Hydrology and Earth System Sciences, 9(4), *322–332* (2005) © EGU

Hydrology & Earth System Sciences

Precipitation forecasts and their uncertainty as input into hydrological models

Mira Kobold and Kay Sušelj

Environmental Agency of the Republic of Slovenia, Vojkova 1b, 1000 Ljubljana, Slovenia

Email for corresponding author: mira.kobold@gov.si

Abstract

Torrential streams and fast runoff are characteristic of most Slovenian rivers and extensive damage is caused almost every year by rainstorms affecting different regions of Slovenia. Rainfall–runoff models which are tools for runoff calculation can be used for flood forecasting. In Slovenia, the lag time between rainfall and runoff is only a few hours and on-line data are used only for now-casting. Predicted precipitation is necessary in flood forecasting some days ahead. The ECMWF (European Centre for Medium-Range Weather Forecasts) model gives general forecasts several days ahead while more detailed precipitation data with the ALADIN/SI model are available for two days ahead. Combining the weather forecasts with the information on catchment conditions and a hydrological forecasting model can give advance warning of potential flooding notwithstanding a certain degree of uncertainty in using precipitation forecasts based on meteorological models. Analysis of the sensitivity of the hydrological model to the rainfall error has shown that the deviation in runoff is much larger than the rainfall deviation. Therefore, verification of predicted precipitation for large precipitation events was performed with the ECMWF model. Measured precipitation data were interpolated on a regular grid and compared with the results from the ECMWF model. The deviation in predicted precipitation from interpolated measurements is shown with the model bias resulting from the inability of the model to predict the precipitation correctly and a bias for horizontal resolution of the model and natural variability of precipitation.

Keywords: precipitation forecast, ECMWF, flood forecasting, hydrological modelling, rainfall-runoff, HEC-1, kriging

Introduction

A major characteristic of the Slovenian territory is a very heterogeneous climate and exceptional diversity in terms of morphology, geology, pedology and vegetation. These diversities are reflected in specific hydrological characteristics and highly variable river discharge. The average annual precipitation is 1570 mm (ranging from 750 mm in the north-east to more than 3000 mm in the west of the country). Average drainage density is 1.32 km km^{-2} and average runoff from Slovenia is 590 m s^{-1} (Kolbezen and Pristov, 1998). Specific runoff in the north-west is more than 70 l s^{-1} km^{-2} while in north-eastern and central parts it is less than 7 l s^{-1} km^{-2}. A ratio of extreme discharges to the low flow is a few hundred times for Slovenian rivers.

Complex topography, both for Slovenia and its surroundings, has a strong influence on meteorological phenomena in the region. The most frequent are flash floods caused by heavy rain, especially in mountainous parts of Slovenia. Flash floods are associated with intense localised thunderstorm activity, slow moving or stationary cyclones. The danger of flash floods is high in mountainous areas where orographic uplift may intensify rainfall and where the steep slopes may increase the potential for landslides and mudslides. The term ‘flash flood’ describes the suddenness and unexpectedness of very intense storm rainfall or rapid snow melting in a small catchment through which the resulting flood peak passes too rapidly for flood warnings to be given (Smith and Ward, 1998). Very rapid rise in water level, sometimes within a few hours, combined with large sediment transport, may result in extensive damage to property. Flash floods are difficult to predict. The hydrological forecasts and warnings of the Slovenian hydrological forecasting service depend on hydrological and meteorological measurements on-line and forecast meteorological data. These data are also input into hydrological models.

Hydrological modelling in Slovenia

Hydrological models can give predictions for different impacts on the water regime. The design of hydrological models depends on scope, goals, knowledge and available data (Brilly, 1999). Each basin has its own runoff regime, different for each rainfall event.

In the operational work of the Slovenian hydrological forecasting service, regression models have been developed and used for predicting the peaks of flood waves (Sušnik and Polajnar, 1998). The input to these models is usually 24-hour precipitation data. These models are based on statistical analyses of historical high water levels and precipitation events. In addition to regression models, conceptual rainfall–runoff models are used for some basins. The WMS (Watershed Modeling System) software is used, which integrates digital terrain analysis and hydrological modelling. The advantage of this software is its ability to take digital terrain data for hydrological data development (Kobold and Sušnik, 2000). So far, WMS has been implemented on some Slovenian river basins, as shown in Fig.1. The HEC-1 model is used for surface runoff simulation (Feldman, 1995). It is primarily a flood hydrology analysis tool to model the rainfall-runoff process. HEC-1 is a flood hydrograph package developed by the US Army Corps of Engineers which enables the flood forecaster to develop unit hydrographs using various methods, and to calculate loss rates and route hydrographs, again using a variety of methods including Muskingum-Cunge and kinematic wave approaches.

The hydrological models can be used as a prognostic tool in the hydrological forecasting service and/or as an analytical tool. The hydrological models of river basins are capable of forecasting the flood hydrograph at any location within a river basin.

HYDROLOGICAL MODEL FOR THE SAVINJA BASIN

The Savinja basin is the most flood threatened region in Slovenia and the Savinja River is the biggest tributary to the Sava River, with a drainage area of 1848 km^2. For that reason, the Savinja basin was chosen as a test basin in the EFFS (European Flood Forecasting System) project (EFFS, 2002a). The upper part of the basin is mountainous with altitudes up to 2000 metres. The altitude of the plain area, in the middle reach of the Savinja, is between 200 and 400 m. Due to its runoff characteristics, it has an important influence both on flood wave formation and on the forecast of the lower Sava River in Slovenia. Its drainage area can contribute up to 40% of the lower Sava River discharge following extreme meteorological events. The floods, usually flash floods, are caused by heavy rainfall in headwater mountain areas, especially in the autumn.

The HEC-1 hydrological model of the Savinja basin and

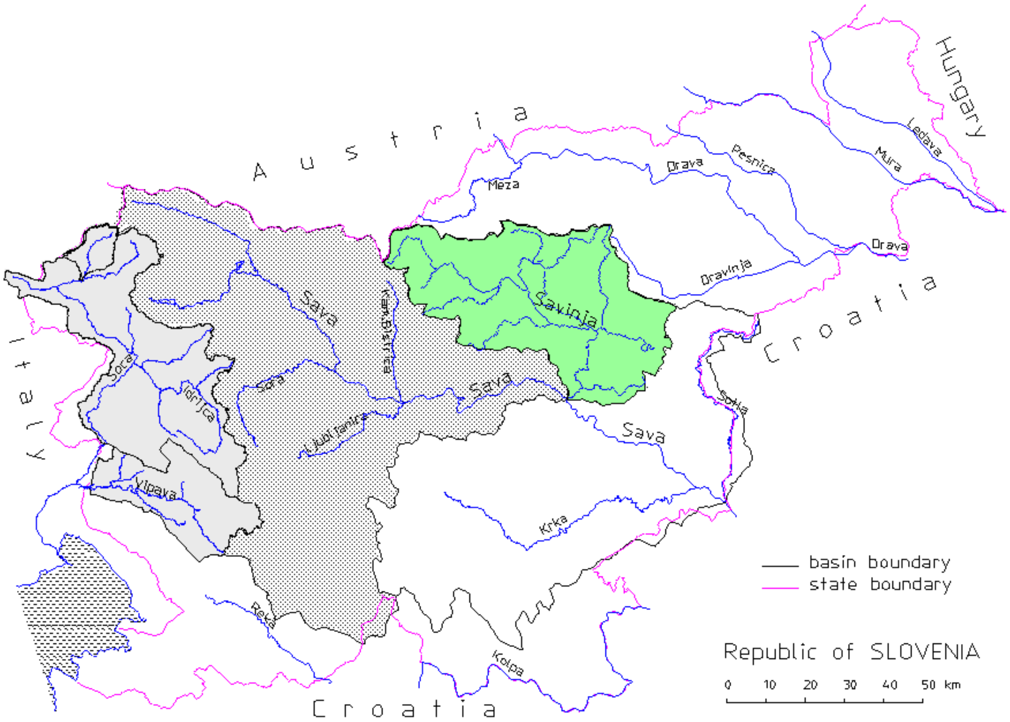

Fig. 1. *River basins in Slovenia covered by the HEC-1 model.*

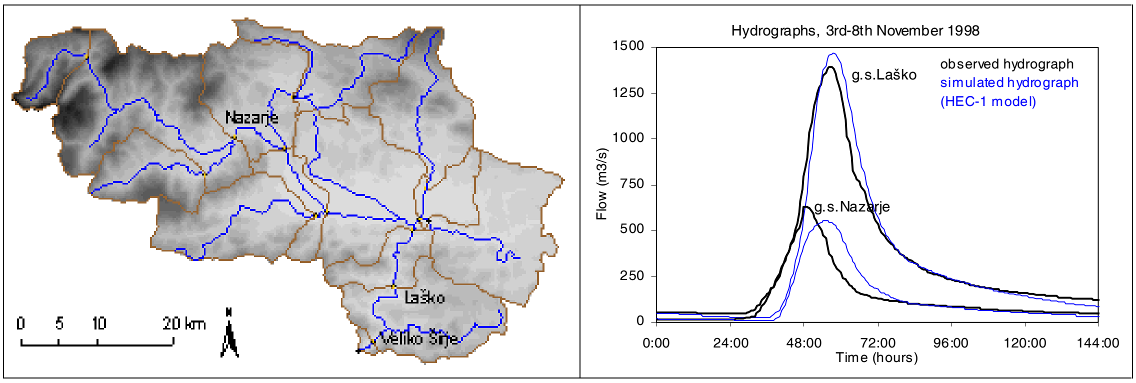

Fig. 2. The HEC-1 hydrological model of the Savinja basin and flood wave simulation from November 1998.

the results of verification of the model are presented in Fig. 2. The model was verified on the last big flood from November 1998 when the peak discharge nearly reached the maximum value recorded during the catastrophic flood in 1990 (Kolbezen, 1991). Near the outlet of the basin at Veliko Širje, the peak discharge reached 1458 m^3 s^{-1} in November 1998, while the value from November 1990 is 1490 m^3 s^{-1}.

The absolute deviation of simulated and observed peak discharges for the flood of 1998 (Fig. 2) is 12.3% for Nazarje and 5.5% for Laško, while the calibration of the HEC-1 model for the Savinja basin (Kobold and Susnik, 2000) gave the average absolute deviations of simulated and measured peak discharges between 20% and 30% for smaller sub-basins, but 10% for the whole basin. The deviations are greater in the mountainous parts of the basin. The main reason for larger deviations in mountainous parts lies in the insufficient number of recording raingauges to take account of orographic influences.

HYDROLOGICAL MODEL FOR THE KORITNICA BASIN

The Alpine valley of the Koritnica lies in the northwestern part of Slovenia below mountain Mangart (2679 m a.s.l.) on the border with Italy. The Koritnica basin covers an area of 87 km^2 in headwaters of the Soca River (Fig.1). It lies between 400 and over 2000 metres above sea level. The slopes of the basin are between 60% and 90%. The highest number of thunderstorms per year is recorded in this part of the Alps. In autumn 2000, excessive precipitation triggered two landslides, the first on November 15 without special damage, and another on November 17 when debris flow killed seven people and destroyed several houses in the village Log pod Mangartom (Mikoš *et al*., 2002).

The period of intense precipitation started in October 2000 and lasted to the end of November 2000. The precipitation from the meteorological gauging station Log pod Mangartom (650 m a.s.l.) located next to the middle of the basin, and the runoff from hydrological gauging station Kal Koritnica 1.7 km upstream from the outlet of the basin, are shown in Fig. 3. The lag time between precipitation and runoff is less than one hour. About 2000 mm of rainfall was registered in the months of October and November 2000 (Mikoš *et al*., 2002). During the night of the catastrophe, about 140 mm of rainfall was registered, common for this area. But the monthly amount of precipitation for November 2000 is 1234 mm being more than 100-year event. The maximum peak discharge from November 2000 is 104 m^3 s^{-1} with return period of five years.

Reconstruction of the event was done by the HEC-1 model. The hydrographs of upstream cross-sections were calculated. The average absolute deviation of analysed peaks for the whole basin is 8% with maximum deviation of 14%. The analysis of deviations for sub-basins was not possible because there was no gauging station upstream at the time of event. But the calculated hydrographs gave the probable discharges regarding the ratios of discharges from their measurements after the event.

The sensitivity of the hydrological model to rainfall

Although the HEC-1 model is limited to simulations of single storm events because no provision is made for soil moisture recovery during dry periods (Feldman, 1995), it can be used for flood forecasting. In that case the predicted precipitation can be input into the model.

Hydrological rainfall-runoff models are sensitive to precipitation input. An analysis of sensitivity of the HEC-1 model to the rainfall deviation has been made for the Savinja basin by multiflood simulation where the multifloods are computed as ratios of a base precipitation event (Fig. 5).

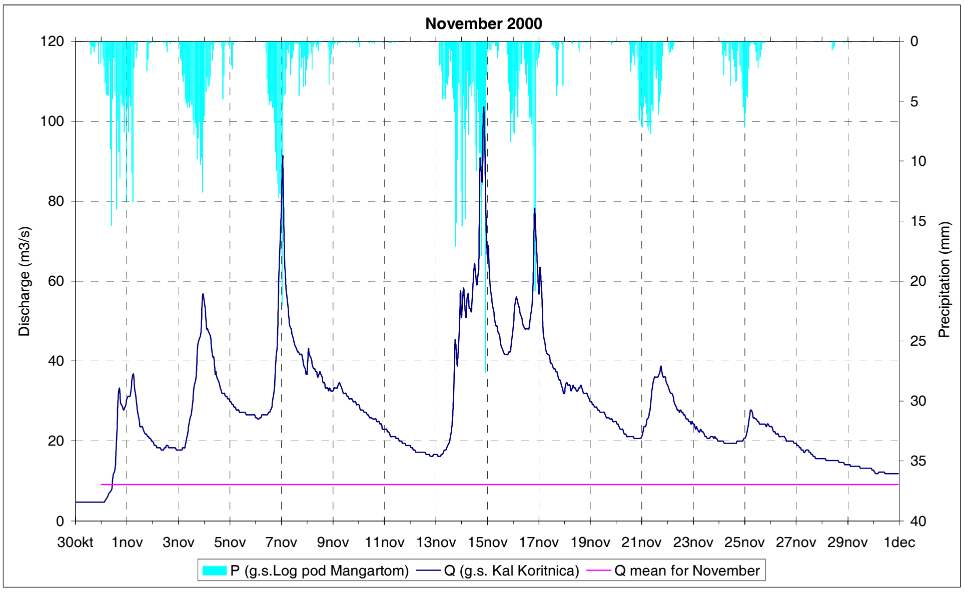

Fig. 3. *River flow hydrograph and precipitation on the Koritnica basin.*

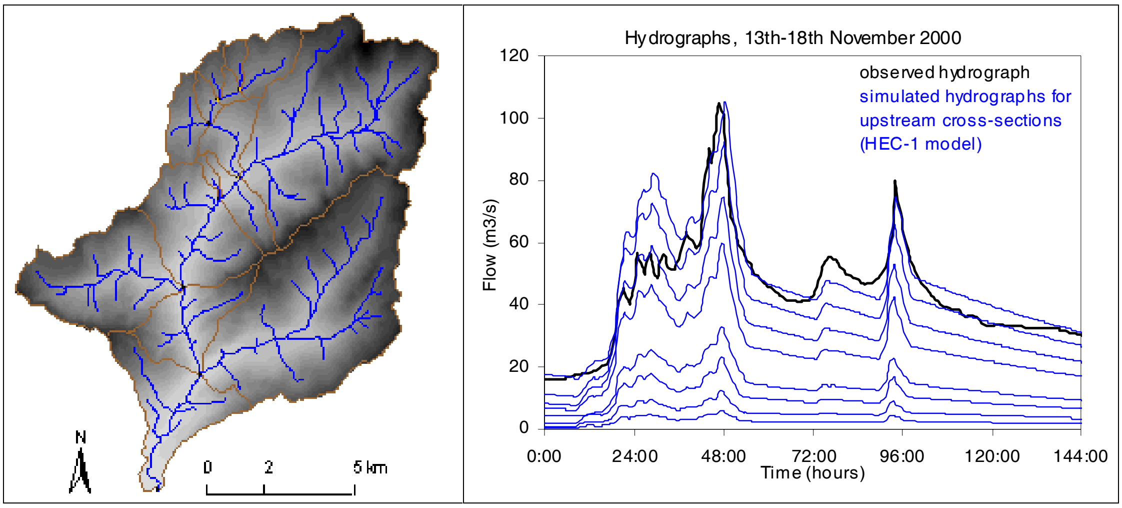

Fig. 4. *The HEC-1 hydrological model of the Koritnica basin as an analytical tool.*

Figure 6 shows the deviation in peak discharges for the Savinja River at Laško for more flood events. It is clear that an error in rainfall leads to greater error in peak disharge: greater precipitation error derives from larger scattering of points. Similar results were obtained for the other hydrological gauging stations on the Savinja basin.

Analysis has shown that an error in the rainfall input into the rainfall-runoff model can result in high runoff deviation. Therefore, accurate representation of precipitation in time and space is essential for hydrological modelling and especially for flood forecasting.

Verification of precipitation forecast

Numerical modelling is a powerful tool for analysis and forecasting of weather. Currently, quantitative precipitation forecasts from four models with very different domain, spatial and time resolution is available at the Agency of the Republic of Slovenia. Results from two global models (ECMWF and DWD/GM) and two limited area models (ALADIN/SI and DWD/LM) are available each day.

The verification of predicted precipitation by the ECMWF model for large precipitation events was performed. Large precipitation events have been chosen from the EFFS events (EFFS, 2002b). EFFS events (December 1, 1994–March

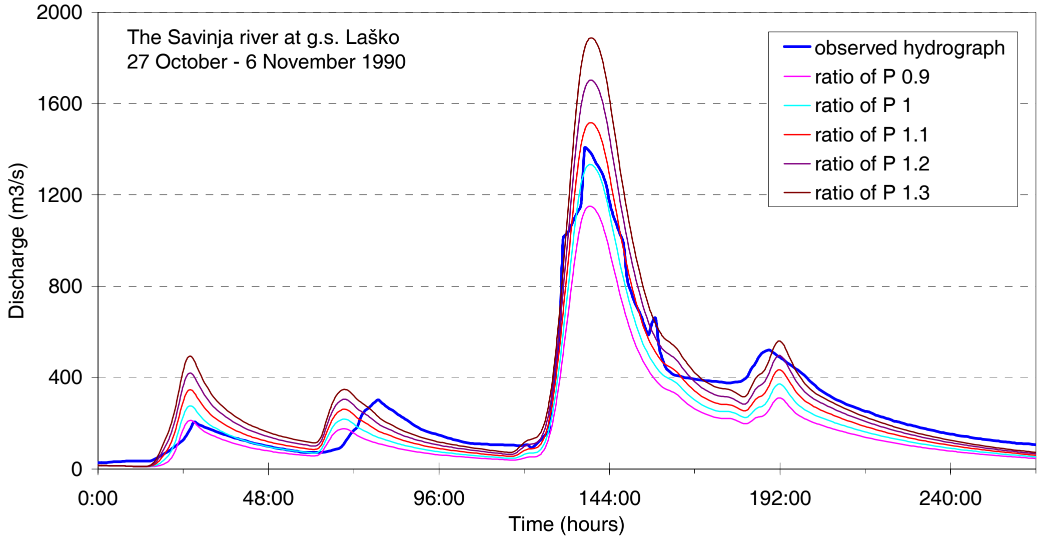

Fig. 5. *Simulated hydrographs by different precipitation scenarious.*

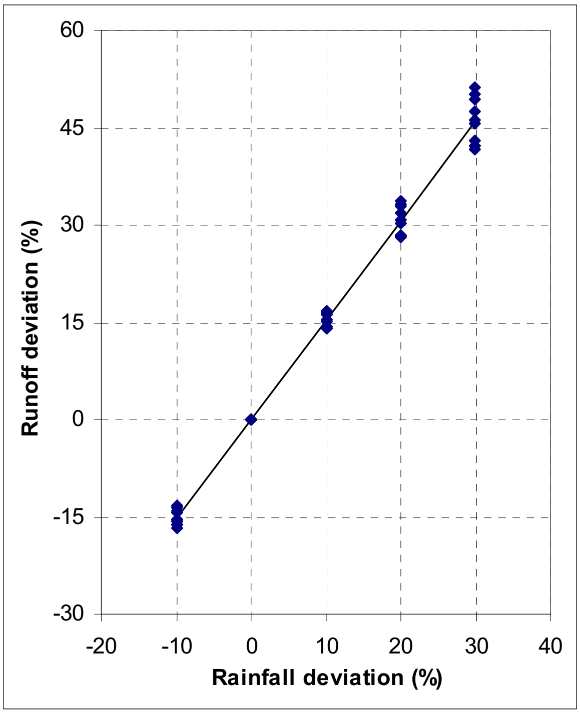

Fig. 6. Runoff deviation to rainfall deviation for the Savinja at Laško.

31, 1995; June 25, 1997–July 31, 1997; October 15, 1994–November 15, 1994) have been chosen to cover some big floods caused by major European rivers. Unfortunately, these events do not match any big flood event in Slovenia. Based on the different weather types for Slovenia (Rakovec and Vrhovec, 2000) data from four different precipitation stations (Luce – 520 m a.s.l., Crnivec – 842 m a.s.l., Žaga – 353 m a.s.l. and Kocevje – 461 m a.s.l.) have been used to choose one-day events with relatively high amounts of precipitation. At least one of these stations measures high values of precipitation for any type of large-scale precipitation. A criterion for choosing one-day events was at least 40 millimetres of measured precipitation on at least one of the precipitation stations (Fig. 7).

MEASURED AND INTERPOLATED PRECIPITATION

Data from around 240 meteorological stations covering Slovenia were interpolated on a 1-km grid using standard kriging procedure (Kastelec, 2001). Kriging is a well-known geostatistical technique for interpolating meteorological fields. The advantage of using kriging is consideration of spatial distribution of precipitation, caused mainly by orographic irregularities. Point precipitation measurements inside one model grid-point can differ a lot, depending mostly on terrain irregularities, precipitation type and model resolution. Comparing the measured precipitation directly with the precipitation from a model can depend on the position of precipitation station rather than the real model bias. To demonstrate this effect, the relative gradient of average yearly precipitation from 1961 to 1990 was calculated from a 1-km precipitation grid (Fig. 8), using Eqn. 1a and 1b:

$$rel.grad. = \frac{1}{RR_y^{i,j}} \nabla RR_y^{i,j} * 100 \tag{1a}$$

and

$$\nabla RR_y^{i,j} = \sqrt{\left(\frac{RR_y^{i+1,j} - RR_y^{i-1,j}}{2\Delta x}\right) + \left(\frac{RR_y^{i,j-1} - RR_y^{i,j+1}}{2\Delta y}\right)} \tag{1b}$$

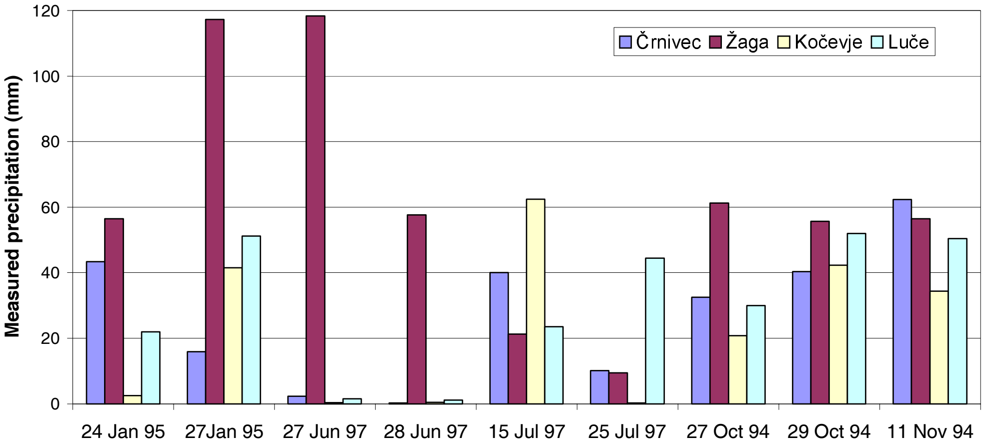

Fig. 7. Precipitation events of four stations representing different weather types.

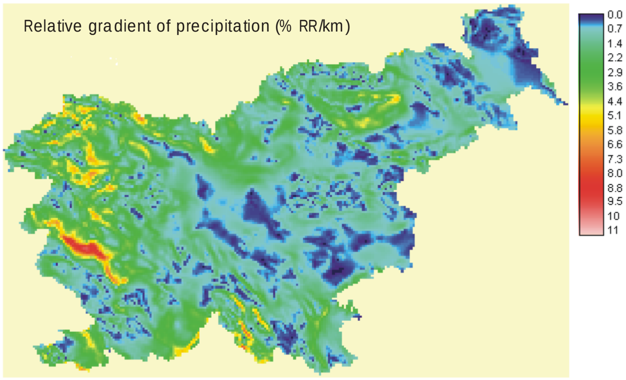

Fig. 8. *Relative gradient of precipitation*

where RR_y is average yearly precipitation from period of 1961–1990, ∇RR_y is precipitation gradient, indices i and j denote latitude and longitude of the precipitation field respectively, and Δx and Δy are horizontal resolutions in longitude and latitude directions. The values of the relative gradient (Fig. 8) can be as high as 10% per km. That means the difference in yearly precipitation measurement at a distance of 1 km can be more than 10%. It is easy to understand that in the case of daily precipitation the gradient of the precipitation field can be very high.

There are three usual types of large precipitation events in Slovenia. First, when a cold front passes across central Europe and consequently northern Slovenia gets the most precipitation. Second, when the Genova cyclone passes Slovenia and north-west Slovenia gets the most precipitation. The third is the case of convective precipitation when the amount and spatial distribution of precipitation are largely unpredictable. None of the events analysed is matched with the first type. However, the analysed events have been classified as three different cases (Fig. 9):

- Genova cyclone passes Slovenia, NW Slovenia gets the most precipitation (24 Jan 1995, 27 Jan 1995, 15 Jul 1997, 27 Oct 1994, 29 Oct 1994 and 11 Nov 1994)
- Convective precipitation in NW Slovenia (27 Jun 1997 and 28 Jun 1997)
- Convective precipitation in NE Slovenia (25 Jul 1997)

COMPARISON OF MEASURED AND ECMWF PREDICTED PRECIPITATION

The European Centre for Medium-Range Weather Forecast (ECMWF) has a global circulation model running operationally with a grid resolution of about 0.5°. Verification has been performed on 10 grid points covering Slovenia. The map is drawn as a latitude/longitude projection (Fig. 10).

The ECMWF model is run every day using as initial conditions analysis of 12 UTC. Results are available for 240 hours in advance. Most meteorological stations measure precipitation daily, at 6 UTC. The first step of the analysis was the comparison of interpolated measured precipitation with ECMWF precipitation forecast for different time intervals:

ECMWF-2: precipitation forecast between +18 and +42 hours ahead
ECMWF-3: precipitation forecast between +42 and +66 hours ahead
ECMWF-4: precipitation forecast between +66 and +90 hours ahead
ECMWF-5: precipitation forecast between +90 and +114 hours ahead

Figure 11 shows the relative difference between modelled

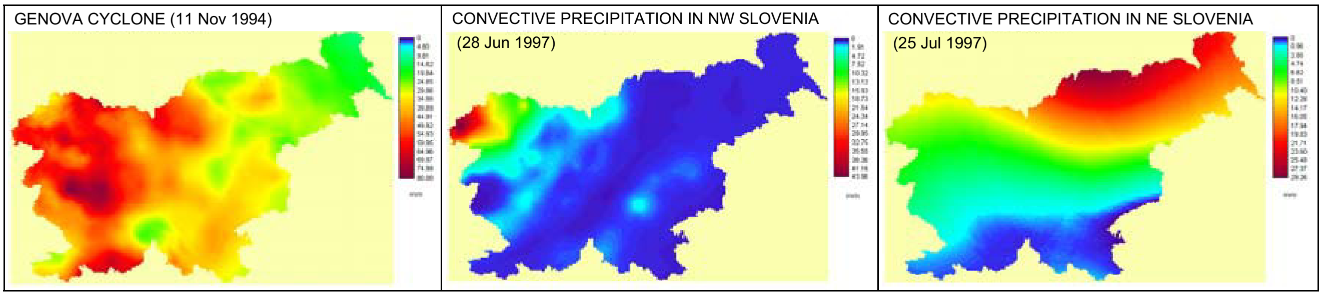

Fig. 9. Precipitation types in Slovenia.

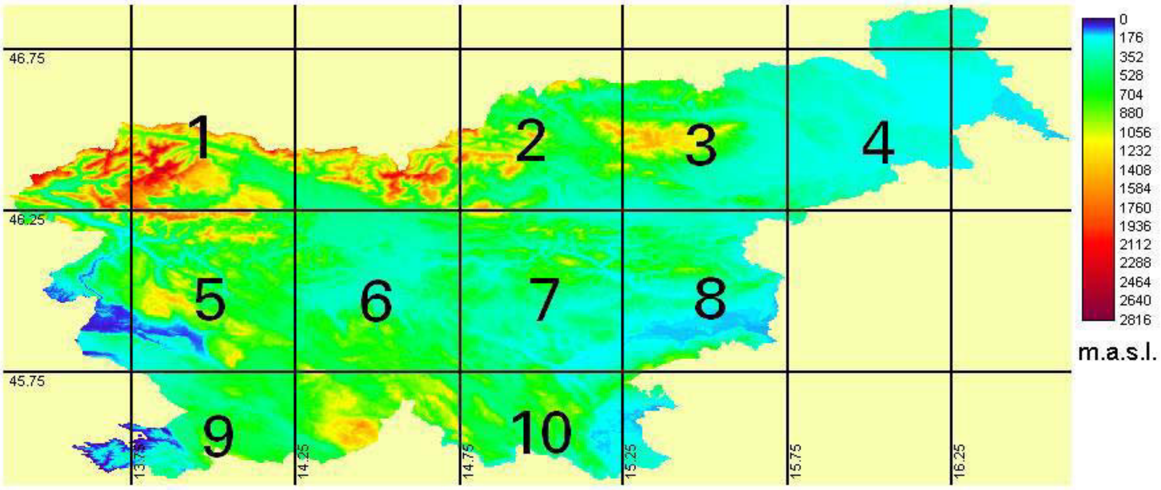

Fig. 10. ECMWF grid points and relief of Slovenia.

and measured precipitation. The relative difference was calculated by the equation:

$$\Delta RR_{rel} = \left\langle \frac{RR_{meas} - RR_{\mathrm{mod}}}{RR_{meas}} \right\rangle * 100 \qquad (2)$$

where RR_{meas} is average measured precipitation inside one ECMWF grid point, RR_{mod} is model output for grid point and $\langle \ \rangle$ denotes averaging by grid points.

The ECMWF model underestimates the amount of precipitation for all except two convective cases (27 Jun 1997 and 28 Jun 1997). In general, although not always, the relative bias of precipitation forecast decreases when time intervals are closer to the measured precipitation (Fig. 11). The underestimation is between 35% and 85%, with an average value of about 60%.

Only precipitation of the closest time interval (ECMWF-2) was analysed further. Precipitation was averaged by the grid points covering Slovenia for one-day events (Fig. 12) and by the events to get the results for each grid point separately (Fig. 13).

The greatest relative differences are in regions with the least amount of precipitation (grid points 3, 4 and 8). In the areas with the highest precipitation in Slovenia, relative differences are smaller (grid points 1, 5 and 6).

By using the quantitative precipitation forecast in hydrological models, precipitation is usually assumed to be uniform inside meteorological model grid points. On such assumptions, the bias of precipitation forecast is composed of two parts: model bias as a result of model inability to predict precipitation correctly and bias caused by assuming

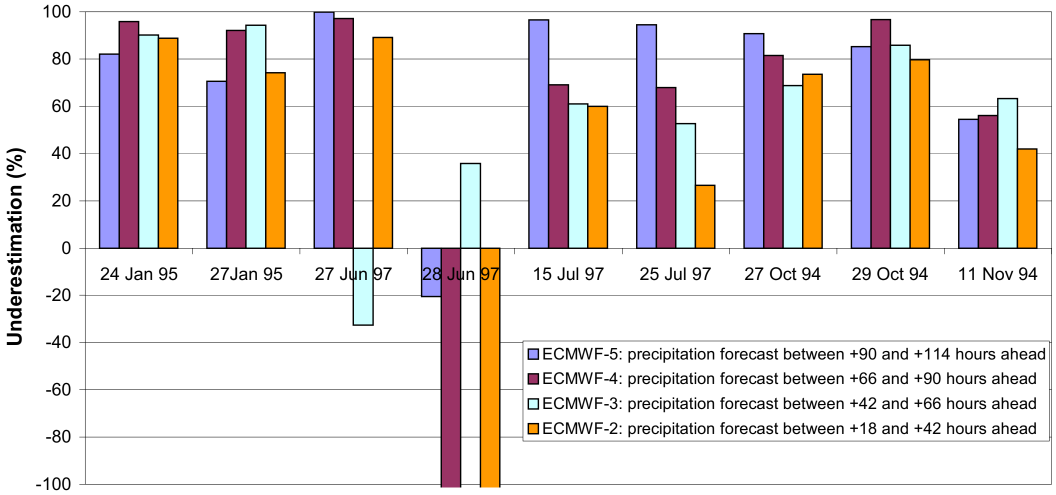

Fig. 11. *Relative difference between modelled and measured precipitation for different time intervals.*

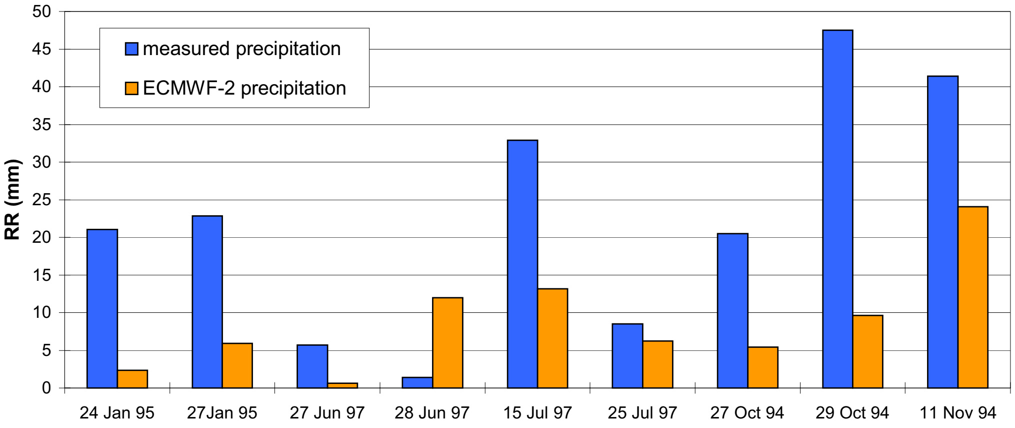

Fig. 12. *Amount of precipitation for one-day events averaged by grid points.*

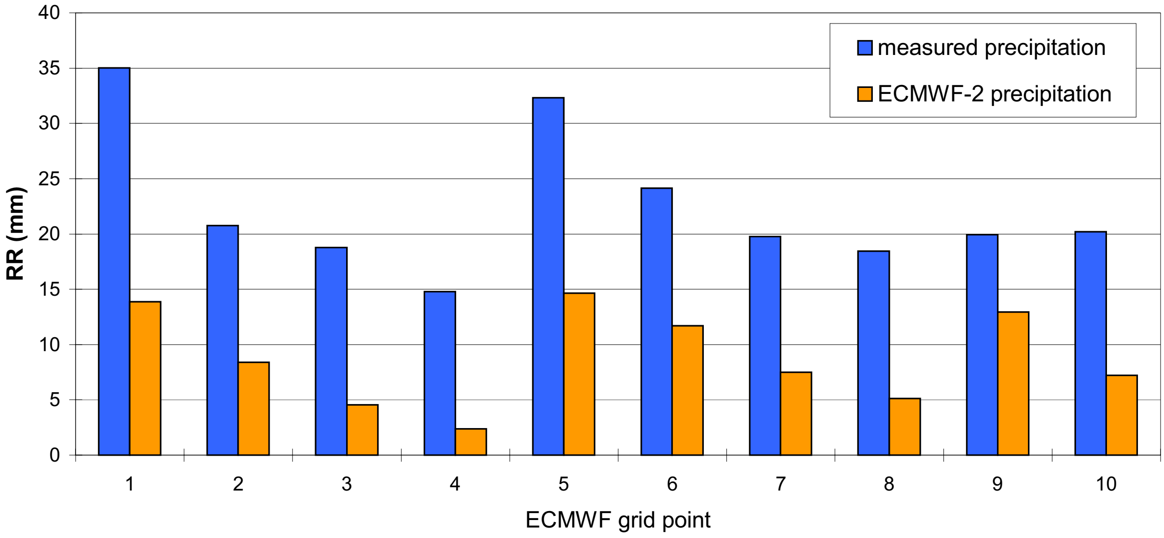

Fig. 13. *Amount of precipitation for grid points averaged by one-day events.*

uniform precipitation inside a model grid point.

$$x^k_{\mathrm{mod}} - x^{i,k}_{mea} = x^k_{\mathrm{mod}} - x^k_{av} + x^k_{av} - x^{i,k}_{mea} \qquad (3)$$

In Eqn. 3, x^k_{mod} is denotes the numerical model result of k-th model grid point, $x^{i,k}_{mea}$ is measured precipitation at location i (index k denoting that location i is inside k-th numerical model gridpoint) and x^k_{av} is average of $x^{i,k}_{mea}$ inside model grid point k.

Calculating variance (second centred momentum with summation over i and k) of Eqn. 3, the following result can be written for variance of error:

$$\sigma = \sigma_{\mathrm{mod}} + \sigma_{ua} \qquad (4)$$

where

$$\sigma_{\mathrm{mod}} = \frac{1}{K-1}\sum_{k=1}^{K}(x^k_{\mathrm{mod}} - x^k_{av}) \qquad (4a)$$

$$\sigma_{ua} = \frac{1}{(K-1)(I-1)}\sum_{k=1}^{K}\sum_{i=1}^{I}(x^k_{av} - x^{i,k}_{mea}) \qquad (4b)$$

Further, $\sqrt{\sigma_{\mathrm{mod}}}$ will be called the standard deviation of model bias, since it is due to model inability to predict precipitation correctly, and $\sqrt{\sigma_{ua}}$ the standard deviation of the bias caused by assumption of uniform precipitation inside the model grid point.

The bias caused by assumption of uniform precipitation inside the model grid point does not depend on the model's ability to predict the precipitation correctly but on the horizontal resolution of the model and the natural variability of precipitation. Its standard deviation was estimated by calculation of standard deviation of precipitation from a 1-km grid of interpolated measured precipitation to the ECMWF grid.

Figures 14 and 15 show the average difference over Slovenian territory between the ECMWF and measured precipitation (measured-ECMWF), standard deviation of model bias (st.dev. (measured-ECMWF)) and standard deviation of bias caused by assumption of uniform precipitation inside the model grid point (st.dev. (subgrid precipitation)). Comparing the standard deviations of biases gives an idea of the most important source of bias introduced in a hydrological forecast. It can be either model bias or poor resolution of the model. Similar to Figs. 12 and 13, Figs. 14 and 15 show the averages over model points and over events respectively (averaging over k in Eqn. 4b).

The standard deviation of the bias caused by assumption of uniform precipitation inside the model grid point is about 10 mm for one-day events (Fig. 14) and it is a little higher in convective precipitation events (25 Jul 1997, 27 Jun 1997 and 28 Jun 1997). In general, it seems that the ECMWF model underestimates the amount of precipitation over all Slovenian territory systematically and this underestimation seems to be the highest error when using precipitation forecasts in hydrological models. In most cases the poor model resolution gives about 10 mm of error, but it is generally smaller than the systematic underestimation of model results. Figure 15 shows that the variability in precipitation is much greater in north-west Slovenia (grid points 1 and 5) where the relief is very mountainous and cut by many deep valleys.

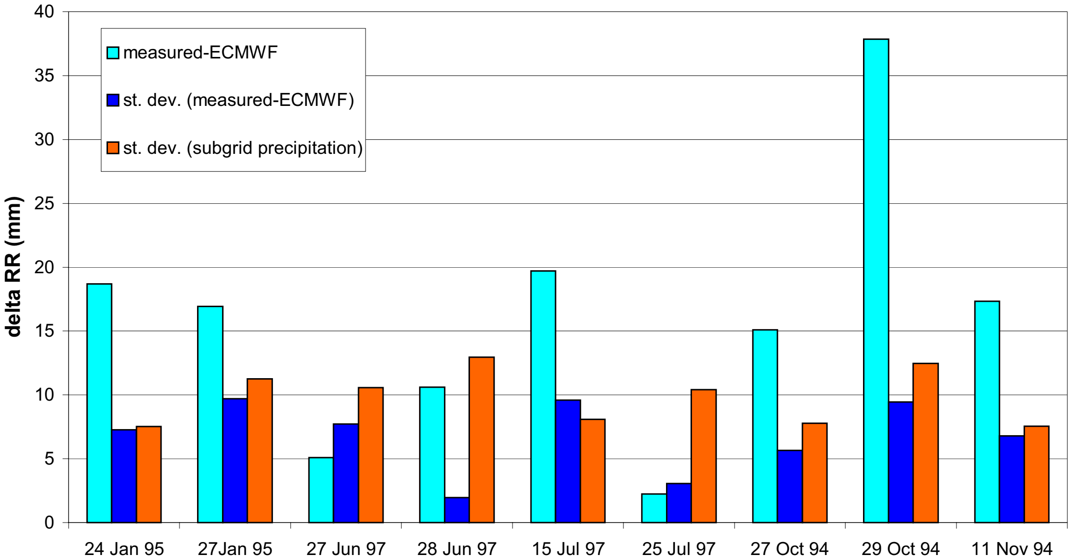

Fig. 14. *Average model bias, standard deviation of model bias and standard deviation of subgrid precipitation of one-day events.*

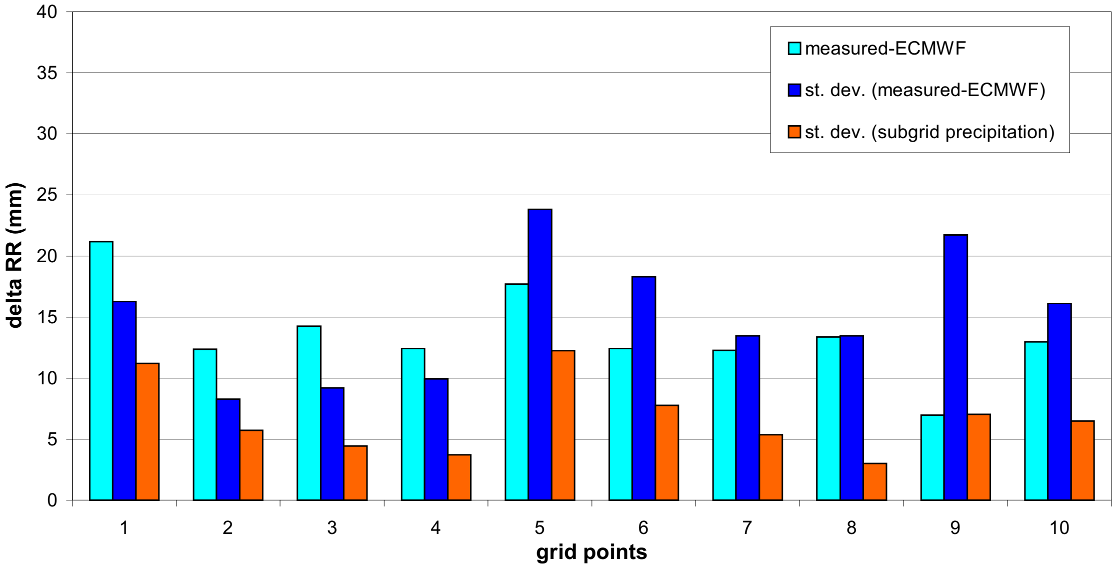

Fig. 15. *Average model bias, standard deviation of model bias and standard deviation of subgrid precipitation of grid points.*

Conclusions

Weather forecasts, coupled with information on river basin characteristics and a hydrological rainfall-runoff model, offer an advance warning of potential flooding. However, hydrological rainfall–runoff models are sensitive to precipitation input. The analysis has shown that the deviation of runoff is much greater than that of the rainfall. An error in rainfall amount leads to 1.6 times greater error in peak discharge. For reliable flood warning, accurate precipitation forecasts are needed.

The analyses performed have shown that using the ECMWF quantitative precipitation forecast in hydrological modelling can cause very high biases in discharges. It was shown that the ECMWF-predicted precipitation tends to very high systematic underestimation of precipitation. The comparison of measured precipitation and that predicted by ECMWF for the precipitation events analysed has shown that, in large precipitation cases, the ECMWF model underestimates precipitation volume by an average of 60%. Also, the variability in precipitation over Slovenia is very high and the ECMWF model, with its coarse resolution, cannot describe precipitation variability properly. However, the reason for poor analysis is the small number of precipitation events; analysing more precipitation events could give a better idea of model performance.

Forecasting smaller-scale phenomena with a finer resolution of the model space is crucial for the accuracy of regional forecasts, and is especially important for countries with variable and complex topography such as Slovenia. Quantitative forecasting of various meteorological variables (such as precipitation, temperatures, etc.) with exact timing and location is needed. Further analysis of measured and forecasted precipitation will be done using the limited area ALADIN/SI model, with a resolution of 11 km over a domain covering the eastern Alpine and northern Adriatic regions (Vrhovec *et al*., 1998). In this way, a comparison of meteorological models could be given and their applicability for hydrological forecasting could be assessed.

Acknowledgements

This work was funded by the EU project European Flood Forecasting System (EFFS). The authors thank to the coordinators of the project and the reviewers for their comments.

References

Brilly, M., 1999. Development of contemporary hydrological models. *Proc. 18th Goljevšcek Memorial Day, Acta hydrotechnica* 17/26, Ljubljana, Slovenia. 31–44.

EFFS, 2002a. *An European Flood Forecasting System*. Report Kickoff Meeting EFFS-NAS, 4-5 November 2002, Contract no. EVG1-CT-1999-00011, WL Delft Hydraulics, Netherlands.

EFFS, 2002b. *An European Flood Forecasting System*. Annual report 2, Period March 2001 – March 2002, Contract no. EVG1-CT-1999-00011, WL Delft Hydraulics, Netherlands.

Feldman, A.D., 1995. HEC-1 Flood Hydrograph Package. In: *Computer Models of Watershed Hydrology,* V.P. Singh (Ed.) Water Resources Publication, Colorado, USA. 119–150.

Kastelec, D., 2001. *Objektivna prostorska interpolacija meteoroloških spremenljivk in njihovo kartiranje* (Objective spatial interpolation of meteorological parameters and their sketching). Doctoral Thesis, University of Ljubljana, Slovenia (in Slovenian).

Kobold, M. and Sušnik, M., 2000. Watershed modelling and surface runoff simulation. Internationales Symposion INTERPRAEVENT 2000 – Villach, Österreich, *Tagungspublikation* **2**, 329–338.

Kolbezen, M., 1991. *Flooding in Slovenia on November 1, 1990*. Ujma 5, Ljubljana, Slovenia. 16–18.

Kolbezen, M. and Pristov, J., 1998. *Surface Streams and Water Balance of Slovenia.* Hydrometeorological Institute of Slovenia, Ljubljana.

Mikoš, M., Vidmar, A., Sraj, M., Kobold, M., Sušnik, M., Uhan, J., Pezdic, J. and Brilly, M., 2002. *Hydrological Analyses of the Stože Landslide*. Ujma 16, Ljubljana, Slovenia. 326–334.

Rakovec, J. and Vrhovec, T., 2000. *Osnove Meteorologije za naravoslovce in tehnike* (Basis of meteorology). Mathematics, Physics and Astronomy Society of Slovenia, Ljubljana (in Slovenian).

Smith, K. and Ward, R., 1998. *Floods: Physical Processes and Human Impacts*. Wiley, Chichester, UK.

Sušnik, M. and Polajnar, J., 1998. Simple hydrological forecasting models: operational experience. *Proc. XIXth Conf. Danube Countries*, Osijek, Croatia. 31–36.

Vrhovec, T., Žagar, M., Brilly, M. and Sraj, M., 1998. Forecasting of intense precipitation using the ALADIN-SI model and modelling of the runoff. Proc. *17th Goljevšcek Memorial Day, Acta hydrotechnica 16/23*, Ljubljana, Slovenia. 71–84.