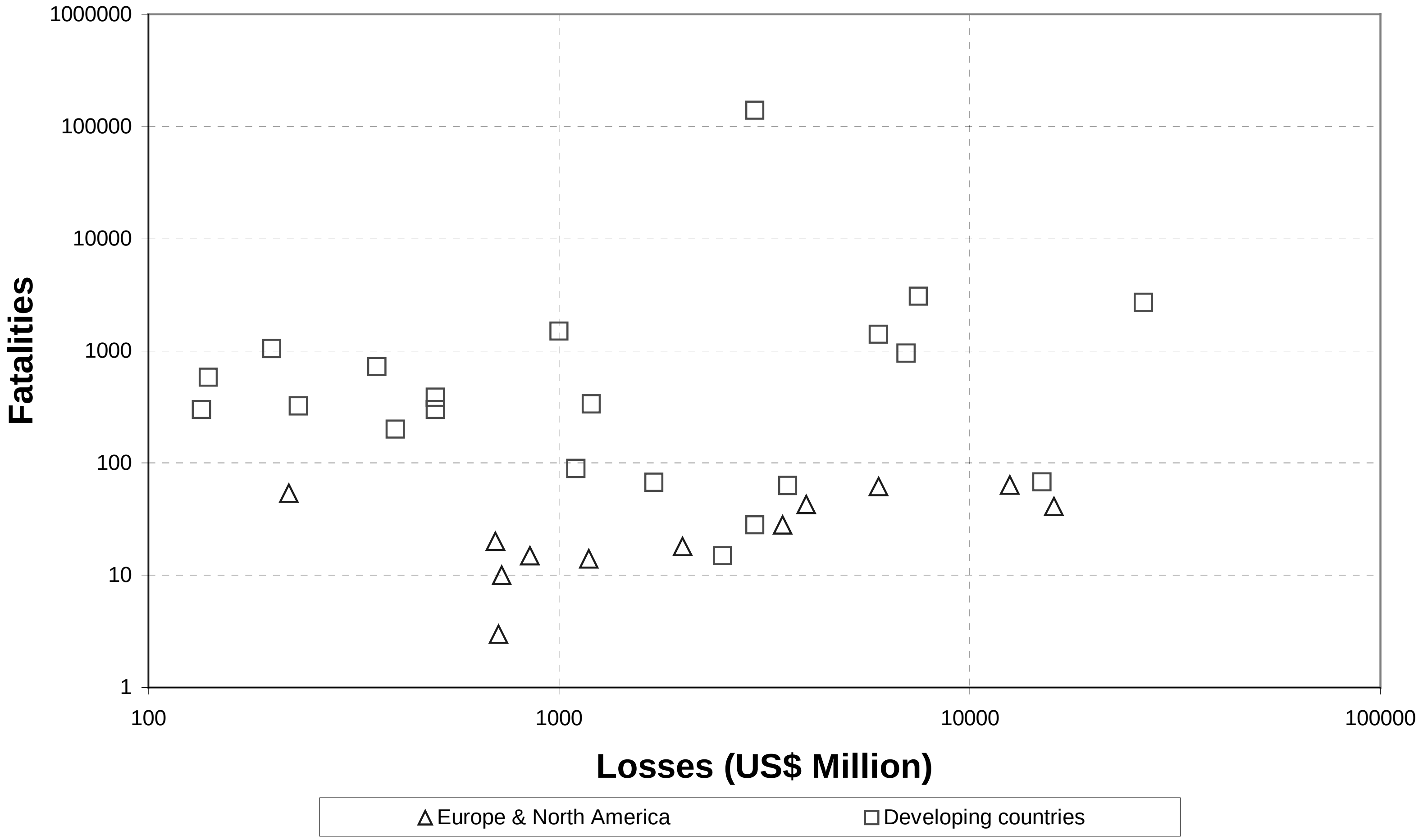
Causes of 5370 natural catastrophes

Causes of 367,000 deaths

Causes of Economic loss

Distribution of insured loss US$ 120 Billion

Figure 2 : Flood fatality / economic loss relationship



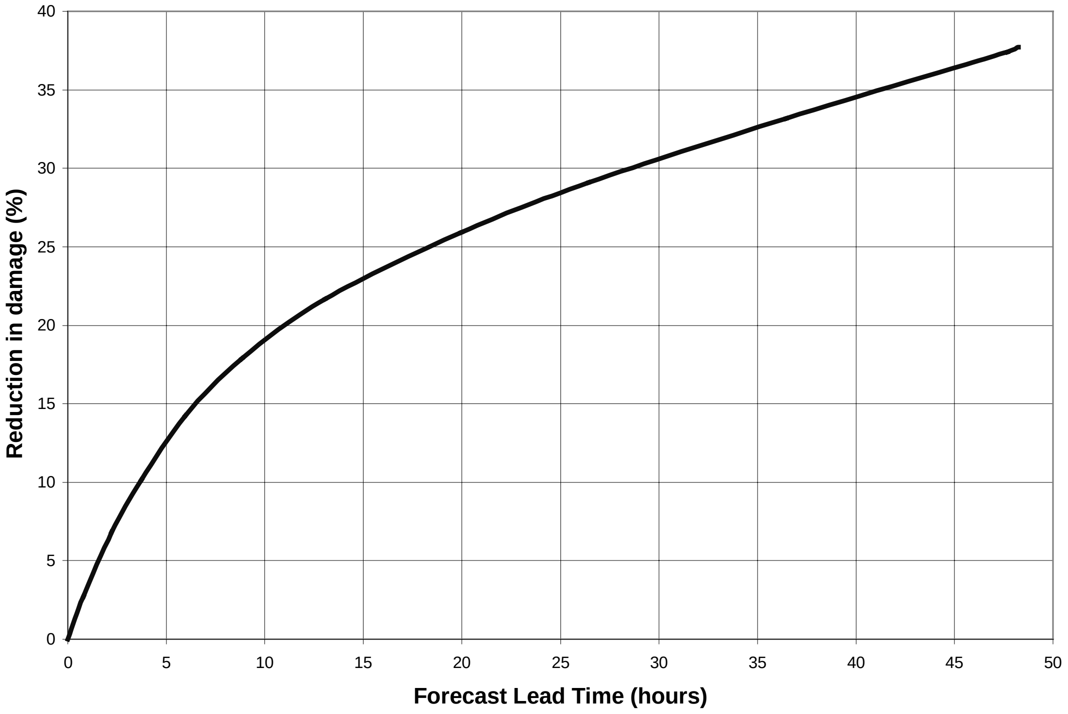


Figure 3: Reduction in flood damages for increasing forecast lead-time
Source: AUTOMATED LOCAL FLOOD WARNING SYSTEMS HANDBOOK
Weather Service Hydrology Handbook No. 2

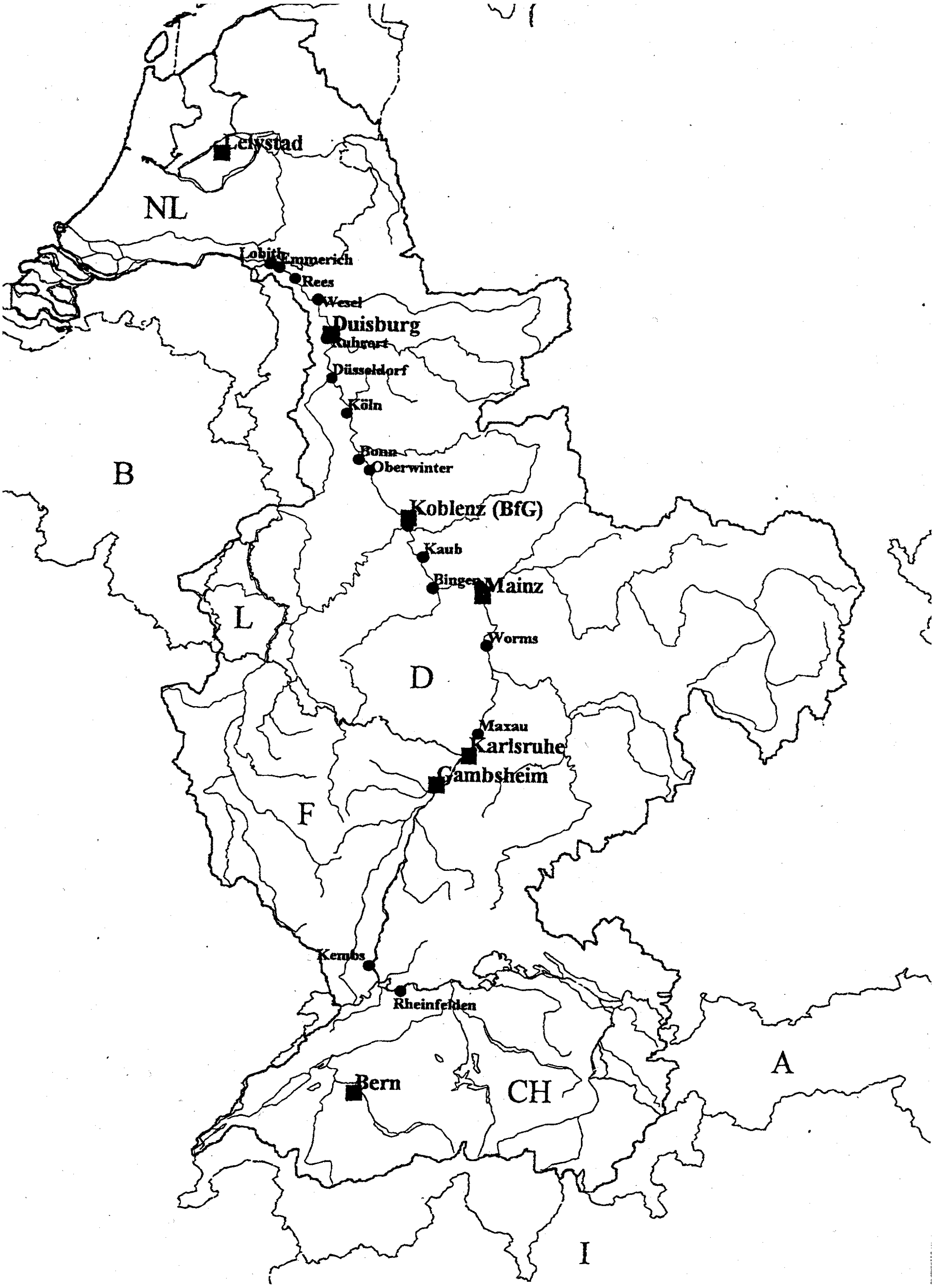


Figure 4 Rhine catchment (source : Wilkie, 1997)

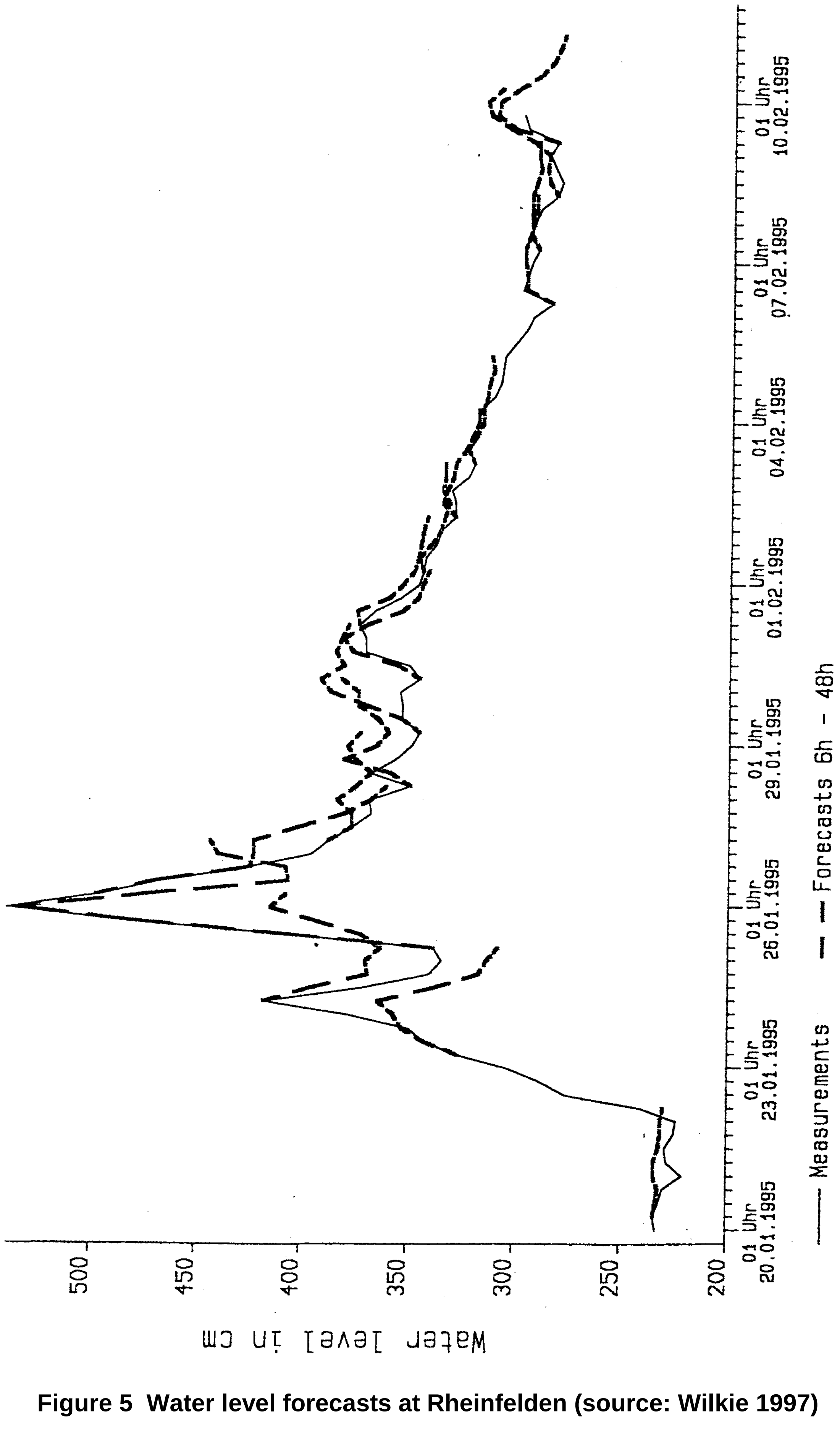


Figure 5 Water level forecasts at Rheinfelden (source: Wilkie 1997)

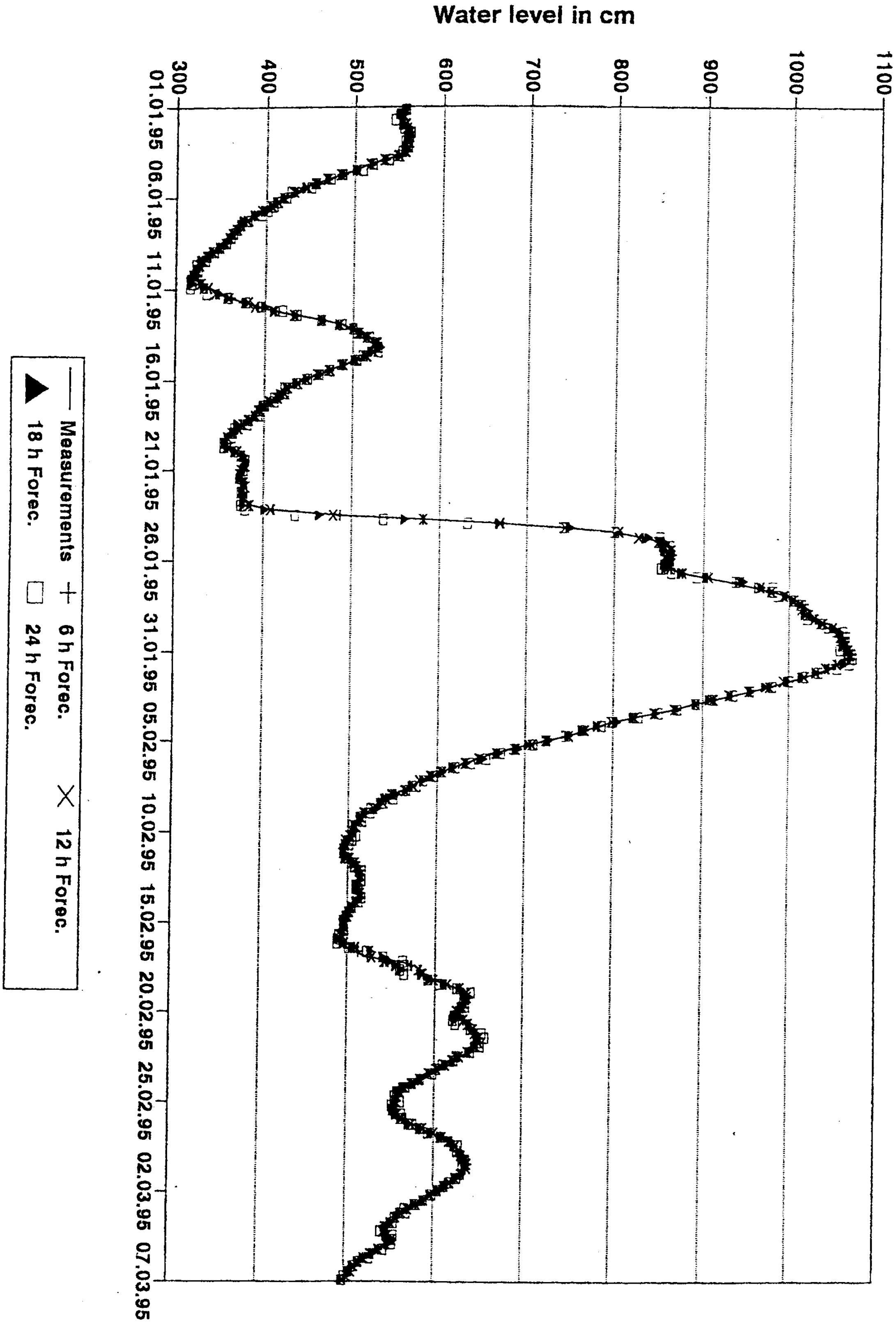


Figure 6 Forecasts at Cologne (source : Wilkie, 1997)

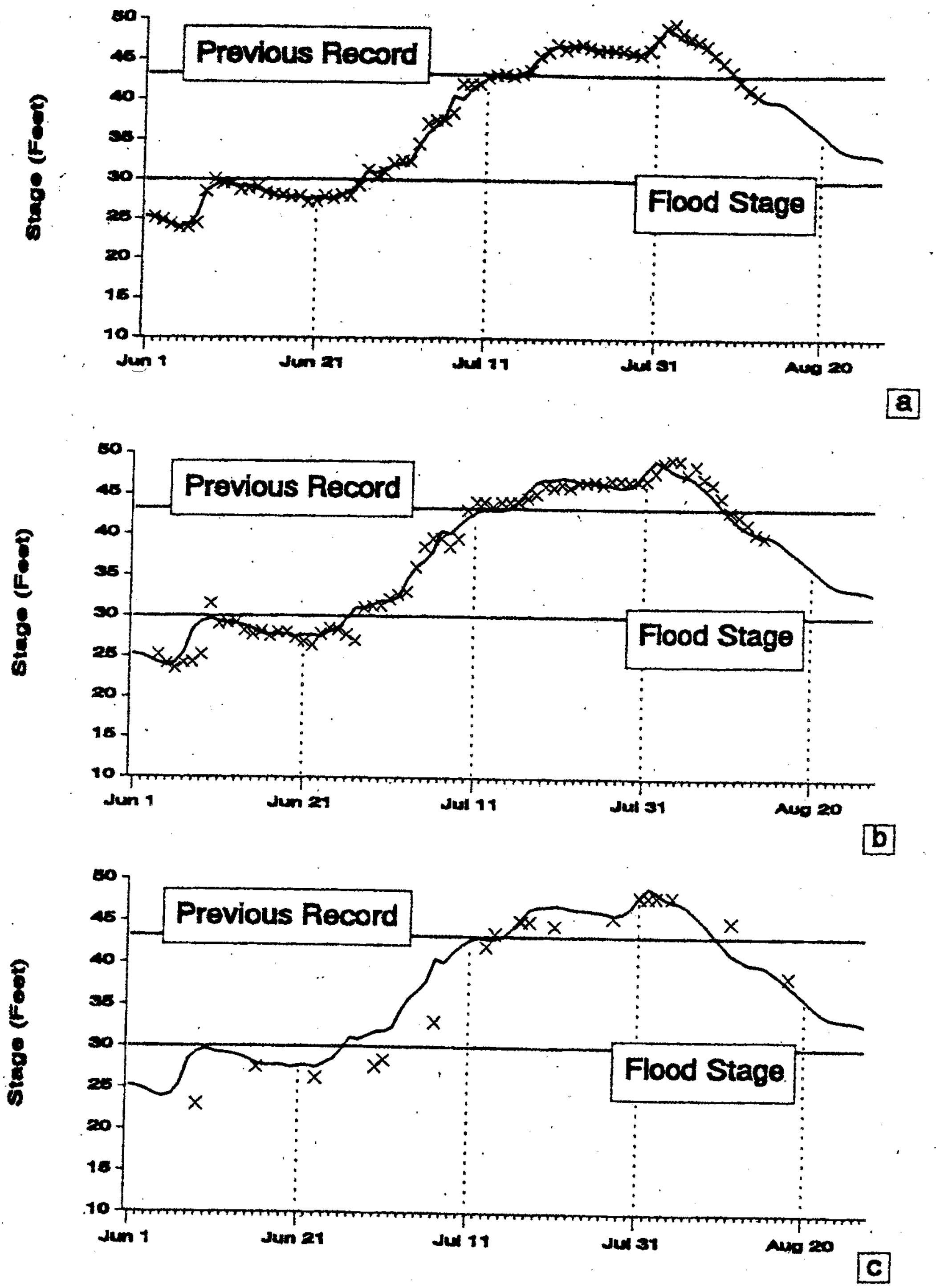


Figure 7 1 (a) , 3 (b) and 7 (c) -day flood forecasts for St. Louis (source : NOAA 1994)

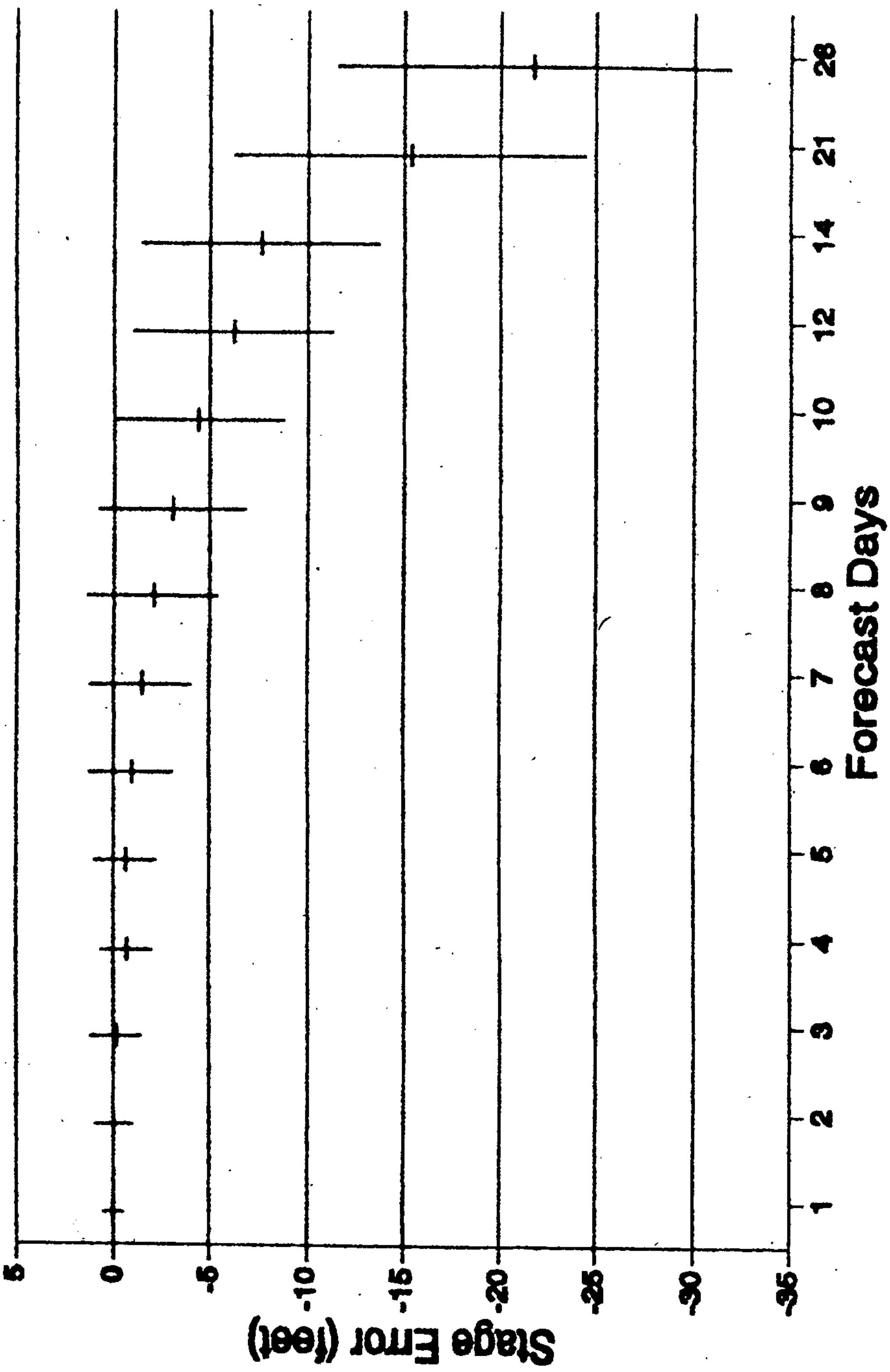


Figure 8 Bias and Error bands vs lead-time for Mississippi flood forecasts (source : NOAA 1994)

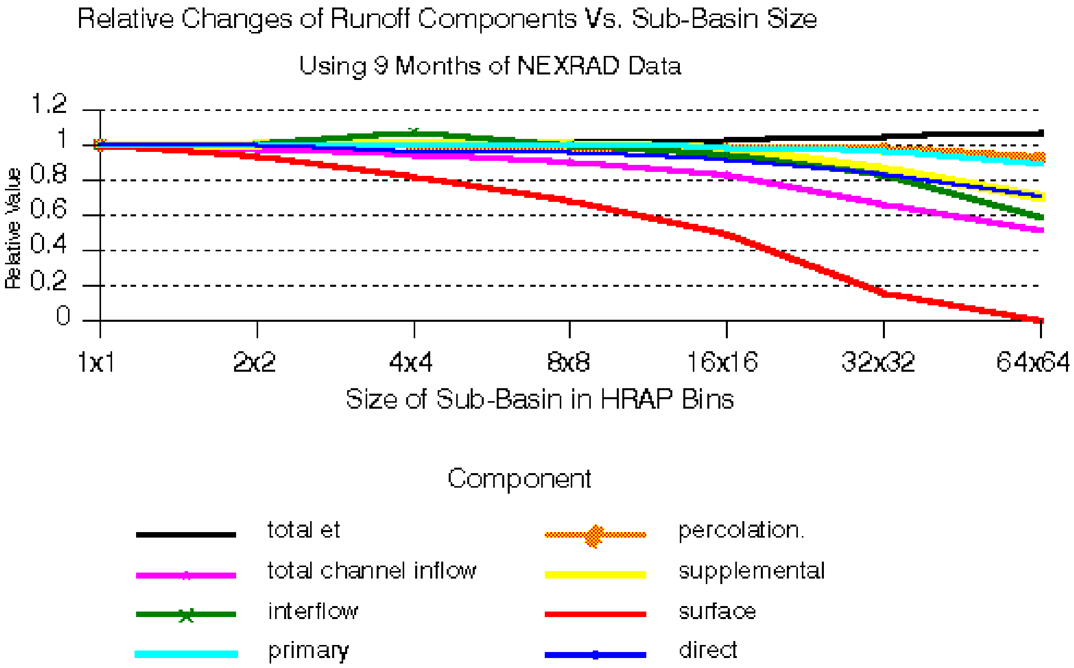


Figure 9 : Effects of scale of precipitation fields on hydrological modelling. (source: Finnerty & Johnson 1997)

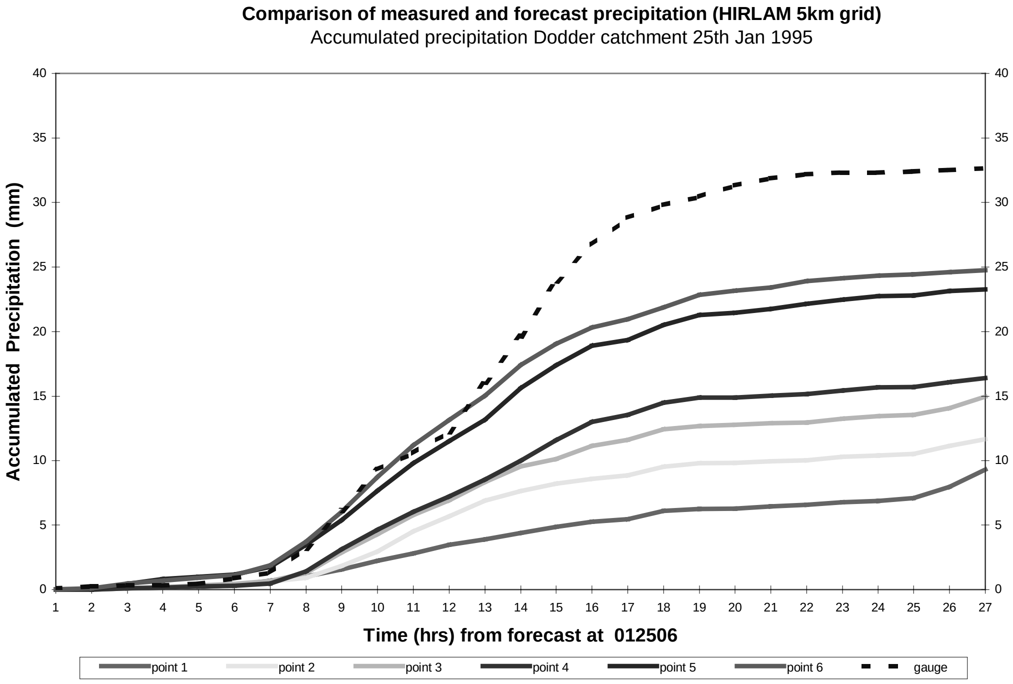


Figure 10 : Example of Precipitation estimate for Dodder catchment.

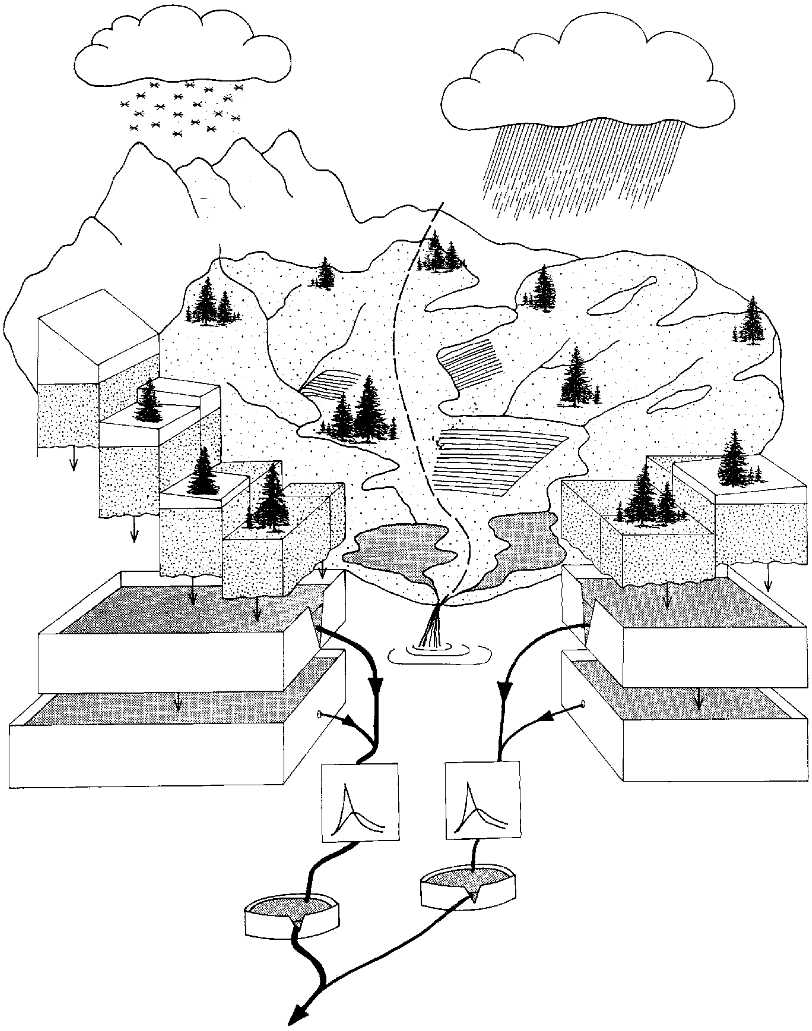


Fig 11. ***Structure of the HBV-96 runoff model.***

(source: Carlsson & Bergstrom 1998)

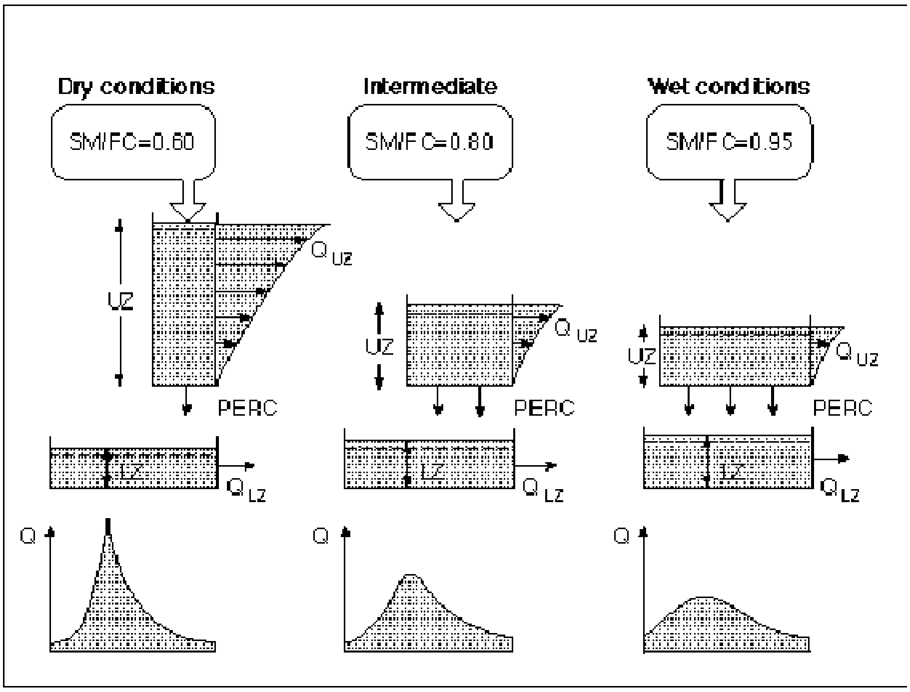


Fig 12 ***Behaviour of the tested new response routine for the HBV model. The input from the soil is assumed to be identical in this example.***

(source: Carlsson & Bergstrom 1998)

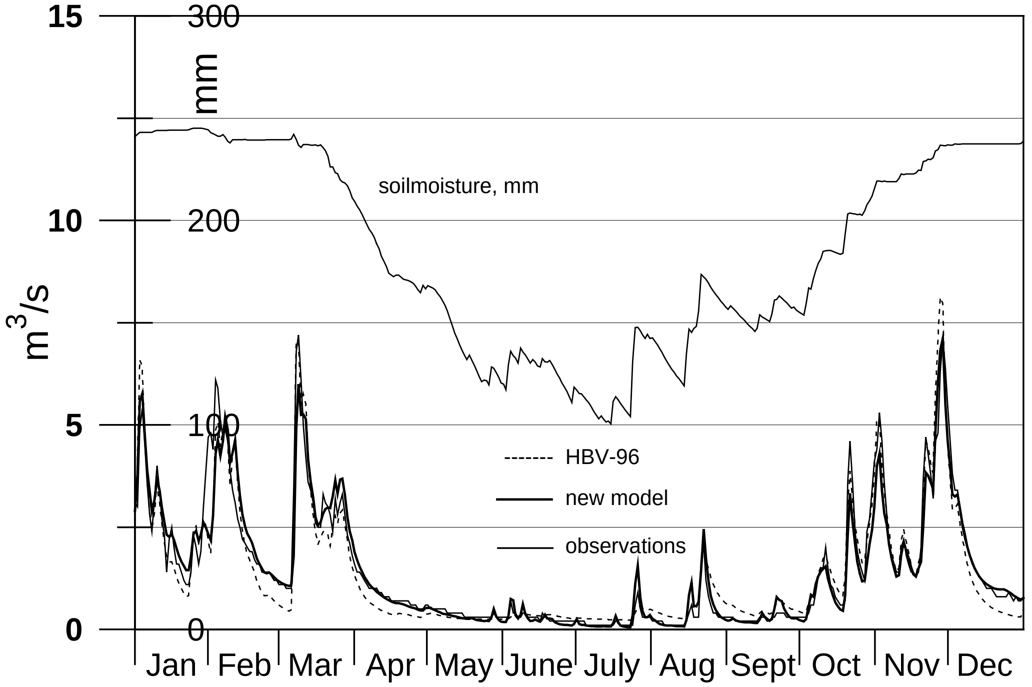


Fig. 13 ***Differences in general behaviour between HBV-96 and the new model exemplified by the simulation for the Tånemölla catchment during a relatively dry period in 1981.*** *(source: Carlsson & Bergstrom 1998)*

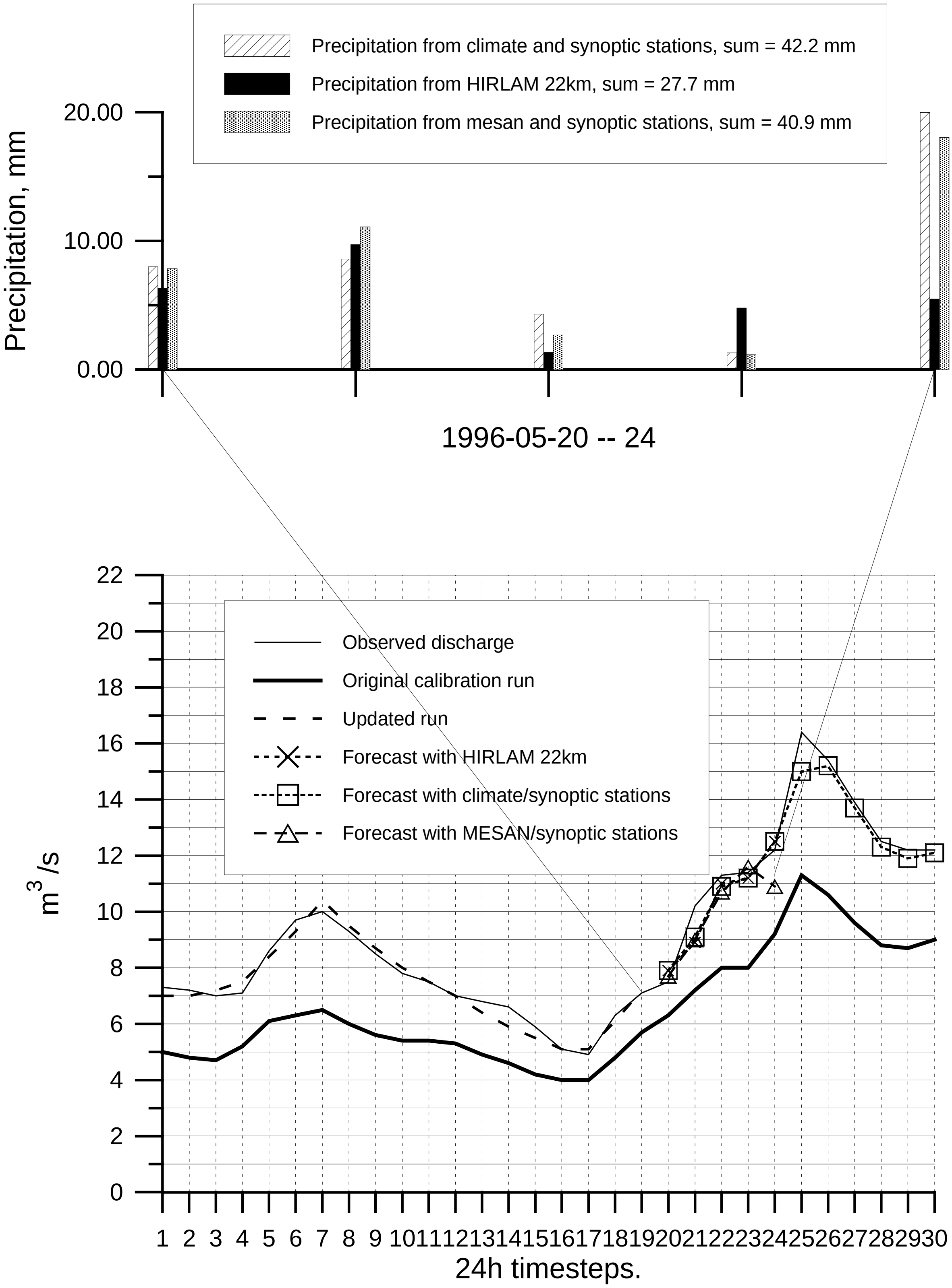


Fig. 14 ***Consecutive 24 h runoff forecasts with precipitation generated from climate stations and HIRLAM forecasts in the Pepparforsen basin in May 1996.*** *(source Gollvik 1997)*

Range (km)	% underestimation by radar of hourly rainfall amounts Summer	 Winter
0 – 40	48 %	30 %
40 - 160	18 %	14 %
> 160	40 %	100 %

Table 1 : Under estimation of rainfall by radar
(source of data: Smith et al., 1996)

Catchment	Location	Area (km^2)	Comments
Pepparforsen	Southern Sweden	380	Flat, unregulated
Dodder	Eastern Ireland	113	One half mountainous, 2 reservoirs
Reno	North Eastern Italy	4127	One third mountainous; high quality hydro-meteorological network.

Table 2 : Main study catchments

Resolution (degrees)	 (km)	Mesh-system	Levels (vertical)	Advection scheme	Timestep (seconds)
0.50	55.0	110 x 100	16	Semi Lagrangian	600
0.25	27.5	110 x 100	16	Semi Lagrangian	300
0.125	13.8	110 x 100	16	Semi Lagrangian	150
0.0625	6.9	110 x 100	16	Semi Lagrangian	75

Table 3 : NESTED arrangement tested

Model	MSE	BIAS	R^2
SMAR	2.51	-0.09	74.6 %
HYRROM	1.82	0.03	81.59 %
HBV_v1	1.36	-0.02	86.27 %
HBV_v2	1.35	0.002	86.33 %

TABLE 4: Calibration performance over entire calibration period

Model	MSE	BIAS	VAR(err)
SMAR	17.28	-0.10	17.27
HYRROM	10.92	-0.16	10.89
HBV_v1	9.45	0.17	9.42
HBV_v2	9.96	0.40	9.80

TABLE 5 : Calibration performance over high flow events only