INCA-CE OPERATIONAL HYDROLOGY TEAM

OUTPUT 3.1.2

TRANSREGIONAL STRATEGY FOR THE USE OF NOWCASTING INFORMATION IN OPERATIONAL HYDROLOGY

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INCA-CE Nowcasting for Central Europe

This project is implemented through the CENTRAL EUROPE Programme co-financed by the ERDF.

Purpose of the document

This document presents a strategy for the use of precipitation nowcasting in the Operational Hydrology, especially in forecasting of flash floods. The shared experience with the flash flood forecasting systems tested in operation in all Central European countries participating in the Operational Hydrology group of the INCA-CE project will help to better understand these complicated natural phenomena and to increase their predictability.

Abstract

In Central Europe floods are the natural disasters causing the greatest economic losses. One way to partly reduce the flood-related damages, especially loss of lives, is a functional objective forecasting and warning system that incorporates both meteorological and hydrological models. Success of the hydrological forecast is strongly dependent on the success of the precipitation forecast obtained usually as output from numerical weather prediction models. The precipitation nowcasting, which is derived from the extrapolation of radar echo, can improve first hours of the precipitation forecast significantly. Thus, the use of precipitation nowcasting in hydrological forecasting systems can result is more precise hydrological forecasts.

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Abbreviations

ALADIN - Aire Limitée Adaptation Dynamique Dévelopement International, weather prediction model used by several Central European countries
COTREC – the radar echo extrapolation method, "Continuity of TREC vectors" where TREC stands for "Tracking Radar Echoes by Correlation"
CELLTRACK – Convective cell tracking algorithm
CHMI – Czech Hydrometeorological Institute
CZRAD – Czech radar network
CZRAD-EXT – Czech radar network extended by the radars of neighbouring countries
IMWM – Institute of Meteorology and Water Management
NTC – National Telecommunication Center
NWP – Numerical Weather Prediction
SHMÚ – Slovak Hydrometeorological Institute
SR – Slovak Republic

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1 Introduction

Floods are natural phenomena necessary for the health and survival of the ecosystem. They are important water sources – for example in Central Europe spring floods caused by snow melting feed the subsurface water storages. On the other hand, extreme floods can cause widespread damage, health problems and loss of human lives.

In Central Europe floods are the natural disasters causing the greatest economic losses. The extreme floods which hit the Morava and Odra river basin in July 1997 caused 47 human losses within the territory of the Czech Republic, and an economic damage of about 2.5 bn. EUR, while the Odra river flood in Poland caused 55 human losses and economic damage of 3.5 bn. EUR. In August 2002, Central Europe was hit by another extreme flood in the Elbe and Danube river basin. In the Czech Republic 17 people died and the total damages reached 3 bn. EUR.

One way to partly reduce the flood-related damages, especially loss of lives, is a functional objective forecasting and warning system that incorporates both meteorological and hydrological models. Success of the hydrological forecast is strongly dependent on the success of the precipitation forecast obtained usually as output from numerical weather prediction models. The precipitation nowcasting, which is derived from the extrapolation of radar echo, can improve first hours of the precipitation forecast significantly. Thus, the use of precipitation nowcasting in hydrological forecasting systems can result is more precise hydrological forecasts.

1.1 Predictability of different flood types

Floods can be divided into several groups according to their origin which is connected closely to their predictability. Briefly, we can speak about three main types of floods typical for Central Europe.

Floods caused by stratiform (long-lasting regional) precipitation or snow melting

These floods usually occur on all watercourses in the area exposed to the precipitation with highest impacts along middle or large-size rivers. The causal precipitation hits area of the size of thousands square kilometres. Such precipitation type is relatively well predicted by numerical weather prediction models. Water level raise is usually not so rapid (in comparison to other flood types). That is the reason why the hydrological forecasts of these floods are relatively successful. A typical example of large-scale flood caused by prevailingly stratiform precipitation type is shown in Fig. 1.1.1 (flood from August 2002).

Floods caused by both stratiform and convective precipitation

These floods may hit large areas as well. Due to the presence of convection the exact spatial and temporal distribution of precipitation calculated by numerical weather prediction models is problematic: The hydrological forecast can be highly uncertain, as the forecasted precipitation can hit a different catchment than expected.

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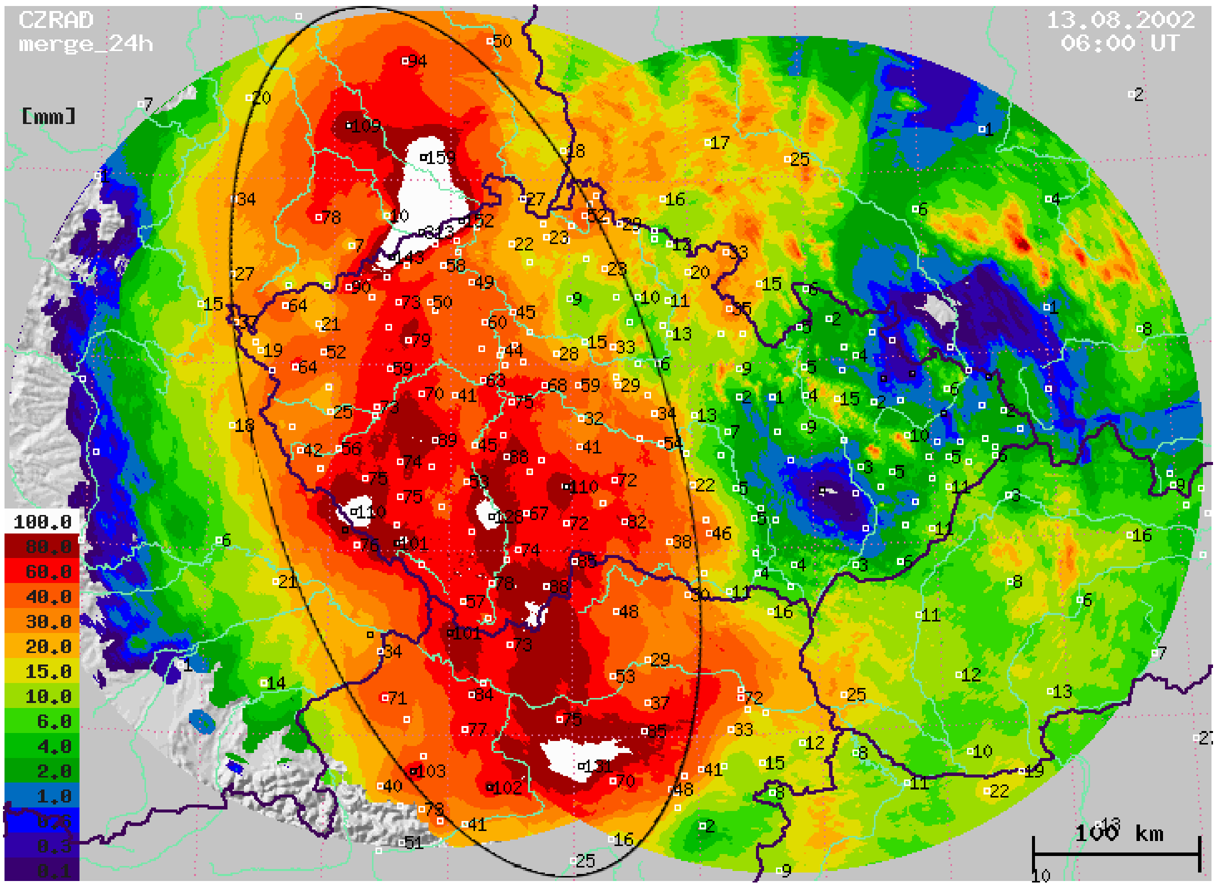

***Fig. 1.1.1** Daily sum of precipitation calculated from a multisensor (combined) radar and raingauge estimate from 13 August 2002, measurement taken at 06 UTC. Widespread record-breaking floods in Vltava and Labe basin were caused by large-scale heavy precipitation with remarkable orographic enhancement in the mountains in the north-west of Bohemia (300 mm on the ridge, 40-50 mm at the foothill on the lee side). In the southern Bohemia convection development was observed, but played only a minor role.*

An example of stratiform and convective precipitation leading to a flood is depicted in Fig. 1.1.2. The causal precipitation resulted in the extreme flood; the peak discharge in Podhradí watergauge station exceeded the 500 years return time period discharge value. The example of the successful use of precipitation nowcasting is presented in Fig. 1.1.3. With the use of 3 hour COTREC precipitation nowcast supplemented by ALADIN precipitation forecast this flood could have been predicted three hours in advance while comparing with the use of ALADIN precipitation forecast only.

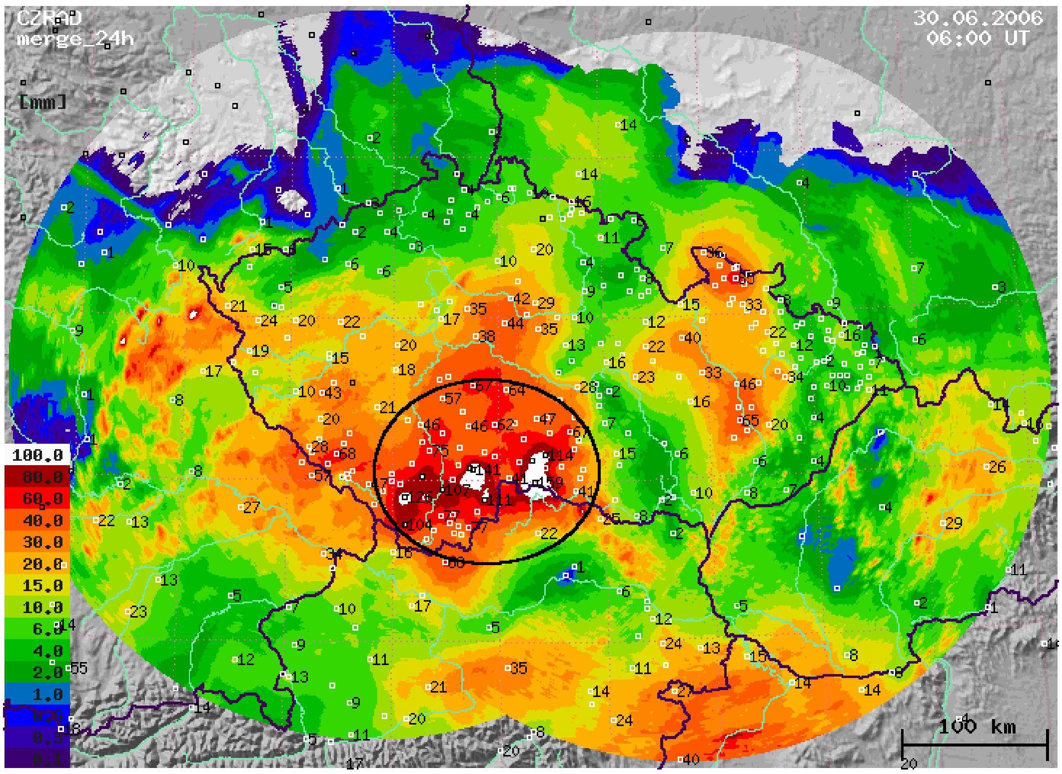

***Fig. 1.1.2** The same analysis as in Fig. 1.1.1. Daily rainfall accumulation from 30 June 2006, measurement taken at 06 UTC. The precipitation resulted from intense and widespread convective activity, accompanied by large scale precipitation which was more pronounced only at the end of the episode. The rainfall resulted in a flood which could be characterized as a large-scale flash flood.*

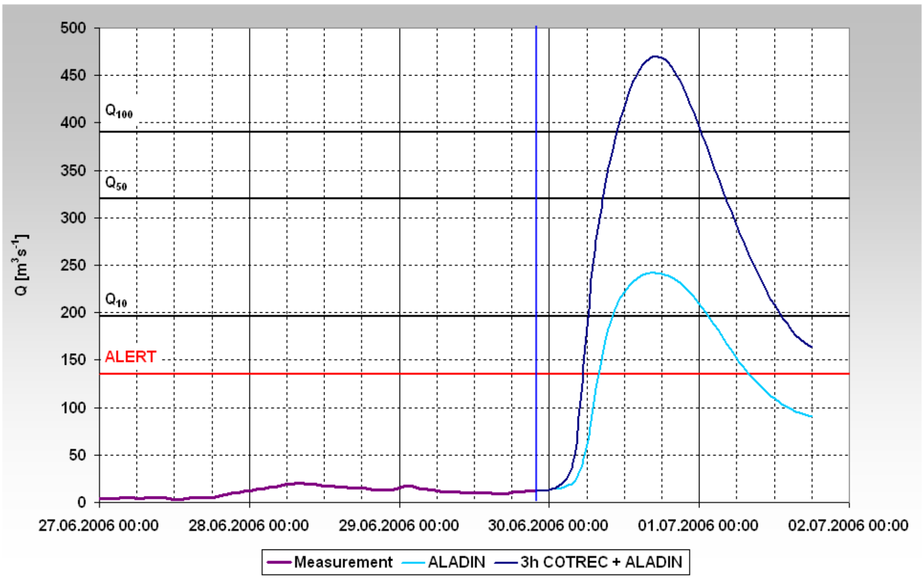

***Fig. 1.1.3** The example of the successful use of COTREC precipitation nowcasting – the real peak discharge exceeded 550 m^3/s.*

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Flash floods

Flash floods originate from storm rain (having an intensity of over 100 mm during several hours) lasting only one or few hours. Fig. 1.1.4 shows an example of pronounced convective development (radar image) which produced a localized flash flood in the depicted region. These floods happen in water courses with small catchments and with relatively narrow valleys. Sudden rise of water level in a very short time period is characteristic for this flood type. Flash floods are usually considered as unpredictable. Development of nowcasting techniques holds some hope. The first test proved that some flash floods can be predicted several tens of minutes in advance – see Fig. 1.1.5. The testing of possibility of flash flood predictability is one of the main goals within the INCA-CE project concerning the application area of hydrology.

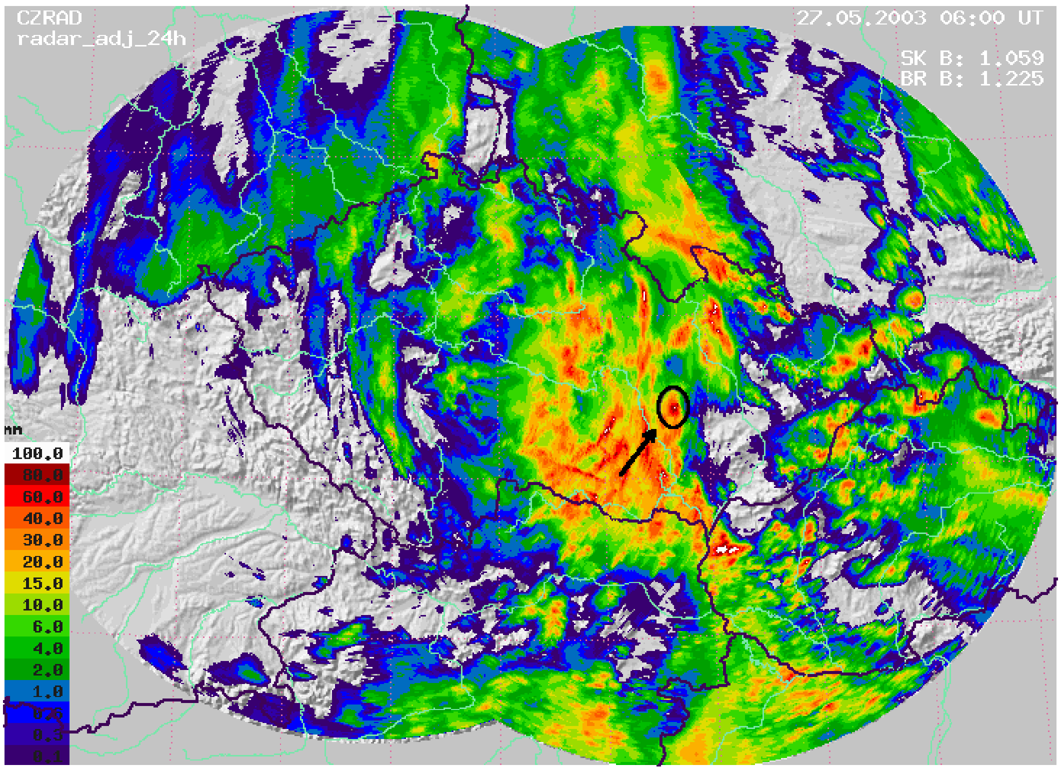

Fig. 1.1.4 *Routinely adjusted radar precipitation estimate of daily rainfall accumulation from 27 May 2003, 06 UTC; example of pronounced convective development which produced a localized flash flood in the depicted region.*

Flash floods can be very destructive. The most tragic and probably the most destructive flash flood in Slovakia has occurred on 20 July 1998 in eastern part of Slovakia, in the Hornad (mainly at left side tributaries) and upper Torysa watersheds. From a meteorological point of view, the main reason of this flood was the position of a deep low pressure system in Western Europe. On the front side of this system, very hot and moist air was inflowing in the area of Central Europe. Re-analyses showed that there was only low probability of possibility of creation of serious storm systems. Only isolated storms were predicted. Despite of this fact, serious series of storms attacked some tributaries of Hornad River and upper part of

Torysa river basin. Most affected was Malá Svinka watershed. Based on radar measurement (there were no raingauge stations in Malá Svinka watershed) the development of vertical clouds started at 11:45 UTC and causal rain started after 13:00 UTC (depending on the location). In specific time intervals, the precipitation intensity exceeded 3 mm per minute, and the average intensity of precipitation of this event was 36 mm per hour. The duration of causal rain was approximately three hours, therefore the whole precipitation amount in the affected area summed up to around 100-120 mm.

Heaviest hydrological response has occurred in the Malá Svinka watershed. In this river basin no watergauge data are available; therefore the hydrological data are based on hydrological reconstruction of this event. In the most affected part of the river basin – Jarovnice village – the reconstructed peak value of this flood wave was 230 m^3s^{-1}. The volume of this flood wave was around 2.28 mil. m^3, and the return period was more than 1000 years. Similar (or slightly lower) return periods have been reconstructed for other small rivers in the affected area as well (e.g. Branisko, Žehrica, Dubovicky Creek and Rencisovsky Creek). Due to the flash flood which has affected the village Jarovnice 50 people died. Most parts of this village have been destroyed. The number of causalities in all affected villages amounts to 58. Moreover, more than 5 000 animals were washed down and got drowned. The economic damages were around 1 bn. in Slovak crowns leading to one of the first impulses for improvement in the system of flood warning in Slovakia (start of project POVAPSYS, flood warning and forecasting system, in Slovakia in 2002).

The precipitation nowcasting is a necessary tool in case of convective precipitation events as they are rather difficult to forecast with classical NWP models. However, the importance of the use of precipitation nowcasting in hydrological forecasting models strongly depends on the predicted flood type. Large-scale floods caused by stratiform precipitation can be successfully predicted with the use of NWP precipitation forecast only. For large-scale floods caused by convective or mixed (both stratiform and convective) precipitation the precipitation nowcasting can be very helpful, while for floods caused by convective precipitation only (flash floods) the precipitation nowcasting is an essential source of rainfall information. These facts are schematically depicted in Fig. 1.1.6.

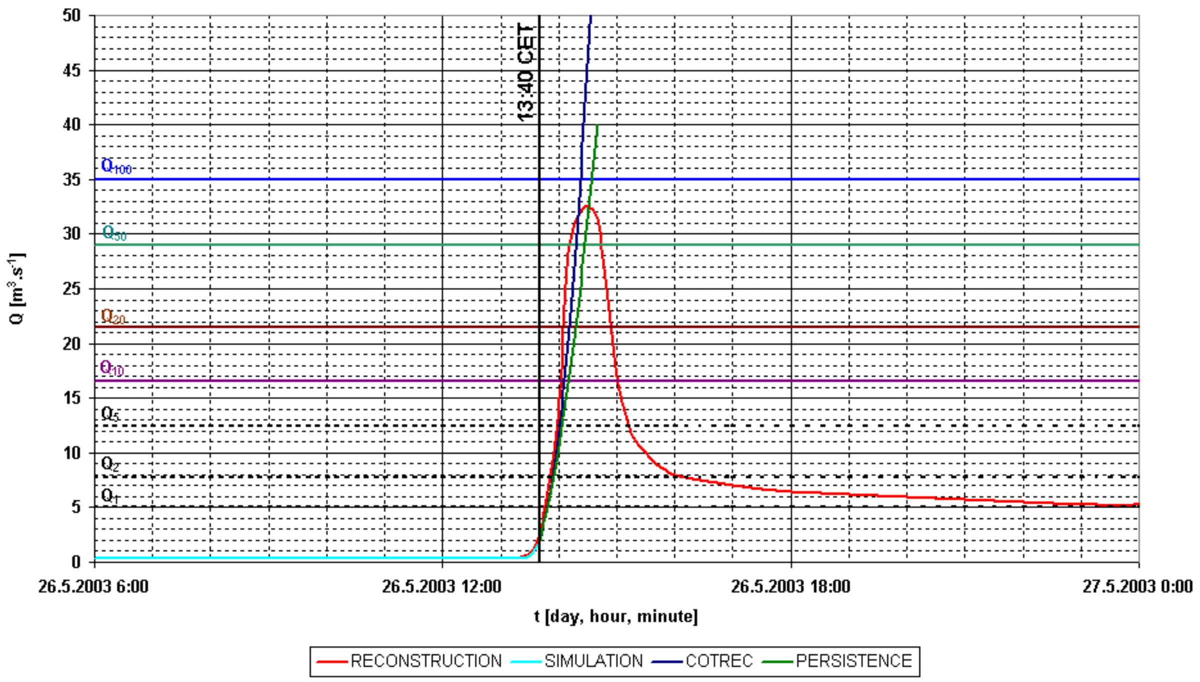

Fig. 1.1.5 *The example of the flash flood forecast using COTREC precipitation forecast (simulation of flash flood which hit Sloupský Creek catchment on 26 May 2003 – source Šálek et al., 2006).*

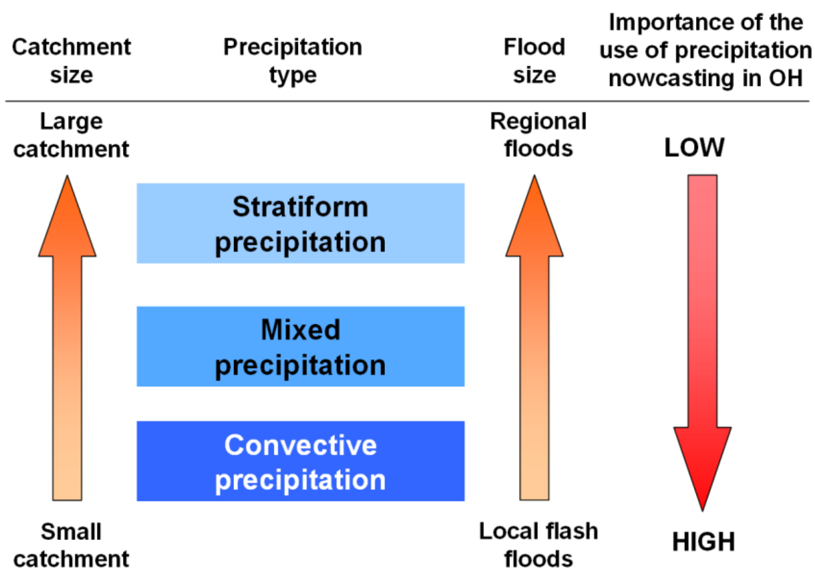

Fig. 1.1.6 *Scheme of the dependences among catchment size, precipitation type, flood type and the importance of the use of precipitation nowcasting in Operational Hydrology (OH).*

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1.2 Flood forecasting systems

The ability of forecasting the river flows requires a deeper understanding of natural processes. The water on the Earth is in permanent rotation (hydrological cycle), in which it keeps changing its states. The hydrological cycle is powered by solar energy and gravitation power and results in the exchange of water between ocean and mainland. Water evaporates above the oceans and is transferred in the form of clouds over the mainland. There it falls back onto the ground as precipitations and flows back to the oceans. The 'little' hydrologic cycle includes only the water exchange either over oceans or over mainland.

A river catchment is the area from which water flows to the single certain point on the river. The amount of water flowing from the catchment through a defined river profile depends on several factors. In Central Europe, precipitation is the most important factor. However, there is no linear relation between rainfall and discharge. This relation is influenced by many climatic and geographic factors. Moreover, the anthropologic factor has to be taken into account.

To define the result outflow and for the simulation of rainfall-runoff processes hydrological models are applied. Many such models exist, and their development is in progress. Apart from operative hydrology they are used in project and design activities, and in research. The model simplifies the reality concerning the infiltration intensity, surface and soil water flow and other processes.

The quality of the hydrological forecast mostly depends on the quality and quantity of input information from which the most important is the precipitation input (especially precipitation forecasts). In the winter season, inputs such as air temperature, information about snow cover and its water content are assumed. Apart from these meteorological inputs, the models take into account the hydrological inputs such as water levels, discharges and manipulations on the reservoirs. The hydrological forecast is preceded by meteorological forecast. For the calculation of the precipitation and temperature forecasts the numerical weather prediction models (NWP models) are used. These models are based on equations describing the atmospheric processes.

Precipitations can be measured using raingauge stations providing relatively precise information, however, related only to the location of the device. Another way on how to measure precipitations is using meteorological radars. They are able to offer spatially continuous information about precipitations over catchments, although the quantitative information about the precipitation amount is rather poor. Therefore, the combination of radar and raingauge measurement is the proper input for hydrological models. Precipitation nowcasting is obtained by the extrapolation of the radar data and usually leads to more precise prediction of rainfalls for the first hours of the predicted period than provided by the NWP models.

It is necessary to stress that hydrological forecasts are often highly uncertain considering the exact local and time information which should be taken into account when interpreting the discharge forecasts. However, the *adaptivity principle* enables the successful operation of the hydrological model. During the flood event its development in the catchment is continuously monitored and the hydrological model outputs are continuously compared to the real development. Therefore it is recommended to update the forecasts according to measured data as often as possible, taking into account the weakening predictability with increased lead time.

The typical lead time of the discharge forecasts for middle-sized and large catchments is 48 hours. These forecasts are published on the web sites. During the flood event the discharge forecast can be a crucial information for the decision makers (for optimized water management and flood emergency commission to mitigate the flood damages, like discharge control of the reservoirs, construction of the flood walls or deploying of sand bags etc.).

A good communication between the meteorologists, hydrologists and end-users of the forecasts is highly important as well. The better the understanding of the process of discharge forecast creation is, the more beneficial the usage of such information can be.

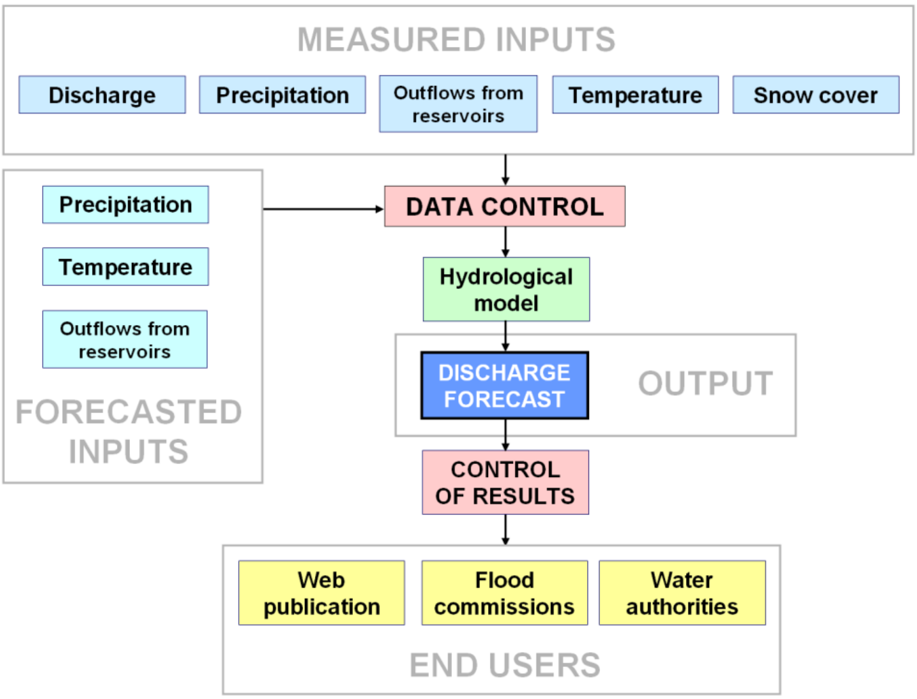

Fig. 1.2.1 *Scheme of the discharge forecast preparation and usage.*

1.3 Transnational cooperation

Floods do not respect borders neither national nor regional ones. Therefore the flood risk management must be transnational for quickly spreading the flood information to ensure timely warnings.

International commissions for border waters assure the implementation of the agreements between the governments of the neighbouring countries. The agreements about the approaches of the international cooperation are declared in the Principles of Cooperation in the Field of Hydrology and of Flood Protection on Border Waters between the Slovak Republic, Czech Republic, Germany, Austria, Hungary, Ukraine and Poland.

Internal cooperation includes exchange of information about ice phenomena and flood activity of cross border rivers. Via an international agreement, diverse partners and end-users are immediately informed about flood activities (i.e. in the case of declaration or exceedance of degrees of flood activity, their cessation, time of culmination of flood wave in important river profiles). Information exchange begins when the limit water levels are exceeded or when degrees of flood activity are exceeded. The frequency of these messages depends on the exceeded degree of flood activity (higher degree – higher frequency of sending of messages). These information messages are sent from the countries from the upper part of watersheds of boundary rivers.

The example – transnational cooperation in SHMI

The hydrological services of Germany, Austria, Czech Republic, Hungary, Ukraine and Poland provide daily hydrological data and send them to the hydrological service of the Slovak republic (represented by SHMU) in an agreed format and manner. The received information contains data on water levels, discharges, air temperature, water temperature and information on daily precipitation measured at hydrological stations. For some stations the 24-hour forecast of water level is indicated. During flood situations the lead time of the forecast is shorter. Hydrological information is distributed through NTC (National Telecommunication Centre) by telephone and by Internet. In the standard regime the information is distributed once a day, in flood situations more frequently (set by agreements).

Hydrological information from the downstream stretch of the Danube is for SHMU's information only, to follow the progress of the flood wave in the downstream stretch. Meteorological data through SYNOP News are distributed via NTC in 6-hour steps (6, 12, 18, and 24 h). This information contains 6-hourly precipitation, terminal air temperature and once a day the snow cover depth. The Slovak hydrological service is using information from 96 hydrological stations and from 77 foreign meteorological stations for the production of hydrological forecasts.

International commissions for border waters assure the implementation of the agreements between the government of the Slovak Republic and the governments of neighbouring states. The agreements about the approaches of the international cooperation are declared in the Principles of Cooperation in the Field of Hydrology and of Flood Protection on Border Waters between the Slovak Republic, Czech Republic, Austria, Hungary, Ukraine and Poland.

Morava River basin

From the hydrological service of the Czech Republic CHMI (Czech Hydrometeorological Institute) information is incoming from 25 hydrological stations of the upper Morava catchment. This information contains the development of water levels during the last 24 hours in 6-hours intervals, the actual water level and discharge (from 6.00 AM) and from one station the 24-hours forecast of water level and discharge. Besides, all 16 stations provide information about the 24-hour precipitation. The data are sent to SHMI via NTC once per day. Moreover, the water stage and discharge data of 4 important watergauges are provided to SHMU through ftp server in one hour step, and these data are updated every hour.

Danube river basin – upstream

Data from 28 hydrological stations in the upper part of the Danube and Morava rivers on the territory of Germany and Austria are transmitted by telephone once a day at 07 50 AM (local time). For selected stations the forecasted water level for the following day at 07 00 AM is provided. Water temperature, measured at 07 00 AM is transmitted in the form of temperature range. In a flood situation, the forecast lead time is shortened from 6 to 2 hours, according to the urgency of the flood situation. Information from specific stations can be obtained directly by the voice transfer from the station, in some cases also from the web pages of the German and Austrian hydrological services and Teletext, respectively.

Information about the observed precipitation sums is received from two sources: by telephone from the hydro-climatic stations of the Austrian hydrological service (5 stations), and SYNOP stations (54 stations) via NTC in the form of international information exchange. The quantitative precipitation forecast is received by telephone from the hydrological service of Austria, with a forecast lead time of 12 and 24 hours and with the subdivision to two regions: Lower and Upper Austria. Online hourly data of water stage from selected watergauge stations from upper part of Danube river basin in Kienstock, Korneuburg, Wildungsmauer, Ybbs) are available in the form of ftp as well.

Bodrog river basin - Ukraine (Tisa, Rika, Latorica, Uh, Turja)

From Ukraine data are received from 14 hydrological stations. Some of them measure the water level only (at 06 00 AM and from the previous day at 06 00 PM), the others additionally measure the air temperature and precipitation. The data are transmitted by NTC once a day in the case of standard hydrological situation. In a flood situation the information is spread via telephone.

Bodrog river basin - Dunajec, Poprad and upper Orava river basin

Daily exchange of hydrological information occurs between SHMU and IMGW (Poland) - by means of the WMO network - via electronic mail between the regional centre of SHMU in

Žilina and hydrometeorological service IMGW Zakopane, as well as between the regional centre of SHMU in Košice and hydrometeorological service IMGW Nowy Sacz. In a standard situation the information is exchanged once a day, in flood situations more often – 2 or 3 times a day corresponding to the rules of international cooperation.

Exchange of hydrological warnings

Warning information messages are sent from the countries from the upper parts of the watersheds. Slovakia receives warning messages from the Czech Republic, Poland, the Ukraine and Austria, and is sending information to Austria and Hungary.

Warning messages are received at the Forecasting and Warning centre at SHMI. In a next step, these are distributed to other responsible institutions as the Ministry of Environment of Slovakia Republic (Slovak Water Enterprises), Ministry of Interior of Slovak Republic (Civil protection and fire and rescue brigades) and to local departments of the Ministry of Environment.

1.4 The purpose of this document

This document aims at demonstrating the potential of precipitation nowcasting when applied in Operational Hydrology. The main focus is given to the problem of flash flood forecasting – the phenomenon which is very actual in the hydrological community nowadays. The INCA system (Integrated Nowcasting through Comprehensive Analysis, see Haiden et al. 2010, 2011) and other nowcasting techniques provide very short range precipitation forecasts which can be used as input for the hydrological model. The latter provides the end-users with the estimation of discharge rise in the respective river profiles of interest. However, the proposed system for flash flood forecasting might be affected by significant uncertainties which are given especially in the case of convective precipitation events. Thus, the obtained hydrological forecasts must be interpreted with care.

The document aims at showing not only the possibilities of the use of precipitation nowcasting in the field of Operational Hydrology, but also to describe the problems and limits connected with the flash flood forecasting. It is true that the hydrological forecast is successful only when it is well interpreted and applied by the end user. Both the recommendations for improvement of flash flood forecasting system and the correct interpretation of the results are provided in the end of this document. These recommendations are based on the case studies made by INCA-CE project partners involved in the "Operational Hydrology" group – Slovak Hydrometeorological Institute, Institute of Meteorology and Water Management (Poland) and Czech Hydrometeorological Institute.

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2 Current situation of using precipitation nowcasts in the CE countries involved in the Operational Hydrology group

2.1 Slovak Hydrometeorological Institute (SHMU)

At SHMI the INCA system has been successfully implemented within the frame of the INCA-CE project. The INCA precipitation analyses and nowcasts are tested as input into a hydrological model.

Five independent watersheds with different natural conditions in various parts of Slovakia have been chosen as pilot areas. In every pilot basin flash flood has occurred in the previous 20 years. In every pilot basin raingauge and watergauge stations must be localized.

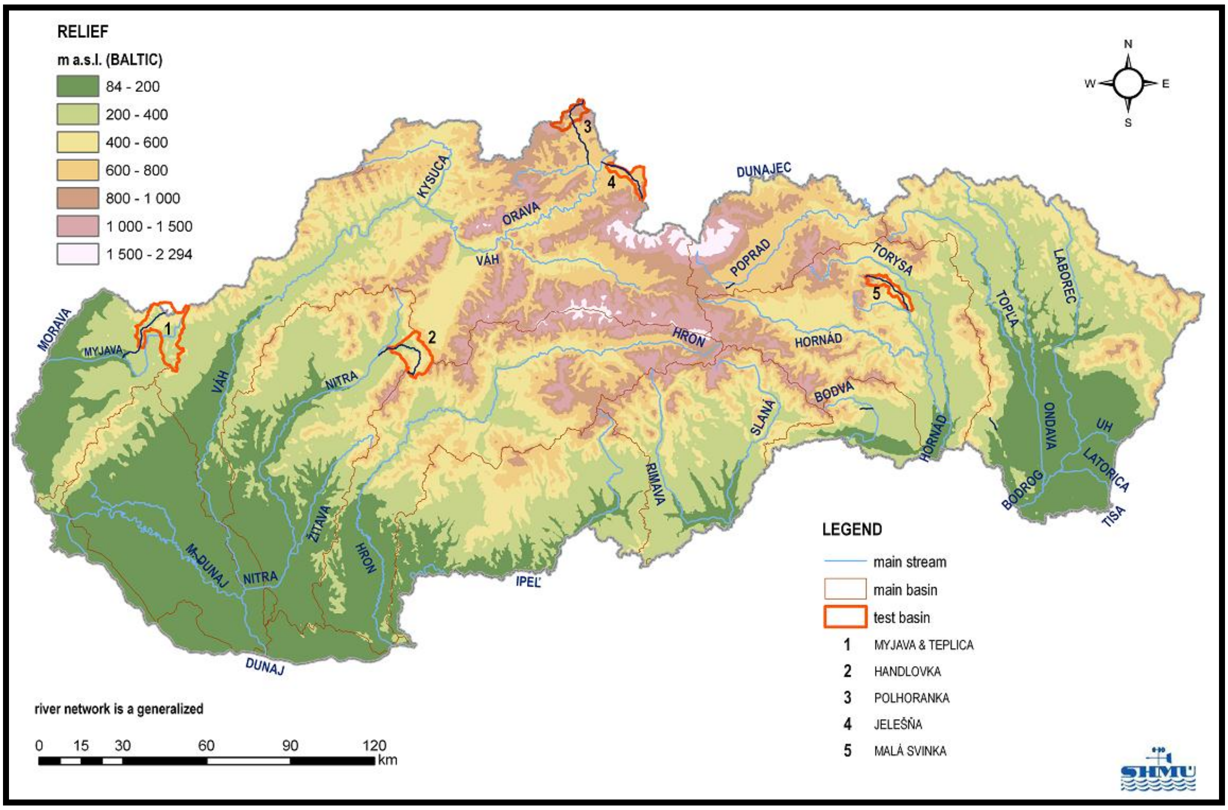

Fig. 2.1.1 *Selected pilot areas (river basins) are Myjava, Polhoranka, Jelešňa, Handlovka and Mala Svinka.*

For the implementation of nowcasting into operational hydrology two independent tools will be used, as described in the following.

HRON model

HRON model is derived from HBV hydrological modelling system and optimized for Slovak conditions. This will be a representative of “classic” hydrological modelling. It is a model with semi-distributed parameters based on a cascade of linear reservoirs, which is used to route the discharge from upper placed sub-basin. HRON model requires basic meteorological and hydrological input data (basin averages in hourly or daily time step) of precipitation, air temperature, discharge (required for model calibration and validation) and long term monthly means of potential evapotranspiration and air temperature.

HEC-HMS model

HEC-HMS is a hydrological model joined with the system of watershed saturation based on CN–method. This system could work with current natural conditions of watershed and could accept spatial rainfall data which are not limited for close neighbourhood of precipitation station. This modelling system requires spatial data of measured precipitation and spatial precipitation forecast. Due to a very short response time in small watersheds, nowcasting precipitation analyses are necessary. Spatial fields of temperature and potential evaporation are another important input data source.

The whole forecasting and warning system will be a combination of many components (models). Precipitation analyses and nowcasts (the latter is the combination of raingauge station measurement and radar measurement), as well as meteorological model outputs will be used as input to the warning system. These meteorological data together with actual natural conditions in the watershed are important input data for the rainfall-runoff model, which assesses the amount of outflowing water and shape of hydrograph (time and value of culmination). If the predicted water level in the closing profile will exceed the warning level, a warning message will be created and disseminated to stakeholders (civil protection, Slovak water management Company, Ministry of Environment and local administration) via telephone and email, and to the general public via Internet.

2.2 Institute of Meteorology and Water Management (IMWM)

In Poland the Institute of Meteorology and Water Management (IMWM) is responsible for hydrological forecast services. The INCA system was implemented for operational services. The precipitation analyses and forecasts provided by the INCA system are tested as an input for the hydrological model MIKE set on the Raba river basin.

Raba River is the Carpathian tributary of the *Vistula River*. Location of the *Raba River* catchment is shown in Fig. 2.2.1 and Fig. 2.2.2. Generally, the river flows in a north-west direction. Its total catchment occupies an area of 1 537.1 km² and its length amounts to about 132 km. There is a water reservoir *Dobczyce* located in the river, with the water level station *Stróża* on top. *Stróża* provides the closing profile of INCA-CE pilot implementations, and it defines the catchment which amounts to 644.09 km^2.

MIKE 11

MIKE 11-NAM model (built in DHI) describes the land phase of the hydrological cycle. The NAM rainfall-runoff model results are used for inflow forecasting of the Dobczyce reservoir and also as an input for the hydrodynamic model.

NAM is a lumped, conceptual rainfall-runoff model which consists of a set of linked mathematical equations, which describe in a simplified form the behaviour of the land phase of the hydrological cycle with parameters that represent average values for the entire catchment. The parameters of the NAM model cannot, in general, be obtained directly from measurable quantities of catchment characteristics, and hence model calibration is needed. The model simulates the hydrological behaviour of the catchment as closely as possible. The process of model calibration is normally done either manually or by using computer-based automatic procedures. In manual calibration, a trial and error parameter adjustment is made. In this case, the goodness of fit of the calibrated model is basically based on a visual judgement by comparing the simulated and the observed hydrographs.

For the purpose of the INCA-CE project the model was calibrated according to the meteorological and hydrological data (from the period: 01.11.2005 – 01.11.2010). The values of potential evapotranspiration were obtained from the EUMETSAT SAF on Land Surface Analysis.

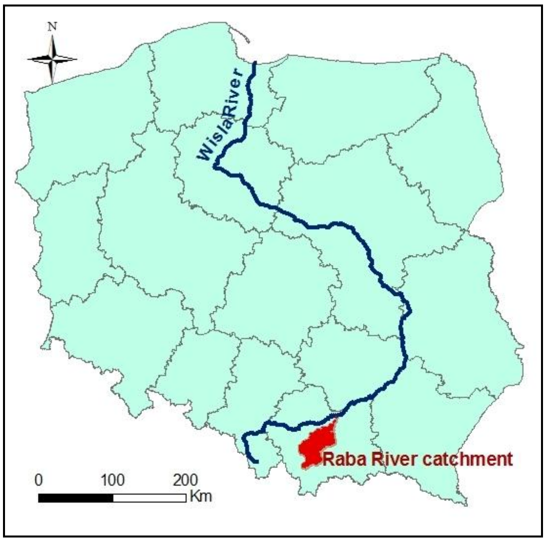

Fig. 2.2.1 *Location of Raba River catchment*

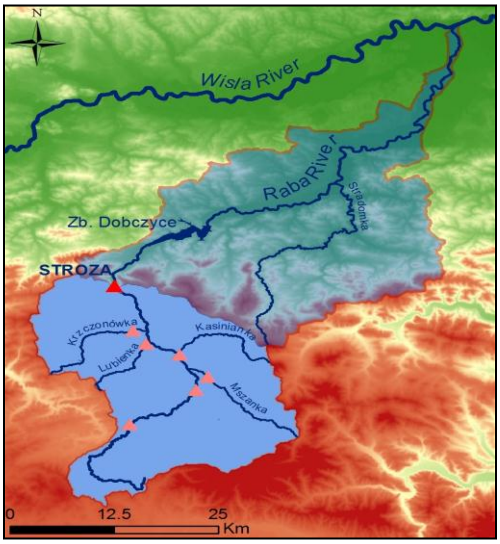

Fig. 2.2.2 *The upper Raba River catchment – water level stations*

2.3 Czech Hydrometeorological Institute (CHMI)

In CHMI the detailed precipitation analyses are based on the combination of radar and raingauge measurement, and are in operational use since 2003 (see Šálek et al., 2004). Since 2004, first tries to use these data as input for the hydrological model HYDROG were undertaken in catchments with insufficient density of raingauges. Since 2006, these precipitation estimates calculated in one hour step became the standard inputs for HYDROG for the whole domain of Morava and Odra river basin. Since 2007, the COTREC precipitation forecast (see Novák, 2007) is used as a standard input for the first three hours of the predicted period for the HYDROG model (mainly due to the results of a case study analysis considering the extreme flood which hit the Dyje catchment in June/July 2006; see Březková et al. 2008, and also the example in Fig. 2.3.1). The first tries to use the precipitation

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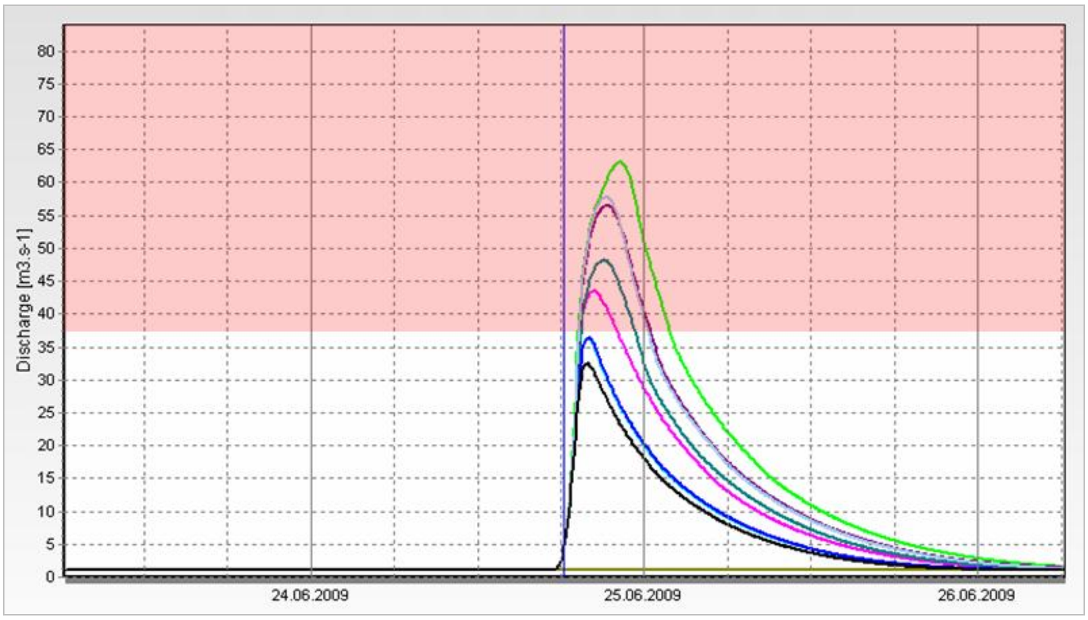
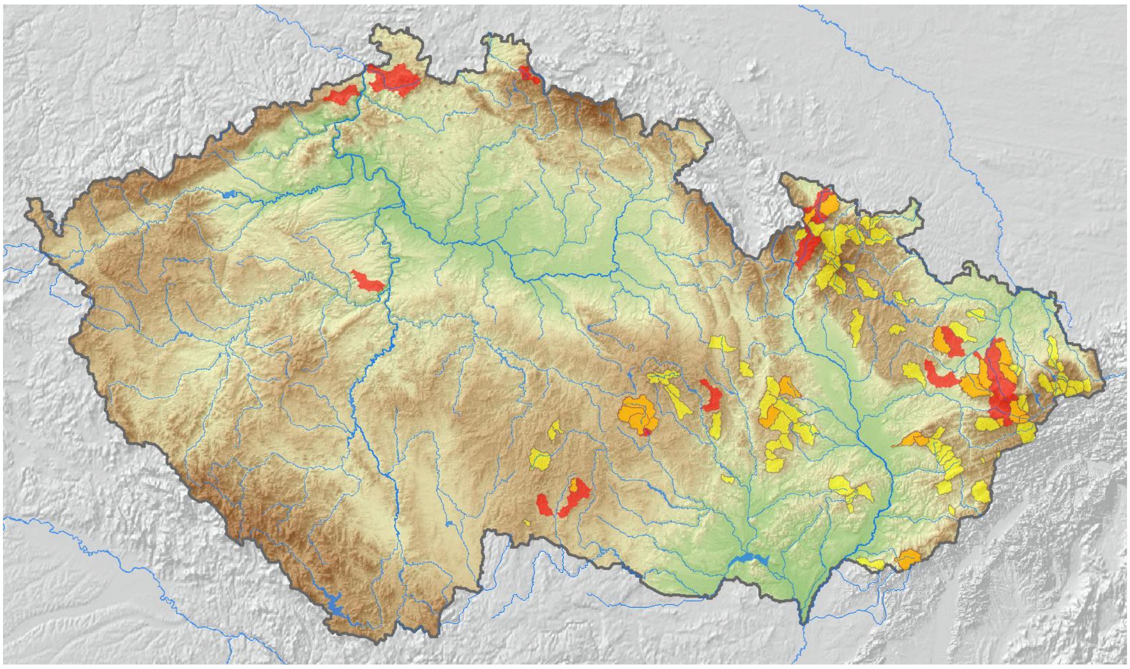
nowcasting for flash flood forecasting were done in 2005 – the results of simulation of floods in Hodonínka and Sloupský Creek catchment proved that



2.3.1 *Example of the probabilistic discharge forecast of the flash flood. The red field depicts the area above limit discharge. The probability of limit discharge exceedance is derived from the set of predicted peak discharges.*



2.3.2 *Catchments chosen for pilot implementation in operational hydrology within Czech Republic. Yellow colour: Fuzzy model; red colour: HYDROG model; orange colour: both methods.*

some of the flash floods can be predicted several tens of minutes in advance (see Šálek et al., 2006). Besides COTREC, the other nowcasting systems were implemented in CHMI – CELLRACK in 2008 and INCA in 2010. The joined information from all nowcasting systems enabled to implement the new tool for flash flood forecasting based on probabilistic approach (see the example of the output depicted in Fig. 2.3.2). This system is now being tested for several small catchments located in the Czech Republic. Two different tools are used for hydrological simulation of the estimation of the discharge raise.

HYDROG

HYDROG model (Starý et al., 2000) is used in a routine for the calculation of discharge forecasts for the whole Morava and Odra river basin within the Flood Forecasting Service for many years (the model for the upper part of Odra catchment was set into operation in 2001). Hydrological forecasts for more than 30 watergauges are issued daily. The experiments concerning flash flood forecasting proved that with the use of precipitation nowcasts some flash floods can be predicted several tens of minutes in advance. Within the INCA-CE project the model HYDROG will be set for the testing operation on 20 catchments (see the map in Fig. 2.3.2).

Fuzzy model

Fuzzy model in hydrological use (Janál et al., 2011) was developed at the Technical University of Brno. The model uses MATLAB Fuzzy Logic Toolbox. Fuzzy logic is an artificial intelligence method. Such a method is able to cope with the non-determination of natural phenomena better than deterministic approaches. The Fuzzy model created for flash flood forecasting uses geomorphologic characteristics of the catchment and data describing the causal precipitation as inputs. The estimation of the peak discharge is the main output. The model was tested on 90 catchments using data from the summer season 2009 when the Czech Republic was hit by many flash floods.

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3 Flash flood forecasting

Within the field of Operational Hydrology the flash floods are a special kind of phenomena. These floods are mainly caused by summer convective precipitation which hits small catchments of a size from tens to hundreds of square kilometres. The rapid water level raise is typical which lasts usually only several hours – however, the damages of flash floods can be huge. One main reason why the inhabitants of the endangered area are often not able to protect themselves from the destructive consequences of such a flood is the very fast occurrence of such an event.

3.1 The uncertainties connected with flash flood forecasting

Flash floods are difficult to predict due to significant uncertainties of data necessary for the calculation of water level raise. The most important uncertainties are as follows:

- uncertainty of precipitation measurement and analyses
- uncertainty of precipitation forecast
- uncertainty of hydrological data (data about discharge / water level)
- uncertainty arising from the used hydrological model.

The precipitation measurements and precipitation forecasts are the data with the biggest uncertainty. However the uncertainty of the used hydrological model is also important as well as lack of online discharge/water level data when taking into account the unobserved catchments.

Precipitation measurements

The convective precipitation events are very local events, and the network of raingauge stations is usually insufficient for their successful monitoring. Therefore the first tries of flash flood forecasting are connected with the development of weather radar measurement and the precipitation estimates derived from radar echo. However, the distant methods of precipitation measurements deal with huge uncertainty – the error of the precipitation measurement can reach several hundreds of percent. The combination of radar fields with the raingauge measurements improves the areal precipitation estimates significantly, but still the error of the resulting precipitation can be several tens of percent. It is necessary to stress that also raingauges themselves measure with an error of approximately 25 percent when considering convective precipitation events. It is obvious that the final error of measurement of convective precipitation can reach really high values and the hydrological simulation which depends strongly on these data can fail in many cases.

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Precipitation forecast

The passage of flash flood is very fast. If the issuing of warning is anticipated at least several tens of minutes in advance a good precipitation forecast is needed. However, precipitation nowcasting is derived from actual precipitation measurement – in principle it is the temporal extrapolation of precipitation field. Therefore the error of precipitation measurement propagates also to the forecast. Moreover, the extrapolation does not take into account the life cycle of convective cells which varies from several tens of minutes to several hours. Simply said, the precipitation nowcasting is only rough estimation of the near future precipitation occurrence – but it is the best estimate which can be available in real operation nowadays.

Hydrological data

The watergauge stations are usually situated on the important river profiles. Most of small catchments are unobserved – therefore many flash floods are not measured at all. Only the damages caused by these floods are known - no information about the water level development is available. The peak discharge can only be assessed from the terrain investigation after the flood event. Moreover, most catchments were never hit by any flash flood. In case of setting up the hydrological forecasting model in an unobserved catchment, the only possibility is to set up the calibration parameters of the model analogically to the observed catchment with similar properties (location, altitude, shape, land cover etc.). But also in observed catchments some problems may arise. The error of discharges derived from water levels with the use of rating curve can be significant when they reach extreme values, usually it is about 10 percent (but it can be more). The measurement of watergauge station or the data transmission system itself can also fail. Briefly said, it is important to realize that the accuracy of discharge values is very uncertain when speaking about flash flood.

The hydrological model

The calibration of the hydrological model comes from the used input precipitation and discharge time series. As it was mentioned earlier – the uncertainty of these data is huge when considering flash floods. Of course, the hydrological model itself is only the simplification of real processes occurring in the nature. Fortunately, the models used in Operation Hydrology are usually accurate enough – at least the uncertainty of the hydrological model simulation is very small comparing to the uncertainty of the precipitation inputs.

3.2 The requirements for the flash flood forecasting system

Every flash flood forecasting system consists of some basic parts depicted in Fig. 3.2.1. For each part, some specific requirements will be delineated. The main purpose is to decrease uncertainties by:

1. Improvement of measurement/forecast techniques (set up new measuring points, improve the precipitation algorithms, improve the hydrological model etc.)

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2. Rapid updating of input/output data (the development of flash flood is very fast and changes within tens of minutes, therefore it is necessary to get new data as often as possible and re-calculate the forecasts).

3. Self-learning system (to run the system continually, to analyse each event, to improve the knowledge of the forecasters, the warning strategy, the education of the end users etc.)

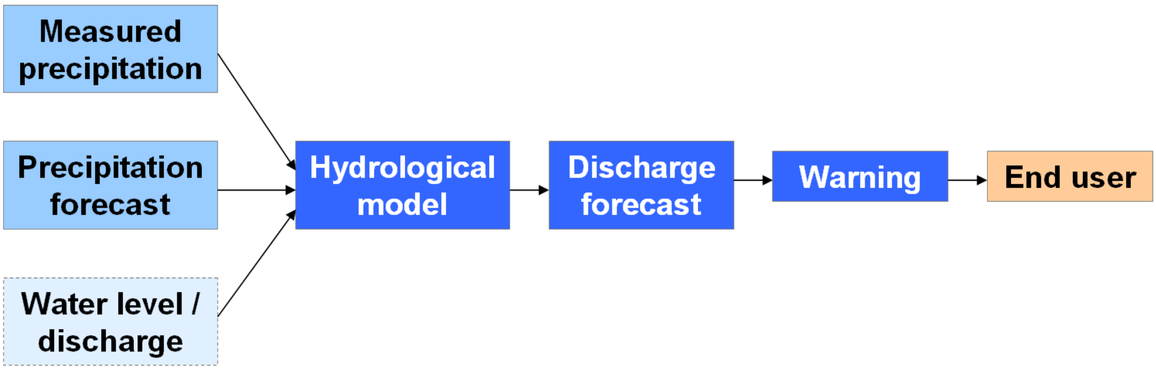

Fig. 3.2.1 *General scheme of the flash flood forecasting system.*

Measured precipitation

The precipitation measurement is based on the combination of the precipitation estimate fields derived from the radar echo measurement and the raingauge measurement. The radar measurement is usually updated every 5 or 10 minutes, the raingauges measure usually in 1-hour intervals; however, **a shorter interval (up to 10 or 5 minutes) is required**. The combination of 10-minute precipitation sums derived from radar measurement with 10-minute precipitation sums from raingauges can result in significant errors due to the phase shift (when taking into account dynamic convective precipitation).

The INCA system enables to calculate the precipitation fields in 15 or 10 minutes step, in dependence on the time interval of raingauge measurement. The INCA system is run operationally in all the institutes involved in the Operational Hydrology group within INCA-CE project - SHMU, IMWM and CHMI.

In CHMI another system for the calculation of the quantitative precipitation estimates is used since 2003. The precipitation fields are obtained by so called radar-raingauge merge algorithm (see Šálek et al., 2004, the examples of this product are depicted in Figures 3.2.2, 3.2.3 and 3.2.4), where the radar echo field is transformed to the precipitation estimates with the use of Marshal-Palmer formula, then it is multiplied by the bias calculated from the difference between radar precipitation estimates and values measured by raingauges, and finally this so called "adjusted radar field" is combined with the field obtained by the spatial interpolation of the raingauge values. The process of adjustment enables to remove the "rough" error of the radar precipitation estimates while the combination with the raingauges (done by Krieging method) tries to improve the precipitation estimates as much

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as possible. For the flash flood forecasting system the precipitation inputs are set according to the scheme given in Fig. 3.2.2. The precipitation inputs are updated every 5 minutes. The 1-hour precipitation sums are completed by 10-minutes sums, respectively by 5-minutes sums. 1-hour precipitation sums are the most accurate input, while 5-minutes sums obtained as adjusted radar field is of the smallest accuracy. On the other way, 5-minutes adjusted radar sums are available in 3rd minute after the radar measurement, while 1-hour radar-raingauge sums are available in 20th minute after the nominal hour.

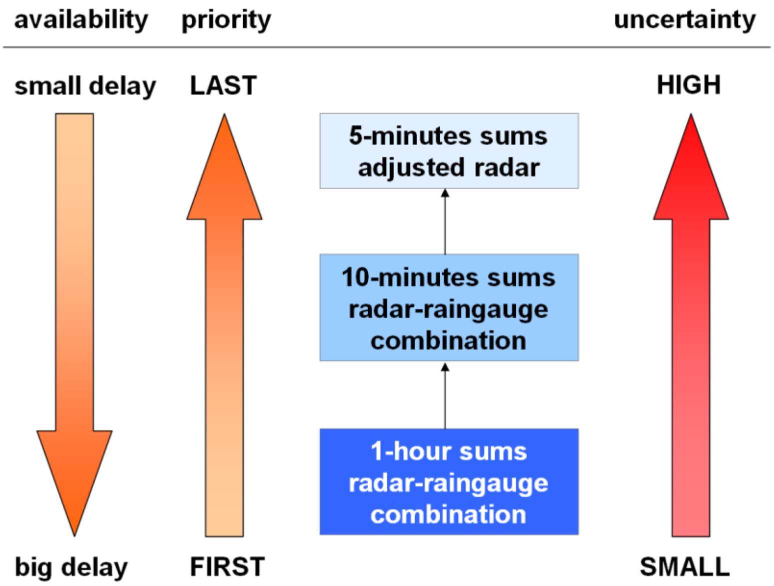

Fig. 3.2.2 *Scheme of the setting of input data sets for flash flood forecasting systems used at CHMI.*

The best way how to decrease the uncertainty of the measured interpretation is **to install the raingauge station with automatic data transmission nearby the catchment** where the system of flash flood forecasting is being set. This can help to optimize the parameter settings and calibration in the flash flood forecasting system.

The **international exchange of radar data** (initialized by OPERA project) can improve the radar fields significantly, especially in border areas of individual countries. At CHMI two variants of radar echo fields are being calculated operationally – the first one is based on radar from Czech radar network only (so called CZRAD, updated in 5 minutes step), the second uses also the radar data from neighbouring countries (so called CZRAD-EXT, updated in 10 minutes step). Consequently, two variants of precipitation estimates can be calculated and used as inputs for the hydrological model.

Besides the deterministic expression of the measured precipitation data, **a stochastic approach is highly recommended**. For example - if the error of the precipitation fields from the historical data is evaluated, the actual precipitation field can be modified with the use of stochastic generators, and the obtained set of precipitation fields can be used for the repeated hydrological simulation. In such a way the propagation of the uncertainty of measured precipitation can be assessed in relation to the uncertainty of the outflow response. However, it is necessary to realize that the stochastic approach is more time consuming.

Precipitation forecast

As it was already mentioned, the very short precipitation forecast (nowcasting) is calculated by temporal extrapolation of actual radar echo. Since the development of convective cells is very rapid, it is also necessary to update the precipitation nowcasting as often as possible. The INCA system calculates the precipitation forecast in 10 or 15 minute step (depending on the time interval of the measurement of raingauges). **The best interval for updating is 5 minutes** (depending on the updating of radar measurement).

At CHMI next to INCA other nowcasting systems are being operated – COTREC (see Novák, 2007) and CELLTRACK (Kyznarová et al., 2008). These systems can be updated in 5 minutes step using data from CZRAD, or in 10 minutes step using the data from CZRAD-EXT. Both variants are being calculated operationally. The INCA precipitation forecast is updated every 10 minutes also in two (CZRAD and CZRAD-EXT) variants.

The precipitation nowcasting should be calculated maximum **3 hours in advance**. The first hour of the precipitation nowcasting is usually relatively accurate, the accuracy of the second hour is lower and the accuracy of the third hour of the nowcasting is comparable to the accuracy of the forecast calculated by NWP models (e.g. almost improper for the use for flash flood forecasting) – as it is depicted in Fig. 3.2.3.

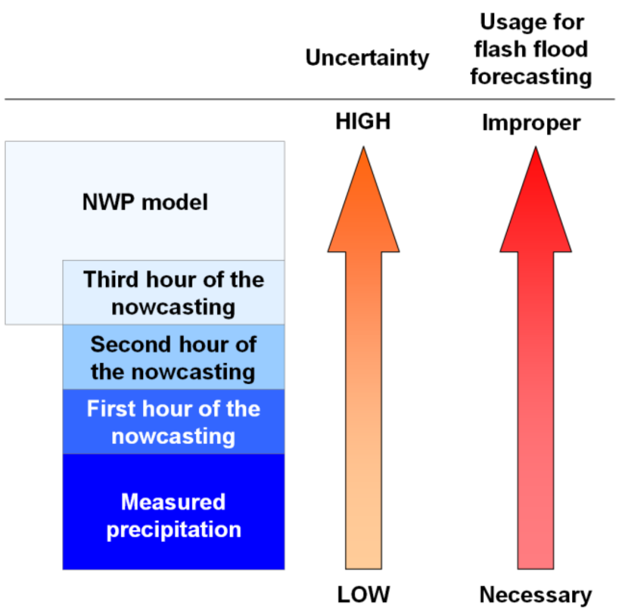

Fig. 3.2.3 *Scheme of the uncertainty of precipitation inputs used in flash flood forecasting.*

Since the precipitation nowcasting is derived from the actual precipitation measurement, the same requirements as for measured precipitation are recommended – e.g. to install the raingauge station near the catchment of interest and to use the radar data from neighbouring countries - to improve the precipitation fields.

Concerning the precipitation forecast - the deterministic approach is insufficient because the uncertainty of precipitation nowcasting is huge. **The stochastic approach is highly recommended**. Again, it is necessary to stress the higher requirements of stochastic approach in calculation time.

At CHMI the so called "variant approach" is being tested in operation. The main purpose is to use all the data which are available operationally, e.g. all measured precipitation scenarios together with all the precipitation nowcasting scenarios (as it was mentioned above). According to the scheme depicted in Fig. 3.2.4 the probability of limit discharge exceedance is calculated every 5 minutes.

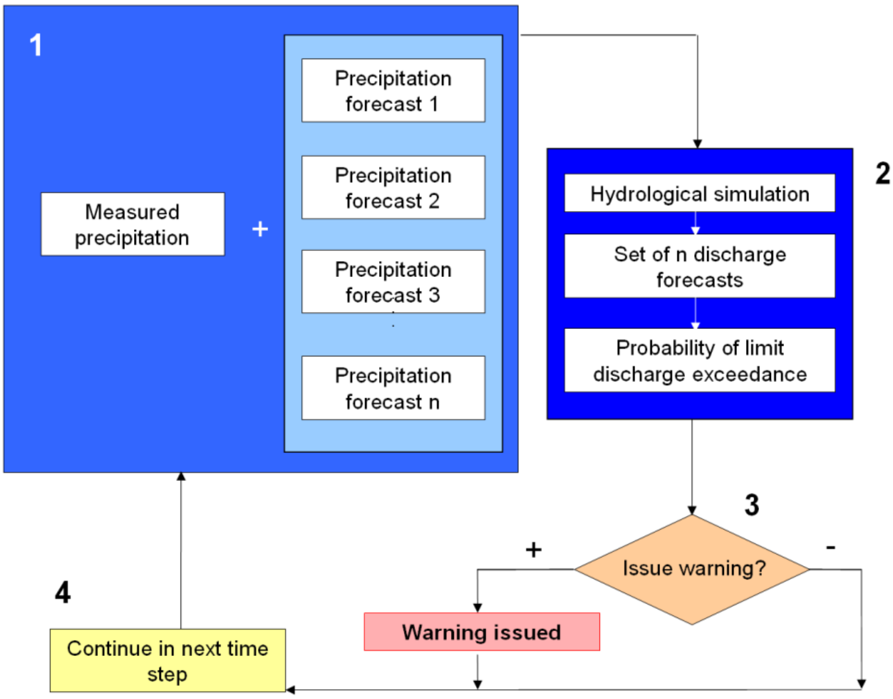

Fig. 3.2.4 *Scheme of the flash flood forecasting system tested at CHMI. The process of flash flood forecasting consist of precipitation analysis and calculation of all available variants of precipitation nowcasting (1), the repeated hydrological simulation (2), warning strategy (3), proceeding to the next time step (4).*

Hydrological data – water level, discharge

Speaking about observed catchments, the data from watergauges can help very much for the verification of calculated results. Of course, due to the high uncertainty – that means probably big error – of precipitation inputs, it has **no sense to compare the exact simulated and observed discharges or water levels**. Moreover, when the significant discharge raise occurs, it is usually "too late" for the issuing of the warning for the municipalities situated upstream. On the other hand, the warning can be very important for the municipalities situated down the stream (if there are any).

In any case, the data from watergauges should be available as often as possible, i.e. **5 minutes interval is recommended**.

In both observed and unobserved catchments the limit discharge in the control river profile must be set. Usually it is the value of full river bed.

Hydrological model

The hydrological model proper for flash flood forecasting must fulfil these requirements:

- **Fast calculation** – this is necessary especially in case of stochastic approach when the hydrological simulations are run repeatedly. The results must be available in very near real time.
- **Fully automatic run** – it is impossible to e.g. change the model parameters during the flash flood – simply there is no time for it, the total duration of flash flood can vary from tens of minutes to several hours.
- **Fast update of the result**s – the situation in the catchment must be analyzed repeatedly, every new information must be involved to the system. The optimum interval of updating is **5 minutes**.

As it was mentioned above, problems with the calibration of the hydrological model may arise due to the lack of reliable input precipitation and discharge time series.

Discharge forecast, warning strategy and end users

Discharge forecast is the result of the hydrological simulation. Concerning flash flood forecasting, the exact discharge values have no sense due to the high uncertainty of inputs, the forecast must be interpreted as "danger of flash flood exist" or "danger of flood does not exist". In a deterministic approach, the danger of flash flood exists when the simulated discharges exceeds the limit discharge, or when the limit discharge is exceeded repeatedly within several runs of the flash flood forecasting system. In a stochastic approach, the danger of flash flood exists when the probability of limit discharge exceedance exceeds a certain value. The detail interpretation of the hydrological forecasts is given in the following section.

It is also obvious that it is rather unrealistic to provide the end users with the discharge forecasts. The information for the end users should be verbal and inform them about the danger of flash flood occurrence. The rules of the warning strategy must come from the results of case studies; they must be clear and set for every catchment individually. A proper warning strategy has a key influence on the flash flood forecasting process.

The end-users have to be well informed about the flash flood forecasting systems, their strengths and weaknesses. Such a system can produce a lot of false alarms – the end users

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have to know the weak points of the system. However, they must also understand the potential of the system and take the provided information seriously. Therefore, a regular training with end users is necessary.

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4 Case studies

Case studies are based on the simulation with the proposed flash flood forecasting system. Case studies are very important because they enable to understand the system in detail – and in a next step to improve it.

Four case studies (for four different catchments – see Table 4.1) made by CHMI are presented. The stochastic system of flash flood forecasting based on the "variant approach" was tested. The continual simulation of the system was undertaken by using data from 20th June to 20th July 2009, when the Czech Republic was hit by a series of flash floods.

Tab. 4.1 *Basic parameters of the tested catchments*

Catchment	**Jičínka**	**Luha**	**Husí Creek**	**Romže**
Area [km^2]	95	96	59	55
Closing profile	Nový Jičín	Jeseník nad Odrou	Fulnek	Stražisko
Limit discharge [m^{3}s^{-1}]	49	37	25	5
Q_{100} (discharge with the return time period of 100 years) in closing profile [m^{3}s^{-1}]	178	87	39.8	35

The Jičínka and Luha catchments were hit by the extreme flash floods on 24th June 2009 which even caused human life losses. The catchment of the Husí Creek was hit a flood (with only low damages) on 2nd July 2009. In the Romže catchment no flood has occurred. In Table 4.2 the summery of the results is presented. The results are very good except for the Romže catchment where a flash flood was predicted 6 times with a probability higher than 25 percent – a new calibration of the catchment will be necessary.

Tab.4.2 *Results of the simulation of the flash flood forecasting system set in Jičínka, Luha, Husí Creek and Romže catchments.*

Catchment	**Number of floods**	**Number of non-zero exceedance probabilities**	**Number of higher than 25% exceedance probabilities**
Husí Creek	1	1	1
Jičínka	1	2	1
Luha	1	1	1

Romže	0	8	6

The detailed result assessment proves that for each catchment a specific warning strategy should be chosen. According to the probability of the limit discharge exceedance the following four categories of flood events were set:

Floods predicted with a probability of 100 percent

Good predictability is typical for this type of floods. The main reason is probably the proper location of the catchment. The raingauge with the automatic data transmission is situated inside or nearby the catchment; the radar data can be quickly adjusted according to the raingauge measurement. The catchment is very well visible by the radar system; therefore the precipitation nowcast (obtained by the extrapolation of the radar echo) is not significantly underestimated. The probability development of the limit discharge exceedance is depicted in Fig. 4.1. The probability increases with time and reaches 100 percent several tens of minutes before the real limit discharge exceedance. Thus, the warning can be issued sufficiently in advance.

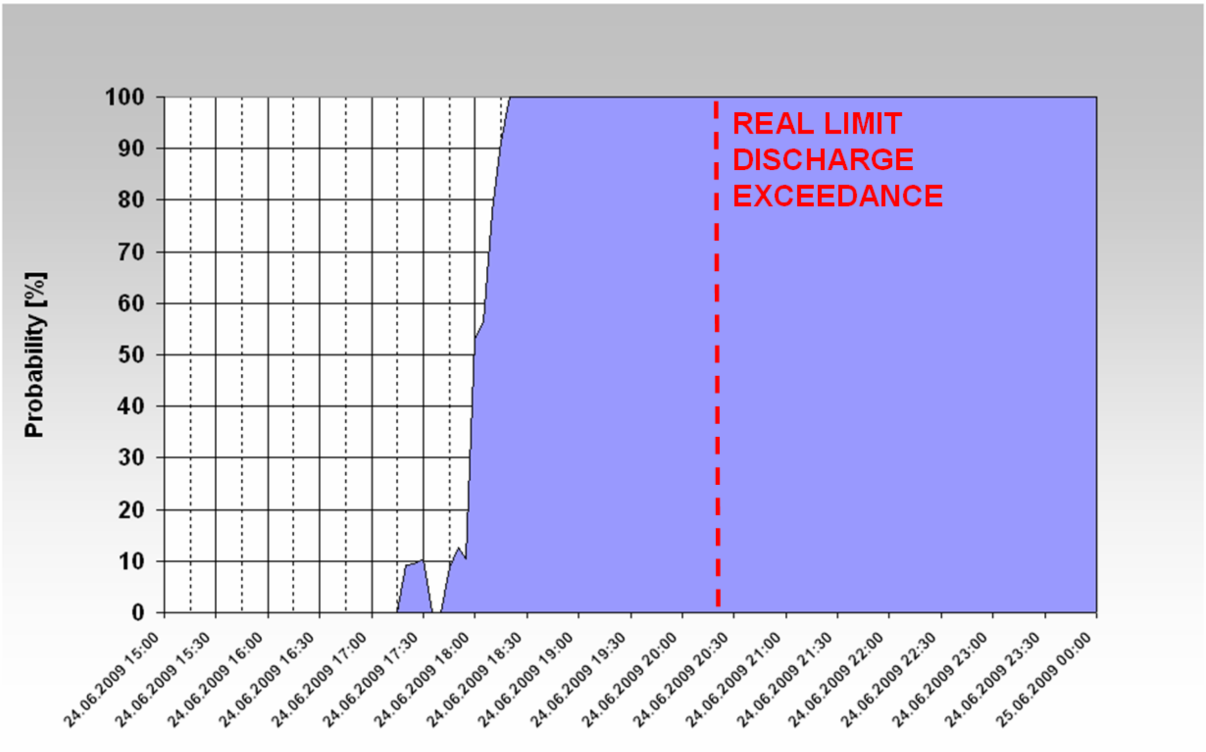

Fig. 4.1 *Time development of the simulated probability of the limit discharge exceedance – example of the flood in the Luha catchment on 24th June 2009.*

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Floods predicted with a probability of less than 100 percent

If the measured precipitation is underestimated in some of the precipitation scenarios, the flood can be predicted only with smaller than 100 percent probability until the real limit discharge exceedance – see the example depicted in Fig. 4.2, where the simulation of the temporal development of the probability of limit discharge exceedance of Jičínka flood on 24th June 2009 is presented. This catchment is located in the area which is not very well seen by the radar system. Moreover, the causal precipitation moved towards the radar, therefore the radar echo was attenuated significantly which caused the significant underestimation of the precipitation estimates. No raingauge with automatic data transmission is available near this catchment, which could improve the precipitation measurement and the precipitation forecast. In this example, the predicted amount of precipitation was underestimated. Therefore this flood was predicted with very low probability (10 to 15 percent). It is hard to say whether the warning would have been issued in such a case. If more cases proved that floods in this catchment can be predicted only with the low probability, it would be better to issue the warning even if the danger of false alarm is high.

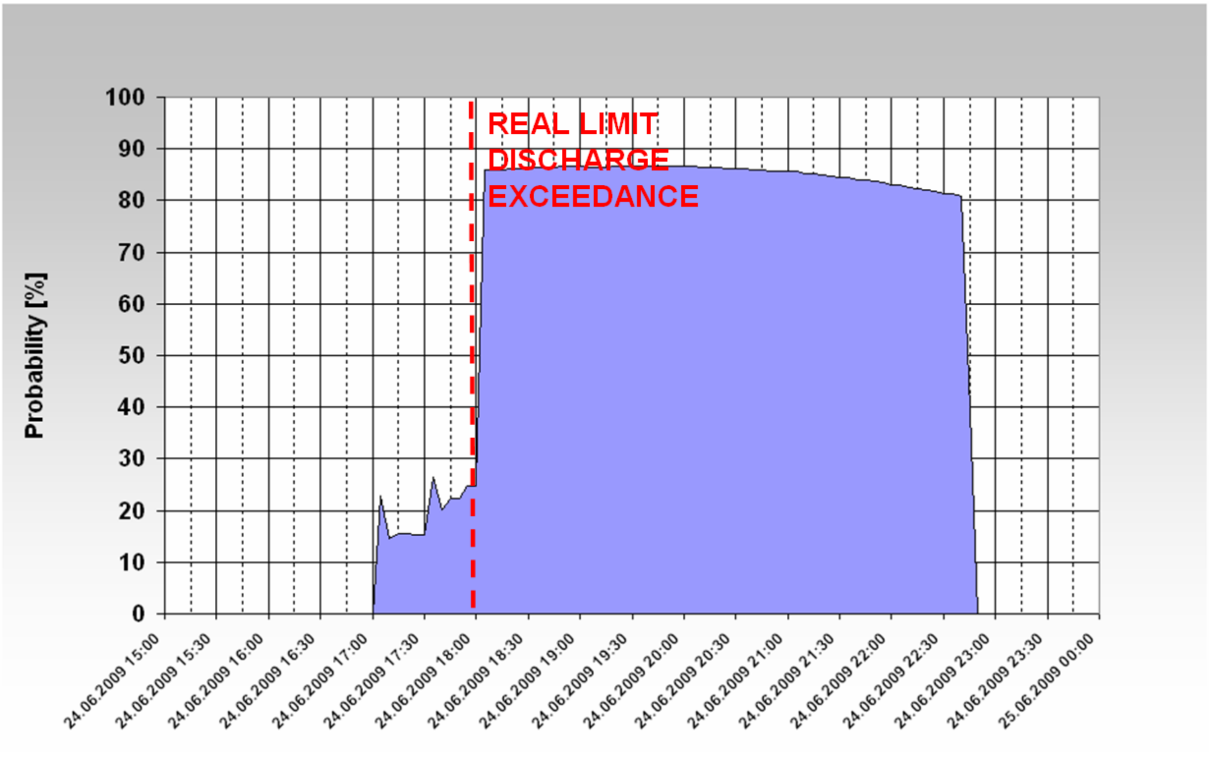

***Fig. 4.2** The time development of the simulated probability of the limit discharge exceedance – example of the flood in Jičínka catchment on 24th June 2009.*

Floods predicted with zero probability

Shown by the example of the Husí Creek flood which is depicted in Fig. 4.3, a flood really occurred. It is obvious that the precipitation forecast was successful; however, the measured precipitation was highly underestimated. In such a case, a raingauge station located inside or nearby the catchment is supposed to increase the accuracy of the measured precipitation field. More case studies should be undertaken to set the rules for issuing of warnings in this and similar catchments. In fact, the issuing of warning is correct in such a case, although the time difference.

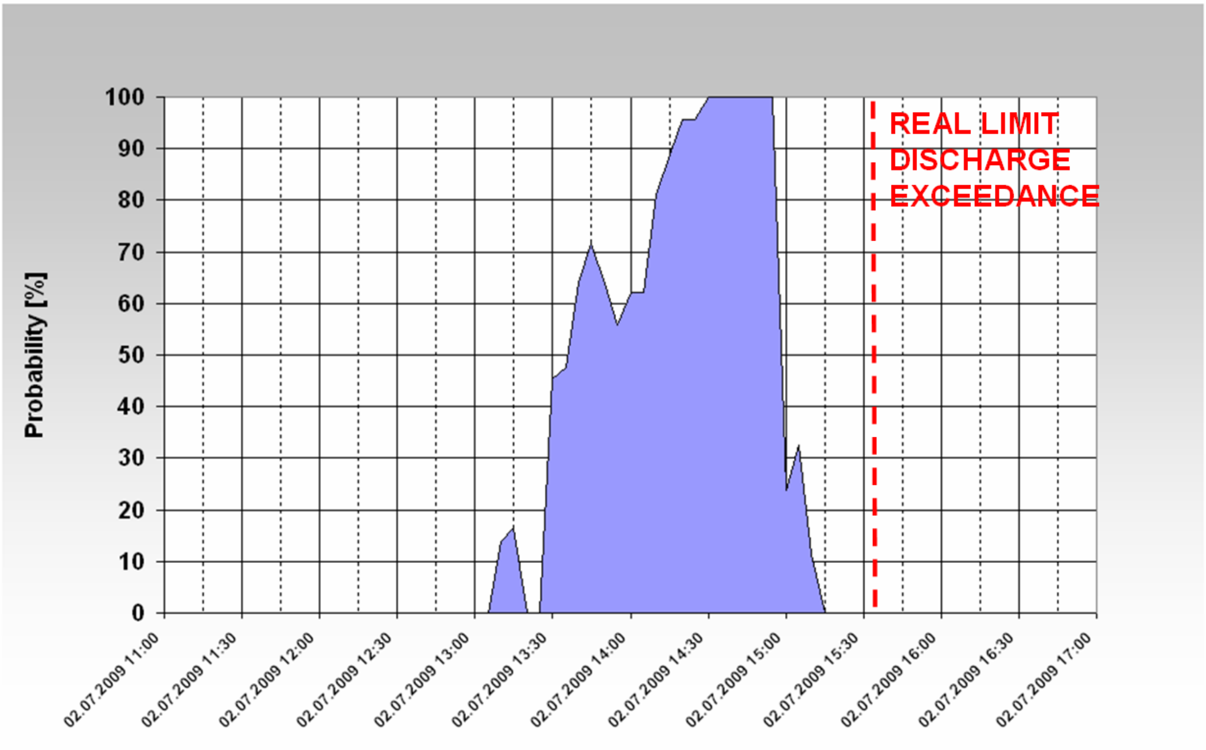

Fig. 4.3 *The time development of the simulated probability of the limit discharge exceedance – example of the flood in Husí creek catchment.*

False alarms

An example of a false alarm is shown in Fig. 4.4: The flood is predicted with quite high probability, but in fact it does not occur. If the hydrological model is well calibrated, the uncertainty arises from the precipitation inputs (the predicted – and sometimes also the measured - precipitation is overestimated).

Due to a frequent false alarm rate the inhabitants might not take the flash flood forecasting system serious - causing dangerous conditions especially in real flooding situations. Therefore the number of false alarms has to be reduced. However, a system producing a high number of false alarms (but also real warnings) is preferred to a system which does not produce any alarms. In any case, the continuous operation of the flash flood forecasting system helps to reveal the problem of frequent false alarm occurrences, and to find a solution.

In other cases, a real flood might be predicted with zero probability (the flood is "missing"). The reason might be that the real flood is not seen as very dangerous, the predicted or measured precipitation was underestimated, and thus the flash flood forecasting system does not predict limit discharge exceedance. Such a case is not dangerous for the inhabitants. In case of a significant flood, it is supposed to be predicted at least with a low probability, as it was the case of the Jičínka flood where the measured precipitation was significantly underestimated; however, the flood was predicted with a probability higher than 10 percent.

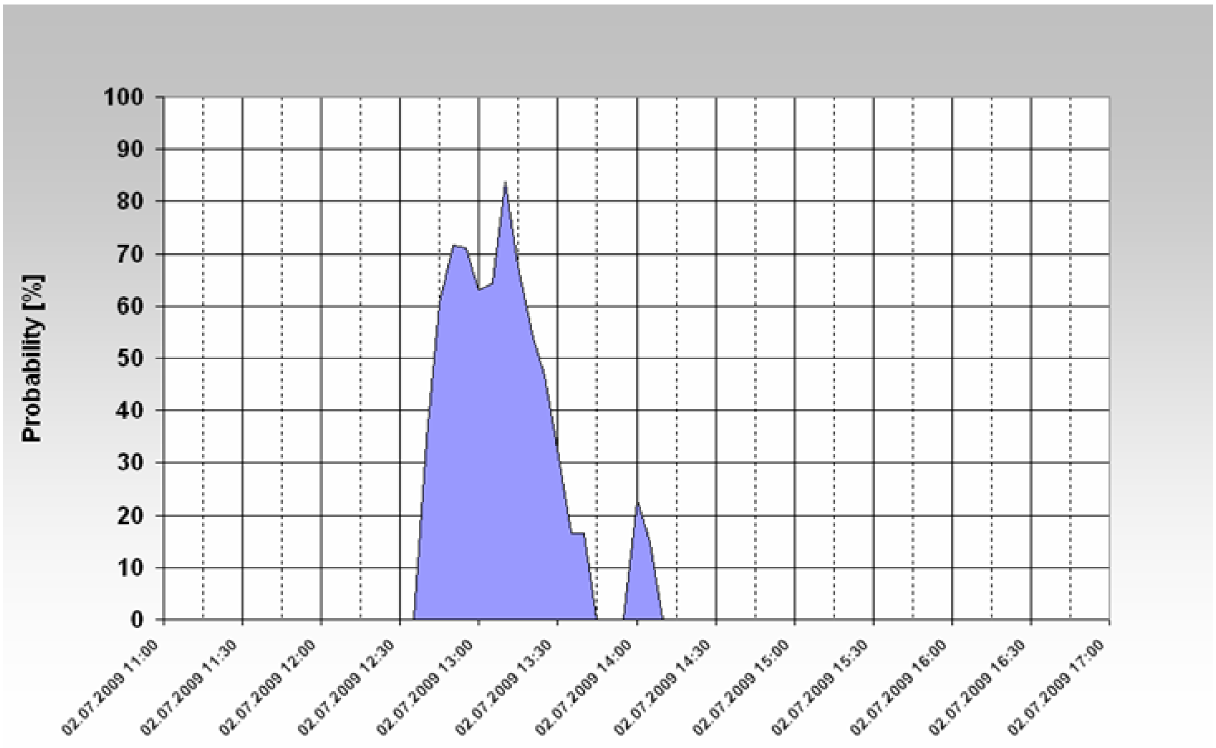

Fig. 4.4 *Time development of the simulated probability of the limit discharge exceedance – example of the flood in the Romže catchment.*

5 Recommendations

In this session the recommendations for the improvement of the flash flood forecasting system are summarized. They are divided into two parts – recommendations considering the precipitation fields (from the point of view of flash flood simulations undertaken by hydrological models), and recommendations considering the interpretation of the discharge forecast and setting the rules of the warning strategy.

5.1 Precipitation fields

For flash flood forecasting the precipitation inputs have a key influence. The accuracy of calculated discharge forecast depends on the accuracy of both predicted and measured precipitation sums. A very high spatial and temporal resolution is necessary. The requirements for flash flood forecasting considering precipitation data are the following:

Detailed spatial resolution of the precipitation fields

The calculated precipitation fields should be of a very high spatial resolution (1 x 1km is recommended). Despite the hydrological models can use simplified precipitation fields (without loss of the accuracy of the flood forecast), these simplified precipitation fields should be always derived from the high-resolution precipitation fields. Concerning hydrological models used for flash flood forecasting the precipitation fields should be simplified to areas of the size not larger than 20 square kilometers.

Rapid update of precipitation fields

Due to the rapid development of convective cells producing heavy precipitation the precipitation field should be updated as often as possible. 5 minute update is the best for flash flood forecasting, however 10 minutes update is also enough. 15 minutes update is acceptable but can be insufficient in some cases. Precipitation analysis together with the forecast should be available to the forecasters as soon as possible; the delay (caused by the late data transmission from raingauges) greater than 10-15 minutes could result in late warning.

Time of precipitation accumulation

The time of the precipitation accumulation should be also very small. However, the combination of the precipitation fields obtained from raingauges with the precipitation fields derived from radar measurement can result in some inaccuracies when the time accumulation of the precipitation is too small (because of the different methods of the precipitation measurement). Therefore the smallest recommended precipitation sum is 10 minutes; however, the use of higher precipitation accumulations can give better results (but 1 hour should not be exceeded).

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Actual precipitation analysis with error estimation

The error of the actual analyzed convective precipitation fields can be great – and the flash flood forecast can fail due to this error. Therefore, the estimation of such an error (obtained for example by the long-time evaluation of the precipitation field accuracy for various rainfall intensity categories) should be provided to the hydrologists and forecasters. Based on this error an optimistic and pessimistic scenario of the flash flood forecast could be calculated and the warning (with the adequate commentary) could be issued more in advance. The information about the accuracy of the precipitation analysis is also necessary for the probabilistic flash flood forecasts (see next requirement).

Probabilistic precipitation forecast

Because the flash flood forecasts are created under the conditions of great uncertainties, the deterministic flash flood forecasts based only on one precipitation scenario are insufficient. The stochastic (probabilistic) flash flood forecasts based on various precipitation scenarios which can occur with a given probability may provide much better information about the expected situation in the catchment. Therefore, precipitation in a probabilistic form is required by the hydrologists and forecasters. The minimal information could be the spread of predicted precipitation sums together with the precipitation sum predicted with the highest probability. The ensemble of several precipitation scenarios or the curve of predicted precipitation sum exceedance could be one of the further steps in future.

International exchange of meteorological data

The meteorological data necessary for flash flood forecasting – not only data from raingauges but also radar data - should be exchanged among the neighbouring countries. The data should be available in real-time and should be exchanged through reliable manners (usually ftp servers).

5.2 Interpretation of the discharge forecast and warning strategy

The case studies presented in section 4 proved that – when taking into account the interpretation of the discharge forecast – the successful hydrological forecast is influenced by many factors, and it is necessary to deduce a warning strategy for each catchment separately. For the simplification of the warning strategy the catchments can be divided into several categories. Since the **radar visibility** of the causal precipitation over the catchment and the **presence of the raingauge station** inside or nearby the catchment are the most important, the four categories can be created based on these two factors and the special warning strategy can be set for each of them. The categories are presented in Table 5.1. The typical properties of the categories together with the warning strategy are described in the following.

***Tab. 5.1** Catchment categories based on two factors – the radar visibility of the precipitation over the catchment and the presence of raingauge station.*

Category	Radar visibility of causal precipitation	Presence of raingauge inside or nearby the catchment
I	Good	Good
II	Bad	Good
III	Good	Bad
IV	Bad	Bad

Category I

These catchments are characterized –amongst others - by a good position of the meteorological radar system. Therefore, the precipitation field causing the outflow response is visible very well. This means that the distribution of the measured and predicted precipitation is sufficiently accurate for flash flood forecasting. Additionally, the presence of the raingauge station ensures the quantitative accuracy of the both measured and predicted precipitation field. For this category, the **measured and predicted precipitation sums** are assumed to be **sufficiently accurate in both distribution and quantity**. Consequently, the subsequent hydrological simulation is assumed to be sufficiently accurate (see example in Fig. 5.1).

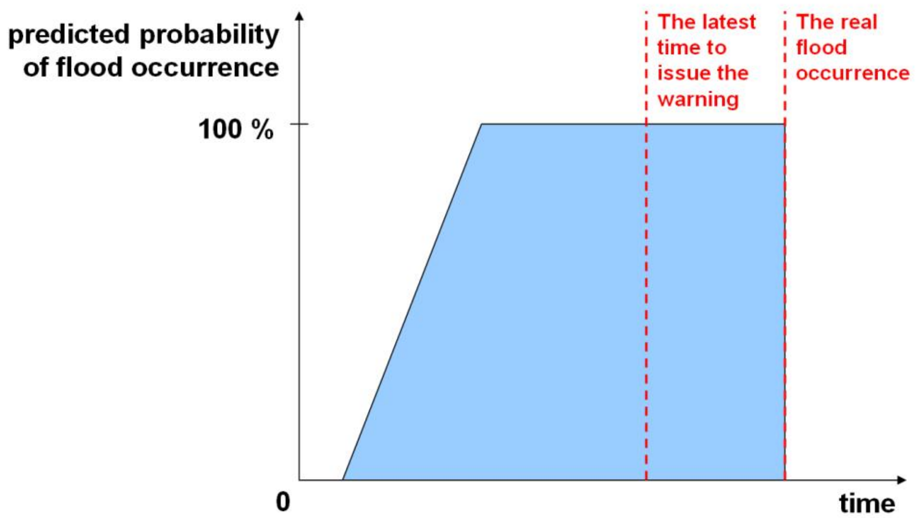

***Fig. 5.1** Predicted probability of flash flood occurrence with respect to the time before the real flood occurrence – category I. The predicted probability of flood occurrence grows in time and reaches 100 percent.*

The rules for the warning strategy can be relatively strict. Speaking about deterministic discharge forecast, the warning should be issued after the (repeated) exceeding of the limit discharge value. In case of a probabilistic approach, the warning should be issued when the probability of limit discharge exceedance is higher than 50 percent or even more, the number of false alarms should be relatively low.

Category II

In catchments of category II, the visibility is bad from the point of view of the radar (usually valleys, mountainous regions). Thus, the distribution of the causal precipitation in the respective catchment is not measured with sufficient accuracy. The presence of a raingauge station inside the catchment can improve the measured precipitation a lot, but **uncertainties in the precipitation forecast** may arise. Concerning the hydrological simulation, there is a high probability that the flash flood will be predicted too late (see example in Fig. 5.2).

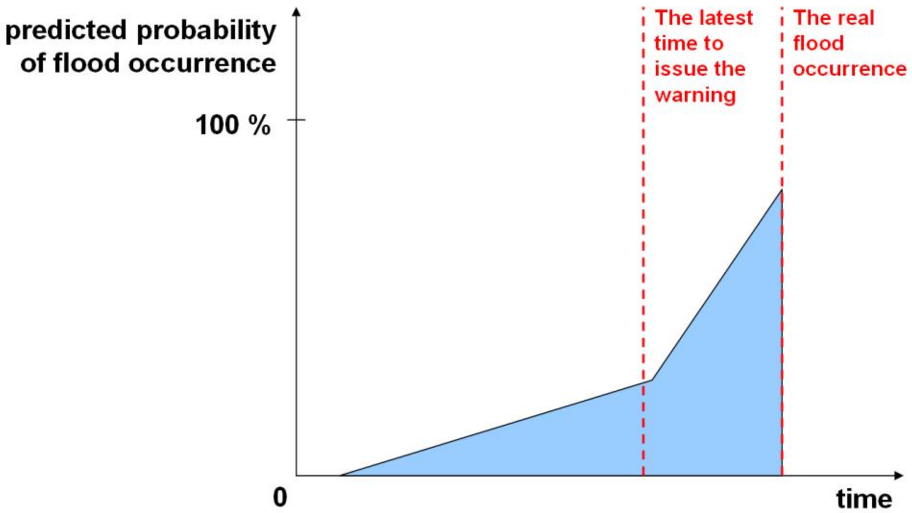

Fig. 5.2 *Predicted probability of flash flood occurrence with respect to the time before the real flood occurrence – category II. The predicted probability of flood occurrence grows in time slowly, but the higher values are reached too late.*

The deterministic flash flood forecasting system can easily miss the flash flood occurrence. A probabilistic system could predict the flash flood occurrence with relatively small probability, increasing with time, but reaching the significant values only shortly before the real limit discharge exceedance. In both cases, the warning should be issued when the first hints of flash flood occurrence are detected by the flash flood forecasting system. The number of false alarms should not be too high.

Category III

For catchments in this category, the distribution of the measured and predicted precipitation field is accurate enough due to the good visibility of the weather radar system. However, the absence of raingauge stations may cause significant uncertainties in the quantitative estimates of the precipitation. Thus, the **measured precipitation will probably be**

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underestimated. Therefore, the probability of flood occurrence is expected to decrease with the time to a very low (or zero) probability as it is depicted in Fig. 5.3.

In this case it is recommended to issue the warning when the deterministic (or probabilistic) flash flood forecasting system will predict the danger of flash flood occurrence (with at least small probability). However, the danger of false alarms is very high, but it is better to issue a warning too often than to issue no warning in case of a real flood.

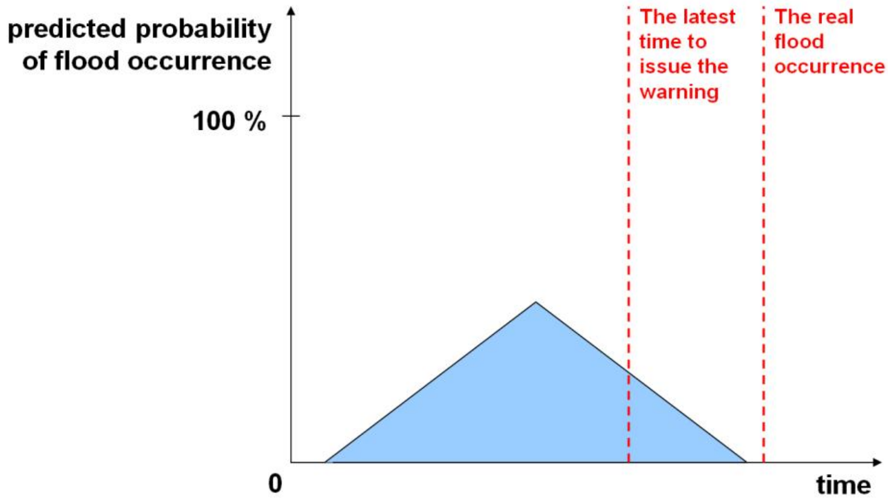

Fig. 5.3 *Predicted probability of flash flood occurrence with respect to the time before the real flood occurrence – category III. At the beginning the predicted probability of flood occurrence increases with the time, later on it decreases to very low probabilities or even to zero.*

Category IV

The catchments in category IV are characterized by a wrong position towards the weather radar systems and with absence of raingauge stations. Uncertainties arise in the measured and predicted precipitation sums. Although the flash flood forecast can be successful in some cases, it is highly recommended to improve the conditions for flash flood forecasting, e.g. to install at least one raingauge station inside the catchment to improve the quantitative precipitation estimates.

The division of catchments into the presented categories I, II, III and IV helps to simplify the process of flash flood forecasting and to suggest an adequate warning strategy. Each flood is different from another, and the development of its prediction can therefore vary a lot from the examples previously presented.

6 Conclusion

In the transnational strategy document for Operational Hydrology the possibilities of the use of nowcasting data were described. The attention was paid especially to the flash flood forecasting which is highly topical in Operational Hydrology nowadays.

The flash flood forecasting system was described in detail, with focus on the uncertainties in input data, especially the uncertainty of measured and predicted precipitation. Based on several case study examples, the potential of a flash flood forecasting system was presented. The results proved that every flash flood has to be evaluated separately. Different categories of warning strategies were suggested based on the two most important factors influencing the accuracy of the hydrological forecast: the position of the catchment with respect to a weather radar system and the presence of a raingauge station inside the catchment.

Although the stochastic approach is highly recommended, the deterministic flash flood forecasting system can also help to warn inhabitants of endangered areas. It is very important to run the system continuously, analyse the obtained results and use the knowledge for the improvement of the system.

The cooperation with end users has a key influence. Without their adequate response to the issued warnings the flash flood forecasting system has no sense. The regular trainings with end users can help them to understand the weak points, especially the danger with respect to false alarms as well as the potential of the system (the rescue of human lives and movable properties).

A transregional and transnational cooperation is necessary for the successful run of the system in cross border areas. The real-time exchange of radar data and data from raingauges can improve the measured and predicted precipitation fields also in endangered areas. The successful transnational cooperation in the field of Operational Hydrology is one of the major purposes within the INCA-CE project (in the application area of hydrology).

Every institute of the INCA-CE project participating in Operational Hydrology tasks, e.g. Slovak Hydrometeorological Institute, Institute of Meteorology and Water Management (Poland) and Czech Hydrometeorological Institute installed their own systems for flash flood forecasting based on INCA precipitation forecast. These systems will be tested in pilot catchments and the results will be evaluated carefully. The communication with the end users is a very important part in this whole process (feedback loop). The obtained experiences will be presented in the final strategy document issued in 2013.

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