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NEZANESLJIVOST PADAVINSKIH MERITEV IN NAPOVEDI PRI MODELIRANJU HUDOURNIŠKIH POPLAV
UNCERTAINTY OF PRECIPITATION MEASUREMENTS AND PREDICTIONS IN FLASH FLOOD MODELLING

Mira KOBOLD, Anton ZGONC, Mojca SUŠNIK

Nezanesljivost simuliranega odtoka je v največji meri posledica netočne ocene padavin na povodju, bodisi iz mreže padavinskih postaj na povodju, radarja ali padavinske napovedi. Od prostorskega merila povodja, gostote padavinske mreže, razporeditve postaj in variabilnosti padavin na povodju je odvisno, kako dobro s točkovnimi padavinami določimo povprečne padavine na povodju. V prispevku je prikazana neustreznost mreže ombrografskih postaj na povodju Savinje za oceno ploskovnih padavin na povodju za modeliranje hudourniških poplav. Merjenje padavin v točkah ne poda dovolj informacije o ploskovnih padavinah, ki so osnovna informacija za modeliranje odtoka in simulacijo hidrogramov. Prednost radarja za merjenje padavin je pokritost območja z veliko časovno in prostorsko ločljivostjo. Za dva visokovodna dogodka je prikazana uporabnost radarskih padavin za hidrološko modeliranje na povodju Savinje. Pri operativnem napovedovanju poplav so vhod v modele padavine–odtok prognozirane padavine meteoroloških modelov. Za povodje Savinje so prikazani rezultati polletnih testnih zagonov modela HBV-96 s produkti meteorološkega modela ALADIN/SI. Narejena je primerjava izračunanih pretokov z merjenimi za prvi in za drugi dan napovedi. Analizirano je odstopanje simuliranega pretoka od merjenega kot posledica netočne napovedi količine padavin na povodju. Analiza hudourniških poplav, ki so prizadele Posavje v avgustu 2005, kaže na težavnost napovedovanja hudourniških poplav in izdaje predhodnih opozoril.
Ključne besede: *napovedovanje poplav, hudourniške poplave, ploskovne padavine, radar, nezanesljivost, model HBV-96, model ALADIN/SI*

The uncertainty of simulated runoff is mainly the result of precipitation uncertainty associated with the average basin precipitation. Therefore it is very important to assure the accurate precipitation input, whether from raingauges or other sources such as radar measurements or meteorological forecast. The estimation of average basin precipitation from point precipitation measurements is dependent on the catchment scale, density of precipitation network, distribution of precipitation stations and variability of precipitation. In the paper, the unsuitability of the number of recording raingauges on the Savinja catchment for areal estimation of precipitation for flash flood modelling is presented. Point precipitation measurements do not give enough information about areal precipitation which is a base for runoff modelling and simulation. On the other hand, radar provides coverage over a large area with high spatial and temporal resolution. The applicability of radar precipitation was presented for two high water events on the Savinja catchment. For operational flood forecasting the predicted precipitation of meteorological models is input into the rainfall-runoff models. The results of half-yearly runs of HBV-96 model for the Savinja catchment are demonstrated using the meteorological forecast of ALADIN/SI model. The comparison of computed and observed discharges was done separately for the first day and for the second day of forecast. The deviation of the simulated discharge from the measured one is analysed as a result of inaccurate forecast of amount of precipitation on the catchment. The analysis of flash floods, which affected the Posavje region in August 2005, shows the difficulties of flash flood forecasting and early warning issues.
Key words: *flood forecasting, flash floods, areal precipitation, radar, uncertainty, HBV-96 model, ALADIN/SI model*

1. UVOD

V Evropi ločimo dve skupini meteoroloških dogodkov, ki povzročijo poplave. Prva skupina se nanaša na frontalne padavine, ki povzročijo poplave velikih rečnih sistemov in kjer lahko maksimalni pretoki poplavnega vala trajajo tudi več dni. Druga skupina so hudourniške poplave, ki so običajno povezane s posameznimi in lokalno zelo intenzivnimi padavinskimi dogodki, ki se zgodijo v majhnih in srednje velikih porečjih. Maksimalni pretoki poplavnega vala trajajo kratek čas, lahko nekaj ur ali pa samo nekaj minut. Hudourniške poplave so značilne za večino slovenskih rek.

V Sloveniji so območja, kjer so poplave reden, pogost ali občasen pojav (slika 1). Glavna in najobsežnejša območja so v nižinsko-ravninskih predelih severovzhodne Slovenije, v predalpskih dolinah in kotlinah ter v osrednji in vzhodni Sloveniji. Poplave s povratno dobo 50 in več let pomenijo katastrofalne poplave. V večini primerov poplave z enako povratno dobo ne nastopijo na celotnem povodju hkrati. Na manjših povodjih so za nastop poplav odločilne intenzivne padavine krajšega trajanja do nekaj ur, ki so najpogostejše v poletnem obdobju, medtem ko so za poplave na večjih povodjih odločilne padavine z daljšim trajanjem, ki nastopijo večinoma v pomladanskem oziroma jesenskem času. Največje poplave v Sloveniji se običajno zgodijo v jeseni ob prehodu hladne fronte prek srednje Evrope ali ob prehodu sredozemskega ciklona iznad Genovskega zaliva. Najbolj izdatne padavine se pojavijo ob kombinaciji ciklonskih in orografskih padavin, ko lahko pade več kot 70 mm/uro in 240 mm/dan.

Hidrološki modeli so učinkovito orodje za simulacijo poplavnih valov in napovedovanje odtoka. Modelov za napovedovanje odtoka je veliko, od preprostih empiričnih enačb ali korelacij med padavinami in odtokom do kompleksnih modelov, ki ponazarjajo fizikalne procese kroženja vode v naravi (WMO, 1994; Singh, 1995; Beven, 2001). Hidrološki modeli so učinkoviti le, če so vhodni podatki o padavinah točni in zanesljivi. Izbira modela torej ni kritična za uspešno napoved, temveč je kritično pomanjkanje podatkov, ki so potrebni za kalibracijo modela in kasneje za operativno

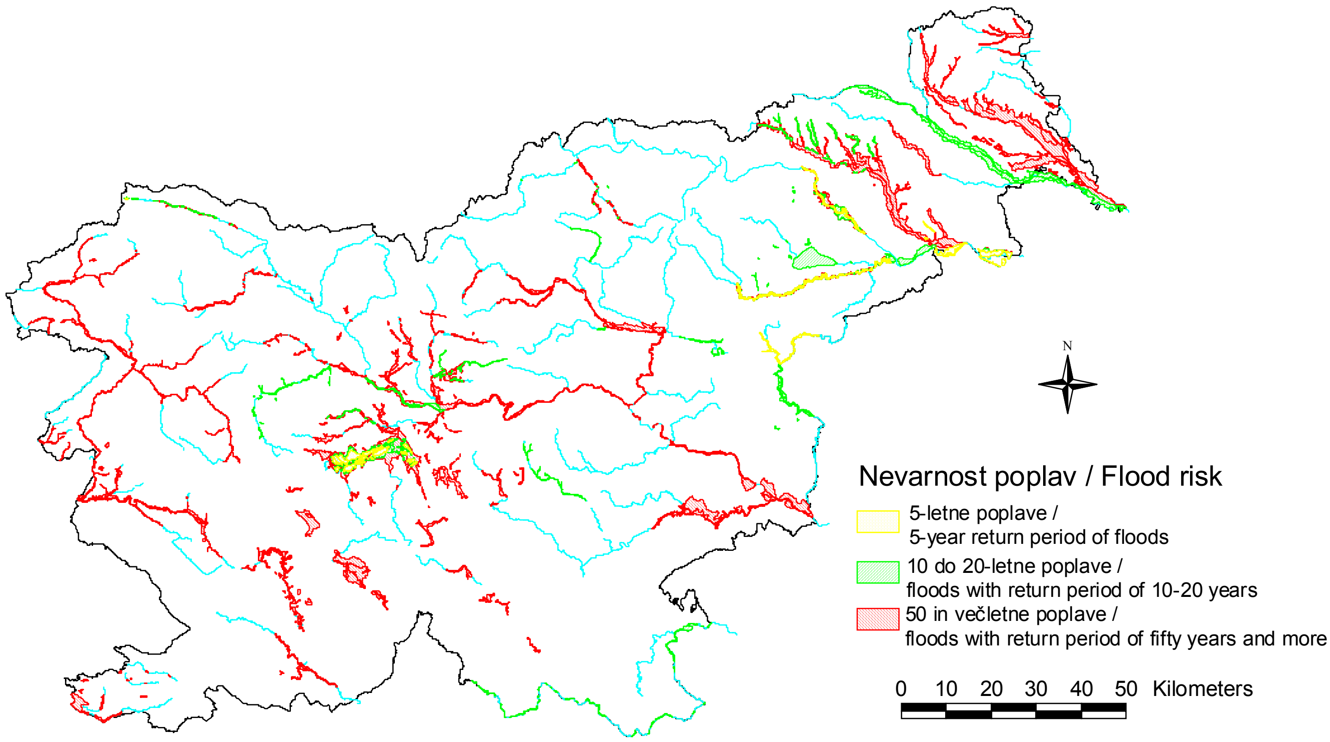
1. INTRODUCTION

Two main groups of meteorological events generating floods can be distinguished in Europe. A first refers to frontal precipitation which causes floods in large river basins and where the peak discharge of flood wave may last a number of days. The second group are flash floods, which are usually associated with isolated and localised intense rainfall events occurring in small and medium-sized mountainous basins. Peak discharges are maintained only for hours or even minutes. This kind of floods is characteristic for the most of Slovenian rivers.

In Slovenia floods are of normal, frequent or periodic occurrence (Fig. 1). The most flood threatened areas are low and plain regions in the north-eastern Slovenia, pre-Alpine valleys and central and eastern Slovenia. Floods with more than 50-year return period are considered catastrophic. Usually the floods with the same return period do not occur on the whole basin at the same time. The intensity of precipitation of only a few hours is critical for floods on small catchments which are especially frequent in summer, while the precipitation with long duration is characteristic for larger basins and occurs mostly in spring and autumn. The greatest floods in Slovenia usually occur in autumn when the cold front passes central Europe, or by passing of Mediterranean cyclone forms in the bay of Genova. The highest amount of precipitation arises by a combination of frontal and orographic precipitation and intensities of more than 70 mm/hour and 240 mm/day are quite common.

Hydrological models are effective tools for simulation of flood waves and flood prediction. Many models have been developed for flood forecasting, from simple empirical formulae or correlations between precipitation and runoff, to the complex mathematical models, representing all phases of the water balance of a river basin (WMO, 1994; Singh, 1995; Beven, 2001). Hydrological models are effective only if the input precipitation data are accurate and reliable. The selection of the model is therefore not critical to the success of the forecast, but critical is the lack of data needed for model calibration and later for uporabo (WMO, 1975; 1992; Askew, 1989; Kokkonen in Jakeman, 2001; Job *et al*., 2002). To se kaže še zlasti pri modeliranju hudourniških poplav, kjer je časovna resolucija modela ena ura ali manj in je pomanjkanje podatkov glavna ovira pri modeliranju in uporabnosti modelov.

operational use (WMO, 1975; 1992; Askew, 1989; Kokkonen and Jakeman, 2001; Job *et al*., 2002). This is shown especially by the modelling of flash floods where the time resolution is one hour or less and the lack of data is the main obstacle in modelling and applicability of models.



Slika 1. Poplavna območja v Sloveniji.
Figure1. Flood areas in Slovenia.

2. OCENA PLOSKOVNIH PADAVIN IZ TOČKOVNIH MERITEV

Za simulacijo odtoka in napovedovanje poplav na povodju Savinje smo uporabili konceptualni model HBV-96 (Bergström, 1995; Lindström et al., 1997; IHMS, 1999). Primarni vhodni podatki v model so točkovne padavine. Splošni problem mreže padavinskih postaj je njena neustreznost. Od prostorskega merila povodja, gostote padavinske mreže in variabilnosti padavin na povodju je odvisno, kako dobro s točkovnimi padavinami opišemo dejanske padavine na povodju. Za hidrološke aplikacije je zelo pomembno ne samo število

2. AREAL RAINFALL ESTIMATION FROM POINT PRECIPITATION MEASUREMENTS

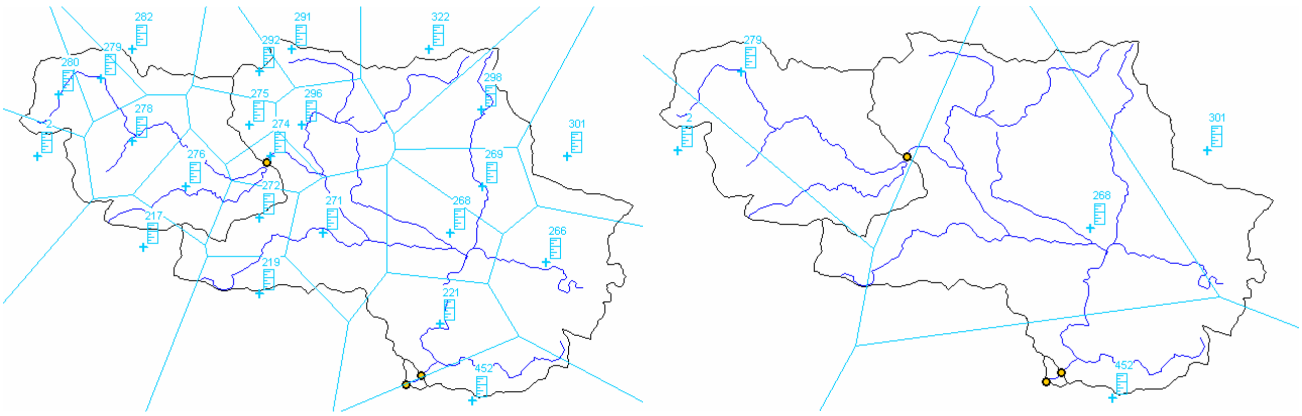
The conceptual HBV-96 model (Bergström, 1995; Lindström et al., 1997; IHMS, 1999) was applied on the Savinja catchment as a tool for runoff simulation and flood forecasting. The primary input data into the model are point precipitation data. The general problem of point precipitation network is its unsuitability. The estimation of real areal precipitation is dependent on the catchment scale, density of the precipitation network and variability of precipitation on the catchment.

padavinskih postaj na povodju, ampak tudi njihova razporeditev. S kompleksnostjo modelov padavine–odtok in modeliranjem pojavov za majhna povodja se povečuje potreba po točnosti informacij v prostoru in času.

Model HBV-96 računa ploskovne padavine z utežmi, ki jih določimo z metodo Thiessenovih poligonov. Ta metoda se v hidrološki praksi še vedno najpogosteje uporablja, čeprav ni primerna za območja z izrazito topografijo, še zlasti ne v primeru nezadostne mreže postaj na povodju (Bonacci, 1994; Ogden et al., 2000). Za model HBV-96 za povodje Savinje z urnim časovnim korakom (Kobold, 2007) smo imeli na razpolago samo pet ombrografskih postaj, kar predstavlja gostoto ene padavinske postaje z zveznim beleženjem intenzitete padavin na 370 km^2. Da bi ugotovili, kolikšno je lahko v modelu HBV-96 z urnim časovnim korakom odstopanje izračunanih ploskovnih padavin iz petih ombrografskih postaj na povodju glede na razpoložljive podatke s 23 padavinskih postaj (ena postaja na 80 km^2), smo izvedli analizo vpliva števila padavinskih postaj na oceno ploskovne količine padavin. Ploskovne dnevne padavine za obdobje 1998–2002 smo izračunali na dva načina: z upoštevanjem vseh postaj na povodju in z upoštevanjem samo ombrografskih postaj, ki so bile vključene v model z urnim časovnim korakom. V obeh primerih so bile uteži postaj izračunane po metodi Thiessenovih poligonov (slika 2).

Not only the number of precipitation stations but also their distribution is very important for hydrological applications. With the complexity of rainfall-runoff models and modelling of phenomena on small catchments there is a greater need of having accurate information in space and time.

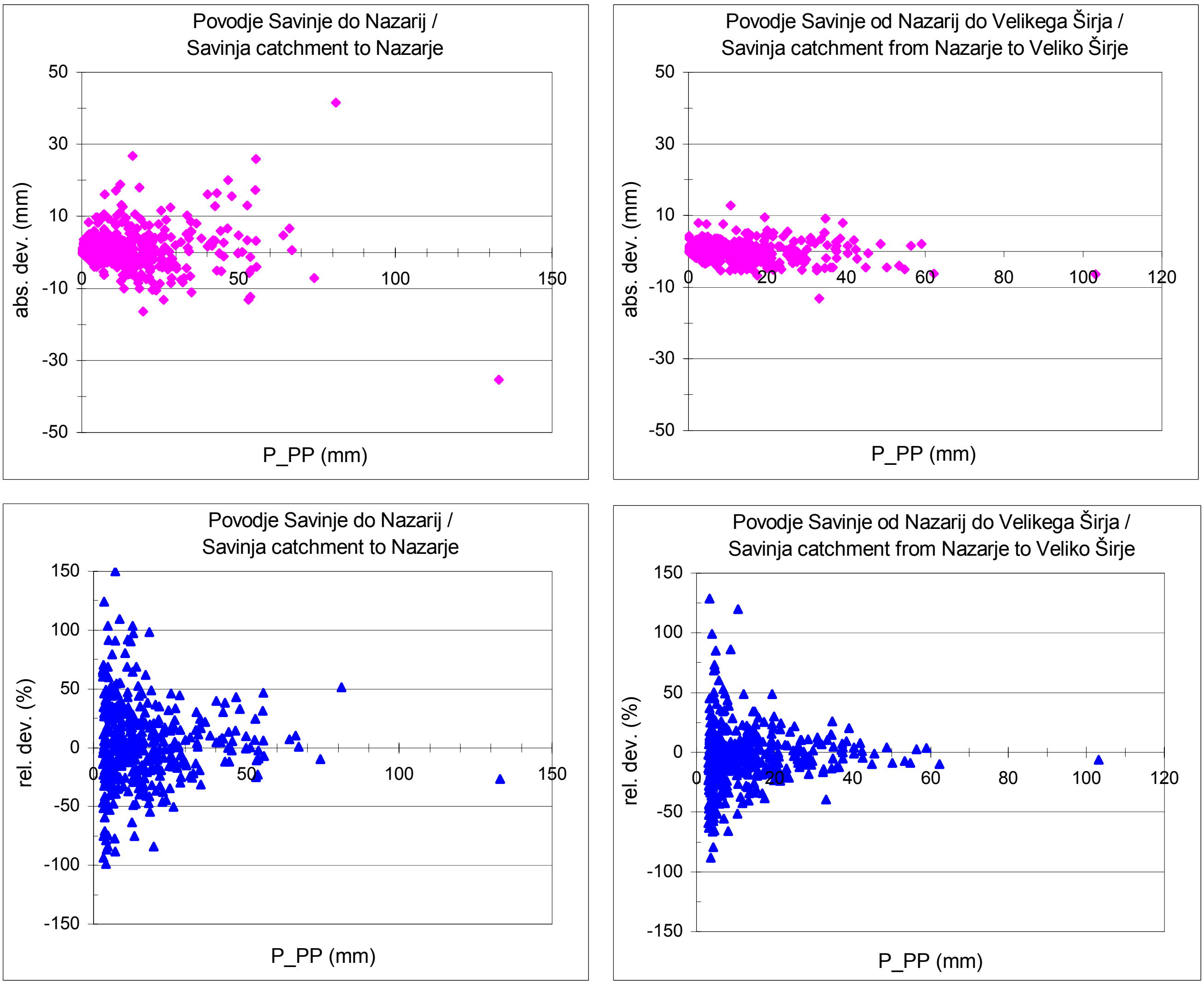
The HBV-96 model calculates the areal precipitation with weights which are determined by Thiessen polygons. This method is still the most frequent method used in hydrological practice although it is not suitable for areas with complex topography, especially in the case of deficiency of point precipitation measurements (Bonacci, 1994; Ogden et al., 2000). Only five recording raingauges were available for the HBV-96 model of the Savinja catchment with time step of one hour (Kobold, 2007), what representing the density of one recording raingauge station for an area of 370 km^2. To find out the deviation of the calculated areal precipitation with five recording raingauges in the hourly HBV-96 model by comparison with the 23 available precipitation stations on the catchment (one station per 80 km^2), the influence of the number of raingauges to give areal precipitation was investigated. The areal daily precipitation for the period of 1998–2002 was computed with two different sets of raingauges. In the first case all raingauges on the catchment were used in the estimation of areal daily precipitation and in the second one only the recording raingauges were included. In both cases, the weights were defined by Thiessen polygons (Fig. 2).



Slika 2. Padavinske postaje in izračun uteži po metodi Thiessenovih poligonov na povodju Savinje.
Figure 2. Raingauge networks and calculation of weights by Thiessen polygons on the Savinja catchment.

Analizo smo izvedli s predpostavko, da so ploskovne padavine, izračunane z upoštevanjem vseh postaj na povodju, točno ocenjene. Te padavine so bile merilo za analizo absolutnih in relativnih odstopanj ploskovnih padavin v drugem primeru, ko so bile ploskovne dnevne padavine ocenjene samo iz petih postaj na povodju (slika 3).

An assumption was made that areal precipitation calculated in the first case considering all raingauges in the catchment was accurate and absolute and relative deviations of areal precipitation were investigated for the second case taking into account only the five recording raingauges (Fig. 3).



Slika 3. Absolutno in relativno odstopanje ploskovnih dnevnih padavin, izračunanih iz petih ombrografskih postaj na povodju Savinje.

Figure 3. Absolute and relative deviations of areal daily precipitation taking into account five recording raingauges on the Savinja catchment.

Ploskovne dnevne padavine, izračunane iz petih ombrografskih postaj na povodju, se lahko precej razlikujejo od ploskovnih padavin, izračunanih iz vseh padavinskih postaj na povodju (slika 3). Absolutno

The areal precipitation estimated from five recording raingauges on the catchment can differ a lot from the areal precipitation estimated from all raingauges on the catchment (Fig. 3). The absolute deviation is between –20 mm and 20 mm for the upper odstopanje je med –20 mm in 20 mm za zgornji del povodja do Nazarij, lahko pa tudi večje, zlasti pri višjih padavinah. Za spodnje podpovodje je absolutno odstopanje v glavnem med –10 in 10 mm.

Relativna napaka pri oceni ploskovnih padavin pod 3 mm je lahko precej nad 100 % za obe podpovodji. Na sliki 3 je prikazano relativno odstopanje ploskovnih dnevnih padavin nad 3 mm. Relativna napaka se zmanjšuje z večanjem količine padavin na povodju. Povprečna relativna napaka znaša pri ploskovnih dnevnih padavin nad 40 mm, ki že povzročijo visoke vode na povodju Savinje, 15,3 % s standardno deviacijo 14,5 % za zgornje podpovodje in 6,4 % s standardno deviacijo 4,8 % za spodnje podpovodje.

Ocena ploskovnih padavin je za povodje Savinje z metodo uteži Thiessenovih poligonov iz obstoječe mreže ombrografskih postaj na povodju zelo nezanesljiva. Ploskovne padavine so lahko precej precenjene ali podcenjene, pri padavinah, ki povzročajo visoke vode in poplave, tudi do 50 %. Odstopanja so večja za zgornji gorati del povodja, kjer je variabilnost padavin večja. Netočna ocena padavin v modelu se odraža v netočni oceni odtoka s povodja. Modeli padavine–odtok so občutljivi na padavine kot osnovni vhodni podatek in ploskovna ocena padavin v največji meri vpliva na simulirani odtok (Kobold in Brilly, 2006; Kobold, 2007).

3. UPORABA RADARSKIH PADAVIN V MODELIRANJU POPLAV

Mreža padavinskih postaj lahko zgreši padavine, zlasti če so te lokalno omejene ali povezane z intenzivnimi konvekcijskimi nevihtami. Redka mreža postaj tudi ne omogoča pravilne ocene ploskovnih padavin ali določitve največjih padavin. Prednost uporabe radarja za merjenje padavin je pokritost velikega področja z veliko prostorsko in časovno ločljivostjo. Radarske podatke, ki v realnem času podajajo podroben časovni in prostorski opis padavin, bi lahko uporabili kot vhod v modele padavine–odtok. Vendar so

sub-catchment to Nazarje, but it can be much greater, especially with higher amount of precipitation. For lower sub-catchment the absolute deviation is mainly between –10 and 10 mm.

The relative error can exceed 100% by estimation of areal precipitation below 3 mm for both sub-catchments. Figure 3 shows only the relative deviation of areal precipitation above 3 mm. The relative error decreases with the amount of precipitation rising. High waters and floods on the Savinja catchment usually occur with precipitation above 40 mm over the catchment area and, considering precipitation above this value, the average relative error is 15.3% for the upper sub-catchment with a standard deviation of 14.5% and 6.4% for the lower sub-catchment with a standard deviation of 4.8%.

The estimation of areal precipitation for the Savinja catchment is very uncertain taking into account only the recording raingauges on the Savinja catchment and the method of Thiessen polygons. The areal precipitation can be rather overestimated or underestimated, the deviation being as high as 50% with precipitation causing high water and floods. The deviations are greater for the upper mountainous part where the variability of precipitation is larger. An incorrect estimation of precipitation further leads to wrong estimation of simulated discharges. Rainfall-runoff models are sensitive to precipitation input and areal estimation of precipitation influences the runoff simulation most considerably (Kobold and Brilly, 2006; Kobold, 2007).

3. THE USE OF RADAR PRECIPITATION IN FLOOD MODELLING

A raingauge network can miss significant precipitation, especially in the case of local precipitation or precipitation associated with intensive convective storms. Moreover, the rare precipitation network does not give the accurate areal estimation of precipitation or determination of the highest precipitation. The advantage of using radar for precipitation measurement is the coverage: the radar covers a large area with high spatial and temporal resolution. Radar data giving real-time areal rainfall totals over catchments or subradarski podatki podvrženi velikim sistematičnim napakam (Divjak, 1995; Borga et al., 2000). Glavni vzrok za napake je vertikalna nehomogenost padavinskih polj, povezana z nezmožnostjo radarja, da bi meril tik nad tlemi zaradi širine snopa, ukrivljenosti zemeljske površine in hribovitosti. Z uporabo primernih korekcijskih metod je možno izboljšati točnost radarskih ocen padavin.

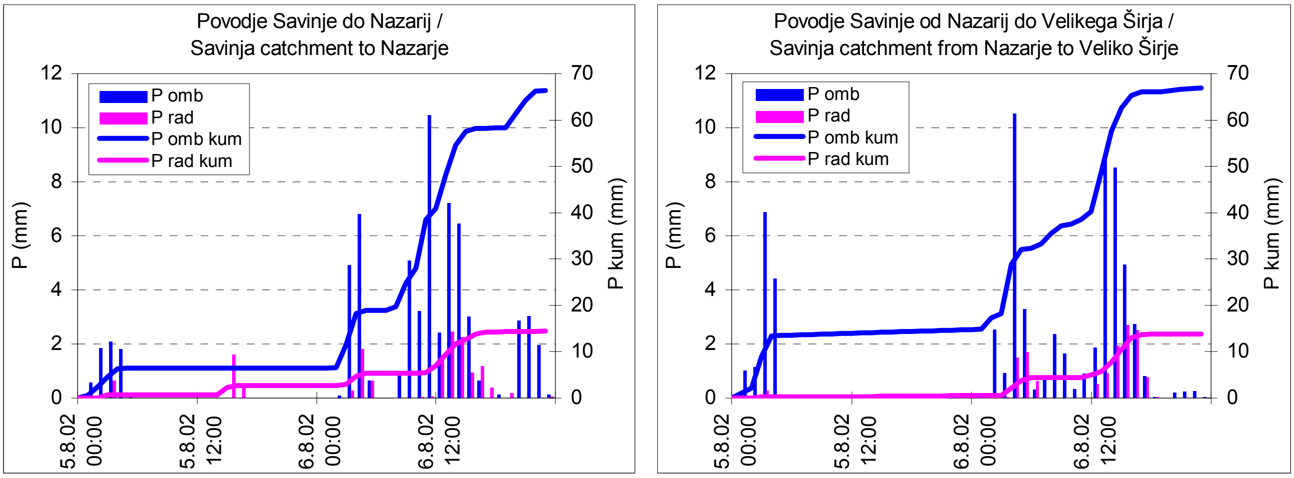
Da bi ugotovili uporabnost trenutno razpoložljivih radarskih padavin vremenskega radarja na Lisci za potrebe hidrološkega modeliranja, smo izvedli analizo dveh padavinskih dogodkov iz avgusta 2002. Za povodje Savinje smo primerjali ploskovne urne radarske padavine s padavinami, ki smo jih izračunali iz padavinskih postaj na povodju (sliki 4 in 5). Primerjava ploskovnih padavin pokaže, da so radarske padavine podcenjene. Za dogodek 1 so skupne radarske padavine podcenjene za faktor 4,6 za podpovodje do Nazarij in za faktor 4,8 za podpovodje od Nazarij do Velikega Širja, za dogodek 2 pa za faktor 5,8 za podpovodje do Nazarij in za faktor 2,6 za podpovodje od Nazarij do Velikega Širja.

Za hidrološke aplikacije je treba radarske padavine korigirati s talnimi padavinami. Glede na to, da so radarske padavine obeh dogodkov podcenjene, smo jih za preizkus simulacije z modelom HBV-96 pomnožili s faktorjem, za katerega so bile podcenjene (dogodek 1 s faktorjem 4,6 za zgornje in 4,8 za spodnje podpovodje in dogodek 2 s faktorjem 5,8 za zgornje in 2,6 za spodnje podpovodje). Simulacija odtoka z modelom HBV-96 s tako poenostavljeno korekcijo radarskih padavin da precej dobre rezultate (slika 6). Simulacijo smo izvedli tudi z nekorigiranimi radarskimi podatki, ki komaj nakažejo povečanje odtoka.

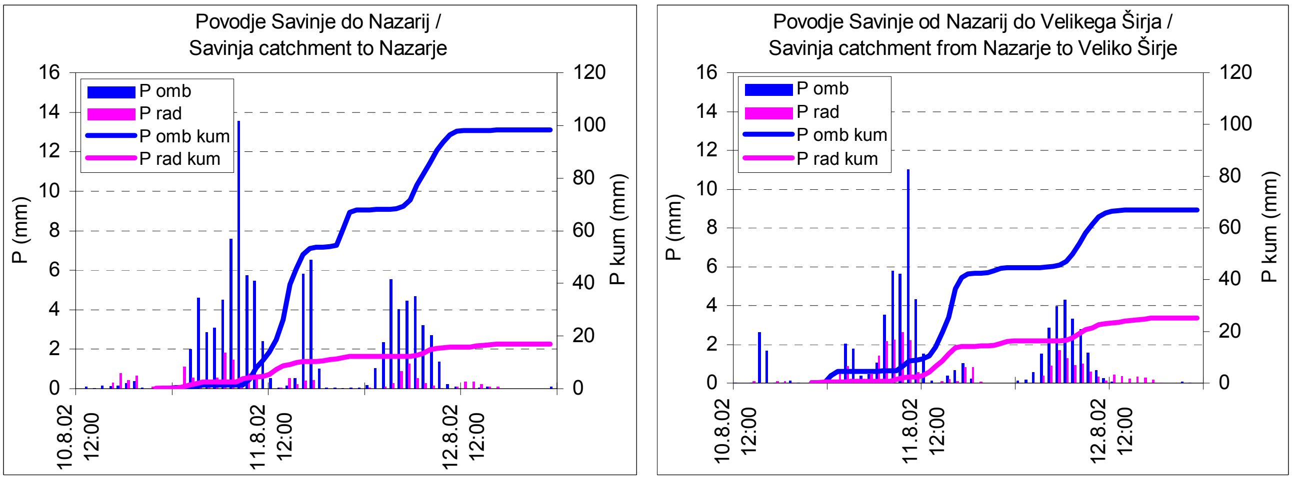
catchments could be used successfully as input into rainfall-runoff models. However, radar measurements of precipitation can have large systematic errors (Divjak, 1995; Borga et al., 2000). The main cause lies in the vertical inhomogeneity of precipitation fields combined with the inability to perform radar measurements close to the ground due to the radar beam geometry, earth curvature and orography. An adjustment method should be used to increase the accuracy of radar rainfall estimates.

To find out the applicability of present radar precipitation from the weather radar located on Mount Lisca in hydrological modelling, two high water events of August 2002 on the Savinja catchment were analyzed. Hourly areal rainfall intensities were calculated for both events and compared with areal precipitation calculated from the raingauges on the catchment (Figures 4 and 5). The comparison of areal precipitation shows that the radar precipitation is underestimated. The factor of underestimation is 4.6 for the sub-catchment to Nazarje and 4.8 for the sub-catchment from Nazarje to Veliko Širje for the first event, and 5.8 for the sub-catchment to Nazarje and 2.6 for the sub-catchment from Nazarje to Veliko Širje for the second event.

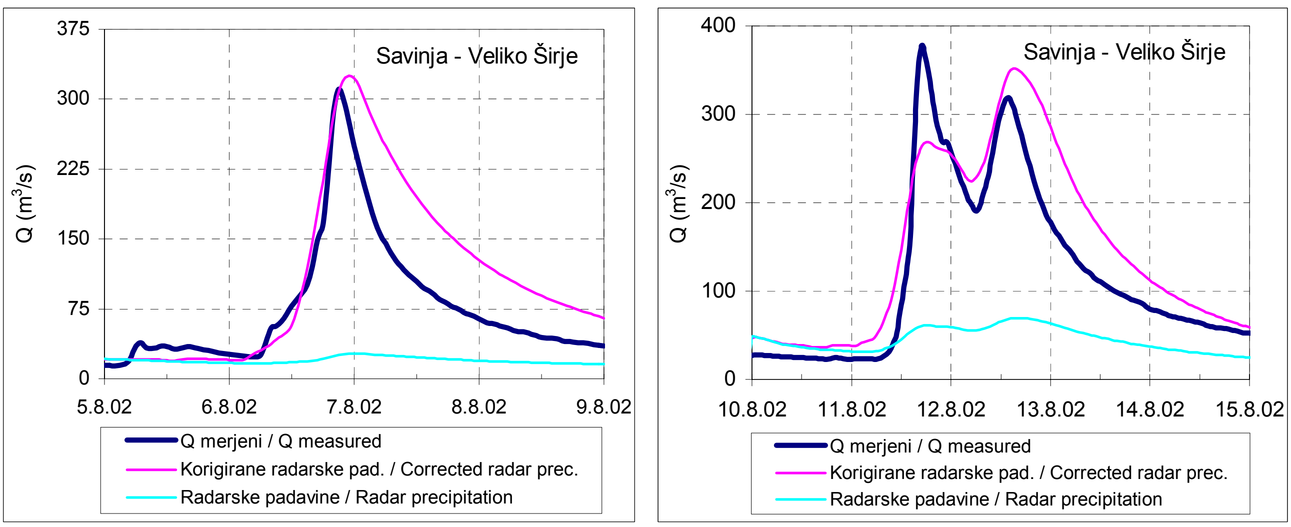
The radar precipitation should be corrected with ground rainfall measurements for using it in hydrological applications. Since in both events radar precipitation was underestimated , the precipitation was corrected with the factors of underestimation (event 1 with factors 4.6 for the upper and 4.8 for the lower sub-catchment, and event 2 with factors 5.8 for the upper and 2.6 for the lower sub-catchment) for the test simulation with the HBV-96 model. The simulation of runoff with the HBV-96 model gives pretty good results with such a simplified correction (Fig. 6). The uncorrected radar data scarcely show rising runoff.



Slika 4. Urne in kumulativne ploskovne padavine za 5. in 6. avgust 2002.
Figure 4. Hourly and cumulative areal precipitation for 5 and 6 August 2002.



Slika 5. Urne in kumulativne ploskovne padavine za 10. do 12. avgust 2002.
Figure 5. Hourly and cumulative areal precipitation for 10 and 12 August 2002.



Slika 6. Simulacija odtoka z radarskimi padavinami.
Figure 6. Simulation of runoff with radar precipitation.

4. NEZANESLJIVOST PADAVINSKE NAPOVEDI

Model HBV-96 z urnim časovnim korakom je bil testiran za kratkoročne operativne napovedi na povodju Savinje med februarjem in avgustom 2004. Vhodni podatki v model so bile merjene padavine in temperature zraka iz padavinskih postaj na povodju Savinje, ki omogočajo prenos podatkov v realnem času za čas pred napovedjo, in napovedane padavine in temperature zraka za obdobje napovedi. Uporabljene so bile napovedi modela ALADIN/SI, ki pokriva območje Slovenije (Vrhovec et al., 1998; Cedilnik, 2005). Resolucija modela ALADIN/SI je okrog 9,5 km, napoved pa je na voljo do 48 ur vnaprej. Model je operativen z zagonom dvakrat na dan.

Na sliki 7 so prikazani rezultati simulacij za vodomerni postaji Nazarje in Veliko Širje za obdobje od februarja do avgusta 2004. Primerjava simuliranih in merjenih pretokov je ločena na napovedi za prvi dan in napovedi za drugi dan. Izpeljana analiza kaže, da so napovedi boljše za prvi dan napovedi. Rezultati so boljši za Veliko Širje, ki predstavlja iztok s povodja Savinje. Korelacijski koeficient *r* je 0,93 za prvi dan napovedi in 0,82 za drugi dan napovedi. Zelo slaba korelacija je za zgornji del povodja do Nazarij. Korelacijski koeficient *r* je 0,73 za prvi dan napovedi in pod 0,50 za drugi dan napovedi.

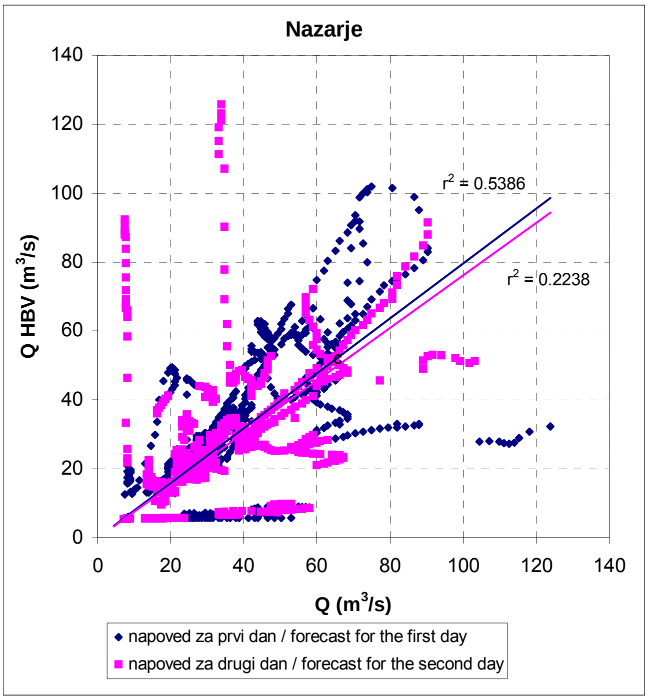
Na odstopanje simuliranega odtoka vpliva predvsem nezanesljivost padavinske napovedi modela ALADIN/SI. Da bi ugotovili, v kolikšni meri so na rezultate vplivale netočne padavinske napovedi, smo primerjali napovedane ploskovne padavine s padavinami, izračunanimi iz padavinskih postaj na povodju. Primerjava urnih intenzitet je narejena za prvi dan napovedi (1–24 ur vnaprej) in za drugi dan napovedi (25–48 ur vnaprej). Raztros točk je velik za obe podpovodji, kaže pa nekoliko boljšo korelacijo za spodnji del povodja od Nazarij do Velikega Širja, vendar je v vseh primerih korelacijski koeficient precej pod 0,5 (slika 8).

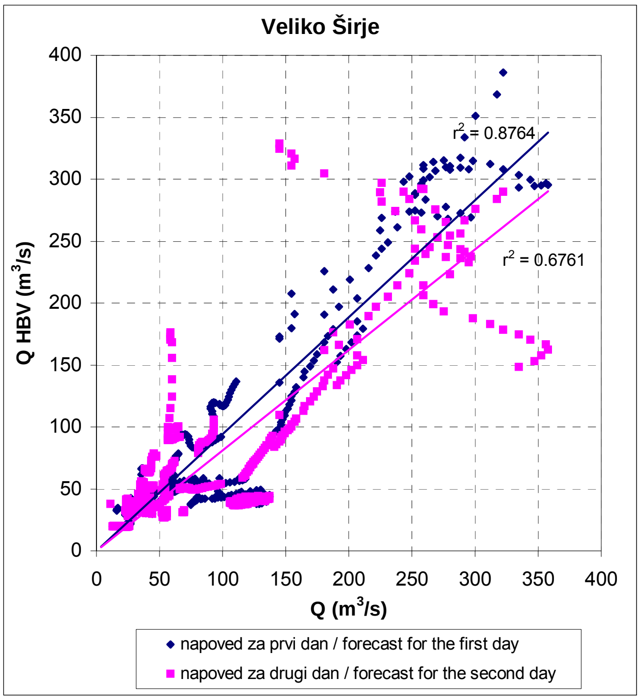
4. THE UNCERTAINTY OF PRECIPITATION FORECAST

The hourly HBV-96 model for the Savinja catchment was tested for operational short-term forecast in 2004, from February to August. In that case the model was run using on-line measured input data of precipitation and temperature for a period before the forecast and predicted precipitation and temperature for the period of forecast. The forecasts of the mesoscale ALADIN/SI model covering Slovenia were used in operational runs (Vrhovec et al., 1998; Cedilnik, 2005). The forecasts of meteorological parameters of the ALADIN/SI model are made in spatial resolution of about 9.5 km and are available up to 48 hours ahead. The model is operational and run twice a day.

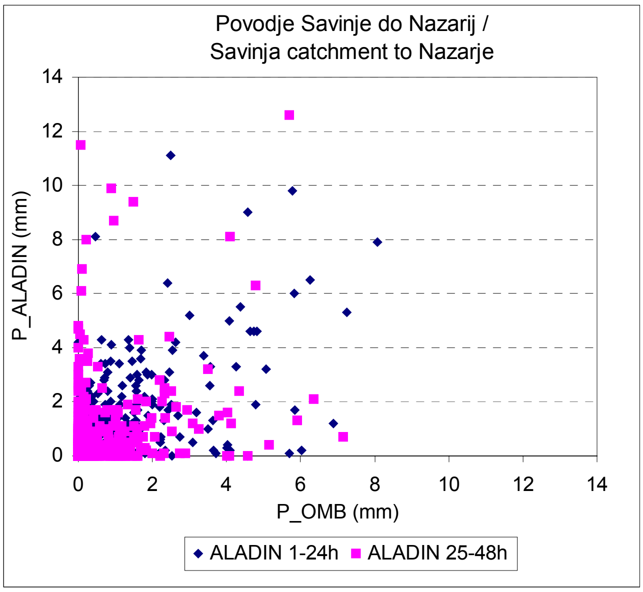
The results of simulations for the period from February to August 2004 are presented in Fig. 7 for water stations Nazarje and Veliko Širje. The comparison of simulated and observed discharges is separated on two parts: forecasts for the first day and forecasts for the second day. The results are better for Veliko Širje which represents the outlet of the catchment. Correlation coefficient *r* is 0.93 for the forecasts of the first day and 0.82 for the forecasts of the second day. A very poor correlation is observed for the upper part of the catchment to Nazarje. Correlation coefficient *r* is 0.73 for the forecasts of the first day and below 0.50 for the forecasts of the second day.

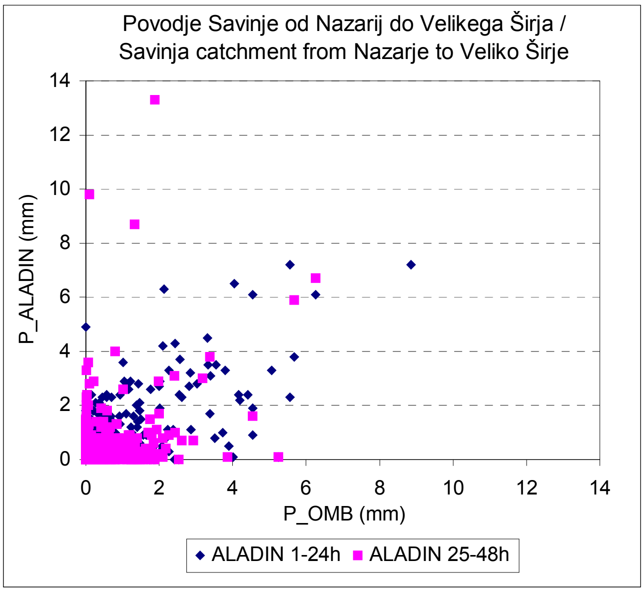
The deviations of simulated runoff are mainly the result of uncertainty of ALADIN/SI precipitation forecast. The further research referred to the accuracy of precipitation forecast. The comparison of areal predicted precipitation and precipitation calculated from raingauges was made for the Savinja catchment. The comparison of hourly intensities is made for the first day (1-24 hours ahead) and for the second day (25-48 hours ahead) of forecasts. The points are scattered for both sub-catchments. The correlation coefficient is below 0.5 in all cases although the correlation is a little higher for the lower sub-catchment from Nazarje to Veliko Širje (Fig. 8).





Slika 7. Primerjava simuliranih in merjenih pretokov za vodomerni postaji Nazarje in Veliko Širje na Savinji (obdobje februar–avgust 2004).
Figure 7. The comparison of simulated and observed discharges for water stations Nazarje and Veliko Širje on the Savinja river (period from February to August 2004).

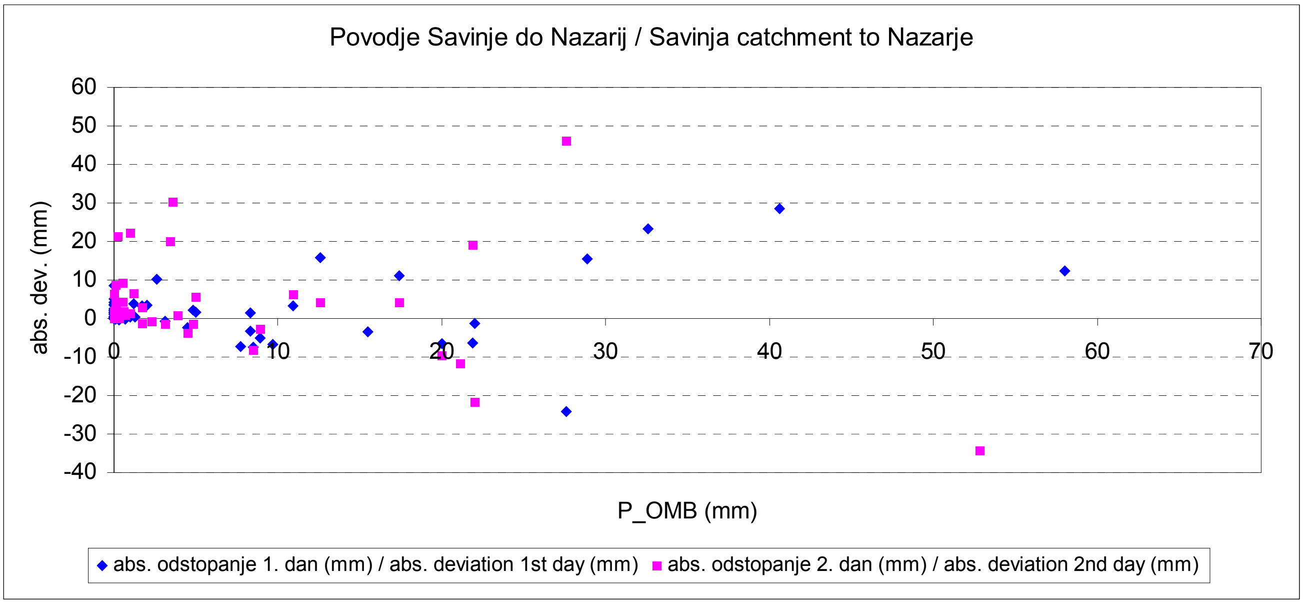


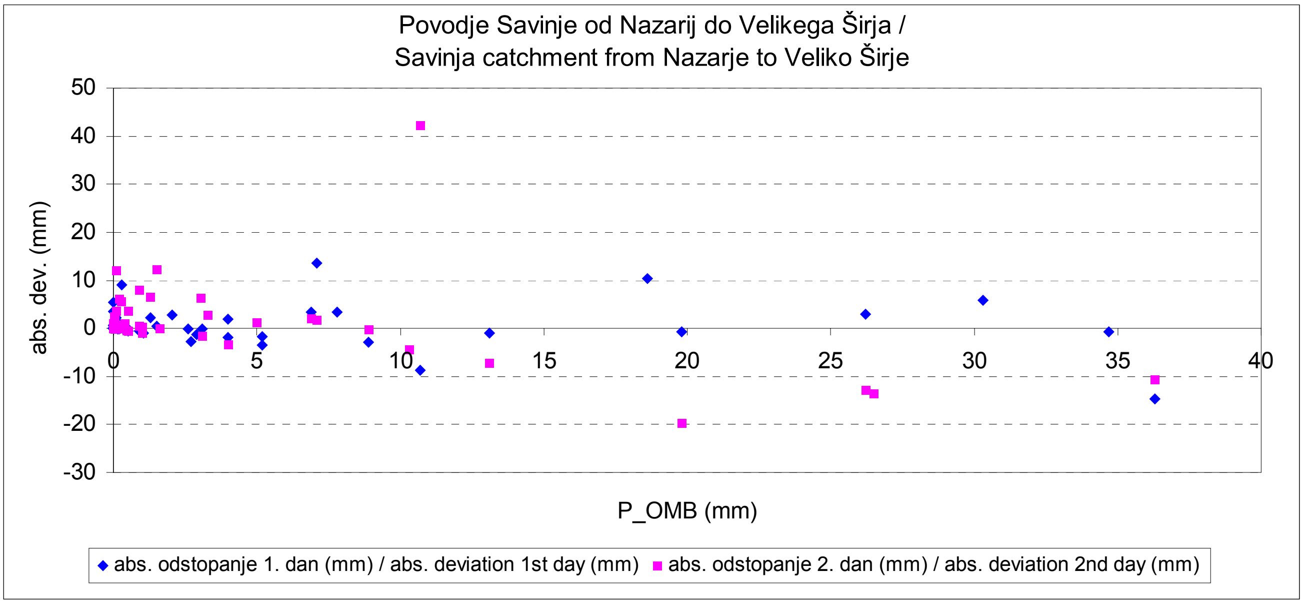


Slika 8. Primerjava urnih intenzitet padavin v testnem obdobju za prvi dan napovedi in za drugi dan napovedi.
Figure 8. The comparison of predicted and measured hourly precipitation for the first and for the second day of forecast in the test period.

V nadaljevanju smo izvedli primerjavo 24-urnih intenzitet, ki da boljše ujemanje od predhodne analize z urnimi intenzitetami. Za prvi dan napovedi je korelacijski koeficient r večji od 0,8 za obe podpovodji, za drugi dan napovedi pa je korelacija slabša, r je okrog 0.5 za drugi dan napovedi. Model ALADIN/SI pravilno predvidi padavinsko situacijo, količina padavin pa je precenjena ali podcenjena (slika 9).

Further, the comparison of daily amount of precipitation was made, which gave better agreement in comparison with the previous analysis of hourly intensities. Correlation coefficient r is above 0.8 for the first day of forecast for both sub-catchments. The correlation is worse for the second day of forecast, r is about 0,5. The ALADIN/SI model predicts the rainfall event well, but the amount of precipitation is overestimated or underestimated (Fig. 9).





Slika 9. Absolutno odstopanje napovedanih dnevnih padavin na povodju Savinje.
Figure 9. Absolute deviation of the predicted daily precipitation on the Savinja catchment.

Odstopanje je večje za podpovodje do Nazarij, za katero je povprečno relativno odstopanje napovedanih padavin od merjenih pri vrednostih nad 3 mm 51 %, standardna deviacija pa 30 % za prvi dan napovedi, za drugi dan napovedi pa se povprečno relativno odstopanje napovedanih padavin poveča na 70 % s standardno deviacijo 43 %. Za podpovodje Savinje od Nazarij do Velikega Širja je povprečno relativno odstopanje napovedanih padavin od merjenih pri vrednostih nad 3 mm 32 % za prvi dan napovedi s standardno deviacijo 25 %, za drugi dan napovedi pa 48 % s standardno deviacijo 28 %. Iz slike 9 tudi razberemo, da so napovedane padavine, ki povzročijo visoke vode, za prvi dan napovedi precenjene ali podcenjene, medtem ko so za drugi dan napovedi v glavnem podcenjene.

4.1 VISOKE VODE IN POPLAVE V AVGUSTU 2005

Zadnje visoke vode in poplave v Sloveniji so bile v avgustu 2005, ki so povzročile tudi precejšnjo gmotno škodo. Avgust 2005 je bil moker in padavine so si sledile z manjšimi presledki že od začetka meseca, zaradi česar so bili pretoki večji kot običajno. Avgustovska količina padavin je bila skoraj povsod po državi večja od avgustovskega povprečja obdobja 1971–2000. Najhuje je bilo med 20. in 23. avgustom na območju jugovzhodne Slovenije in Posavja, ko je samo v dveh dneh, 21. in 22. avgusta, padlo nad 100 mm padavin (sliki 10 in 11). Avgustovska količina padavin je na tem območju za dva- do trikrat presegla avgustovsko povprečje obdobja 1971–2000.

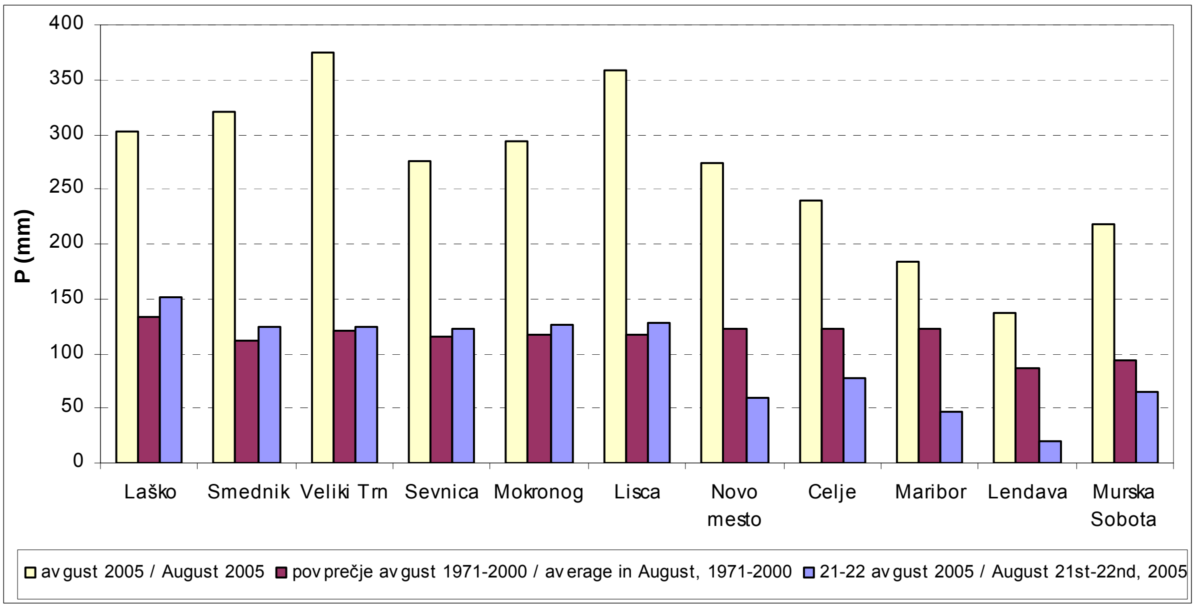
Zaradi obilnih padavin in lokalno močnih nalivov pa tudi dolgotrajnih padavin so hitro narasli in poplavljali hudourniki. Utrgalo se je tudi veliko število zemeljskih plazov. Pretoki manjših rek so presegli maksimalne obdobne pretoke. Povratne dobe velikih pretokov so na najbolj prizadetem območju v vzhodni Sloveniji presegle 50-letno povratno dobo. Od večjih rek je močneje narasla le Krka v obsegu vsakoletnih poplav, zaradi obilnega deževja v Avstriji pa Mura, ki je presegla dotlej izmerjen največji pretok v opazovalnem obdobju.

The deviation is larger for the sub-catchment to Nazarje. The average relative error is 51% for the first day of forecast with standard deviation of 30% taking into account the precipitation above 3 mm. For the second day of forecast the deviation becomes greater; the average relative error is 70% with a standard deviation of 43%. For the sub-catchment from Nazarje to Veliko Širje, the deviation is 32% with a standard deviation of 25% for the first day of forecast and 48% with a standard deviation of 28% for the second day of forecast taking into account the precipitation above 3 mm. It is clearly seen from Fig. 9 that the predicted precipitation causing high waters and floods is overestimated or underestimated for the first day of forecast, while it is, in general, underestimated for the second day of forecast.

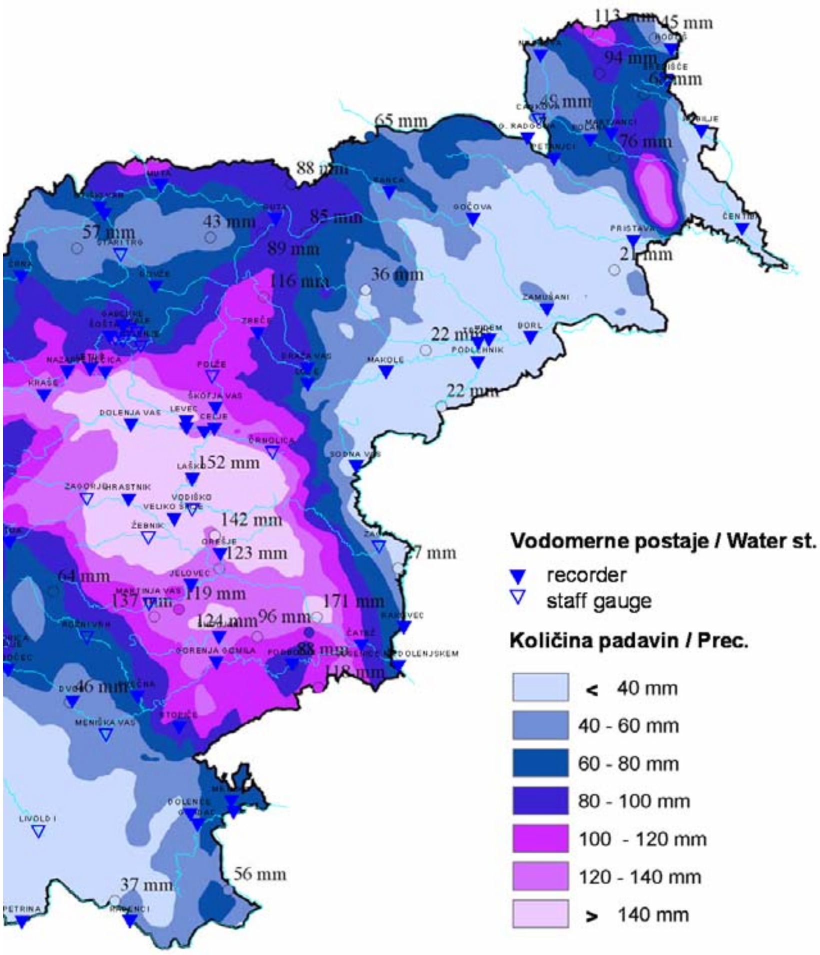
4.1 HIGH WATERS AND FLOODS IN AUGUST 2005

The last high waters and floods in Slovenia happened in August 2005, causing great economic damage. August 2005 was wet with precipitation succeeding with short intervals from the start of the month. The discharges were higher as usual. The amount of precipitation in August 2005 was above the average August values of period 1971–2000 almost in the whole country. The situation was the worst during August 20–23, in the region of southeast Slovenia and the Posavje region where more than 100 mm rain fell in two days, that is, on 21 and 22 August (Figures 10 and 11). The August amount of precipitation in the region was two to three times greater than the mean August precipitation of the 1971–2000 period.

Heavy rains with showers and long duration of rainfall caused flash floods and numerous land slides. The funoff from small catchments exceeded the periodic maximum discharges. The return period of peak discharges exceeded 50 years in the most threatened areas in the eastern Slovenia. From the major Slovenian rivers only the Krka River was in the extent of yearly floods, and the Mura River due to the precipitation in Austria. The Mura River exceeded the periodic maximum discharge until that time.



Slika 10. Avgustovska količina padavin v vzhodni in severovzhodni Sloveniji.
Figure 10. August amount of precipitation in eastern and northeastern Slovenia.



Slika 11. Vsote 2-dnevnih padavin od 8. ure 20. avgusta 2005 do 8. ure 22. avgusta 2005 (vir: Dolinar *et al.*, 2005) in merilna mesta hidrološkega monitoringa na površinskih vodah v vzhodni Sloveniji.
Figure 11. Cumulative 2-day precipitation between 20 and 22 August 2005 (source: Dolinar et al., 2005) and surface water station network in Eastern Slovenia.

Odtok s povodij z najvišjimi padavinami 21. in 22. avgusta, Radulje, Sevnične in Mirne, je presegel maksimalne obdobne pretoke (slika 12).

Maksimalni izmerjeni pretok Radulje v Škocjanu (prispevna površina povodja je 107,96 km^2) je bil 21. avgusta 2005 in je znašal 50,4 m^3/s, kar je več kot 100-letna povratna doba.

Sevnična je poplavljala v Sevnici ter povzročila veliko škode, tudi na vodomerni postaji v Orešju, kjer je aparat deroča voda odtrgala in odnesla in tako za to reko ni podatkov. Prispevno območje Sevnične do Orešja znaša le 39,7 km^2. Na objektih vzdolž vodotoka (slika 13) je vidna sled visoke Sevnične.

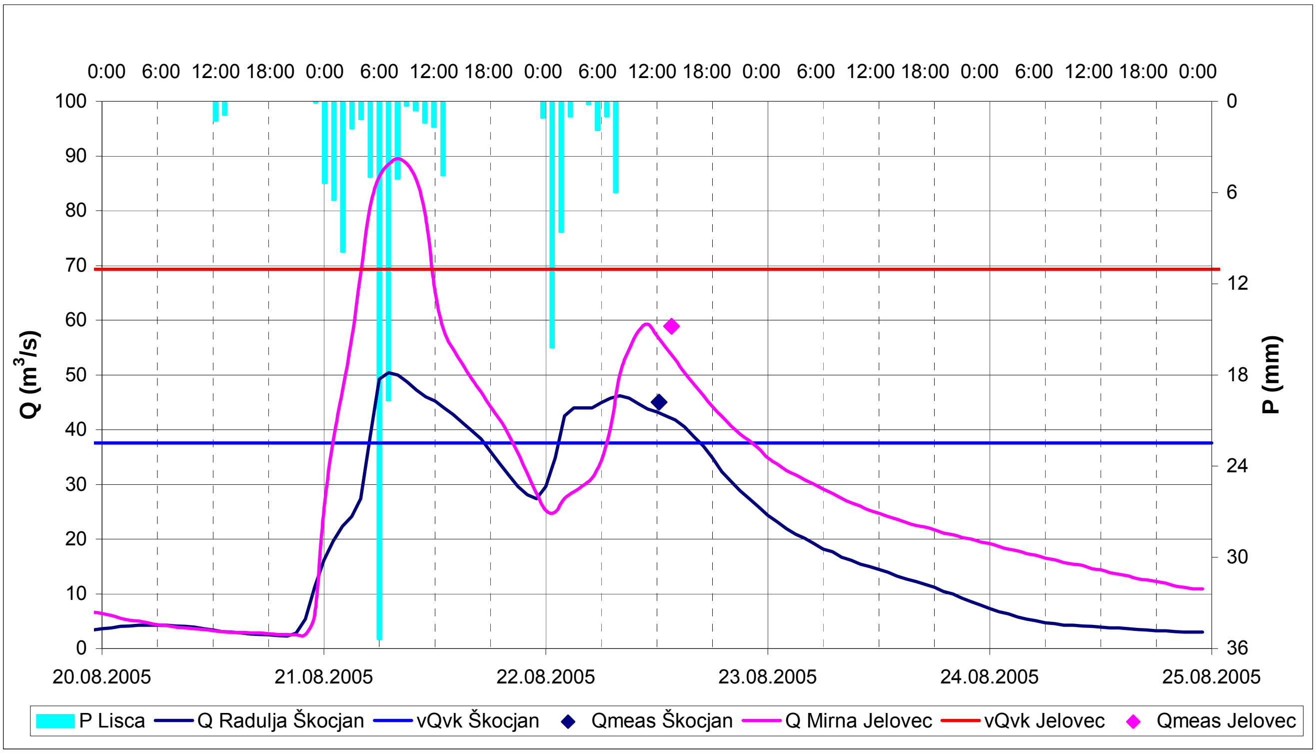
Mirna v Jelovcu s prispevno površino 270 km^2 je dosegla maksimalni pretok 89 m^3/s dne 21. avgusta, kar je 25-letna povratna doba velikih pretokov.

The runoff from the catchments with the highest amount of precipitation in August 21 and 22, i.e. the Radulja, Sevnična and Mirna catchments, exceeded the periodic maximum discharges (Fig. 12).

The maximum measured discharge of the Radulja in Škocjan (drainage area of 107.96 km^2) was 50.4 m^3/s in August 21, 2005, which is more than 100-year return period.

The Sevnična flooded in the town of Sevnica and caused considerable damage, too. This was also the case on water station in Orešje where the rapid stream swept away the equipment and therefore no hydrological data for that river remained. The drainage area of the Sevnična to Orešje is only 39.7 km^2. On the buildings along the stream, there is still a visible trace of the high water (Figure 13).

The Mirna River in Jelovec with a drainage area of 270 km^2 reached the peak discharge of 89 m^3/s in August 21, which is a 25-year return period of the maximum floods.



Slika 12. Hidrogram Radulje v Škocjanu in Mirne v Jelovcu od 20. do 25. 08. 2005, obdobni veliki pretoki (vQvk), hidrometrične meritve (Qmeas) ter urna intenziteta padavin z Lisce.
Figure 12. Hydrographs of the Radulja in Škocjan and the Mirna in Jelovec between 20 and 25 August 2005, periodical maximum discharges (vQvk), hydrometric measurements (Qmeas) and hourly rainfall intensities from Lisca.

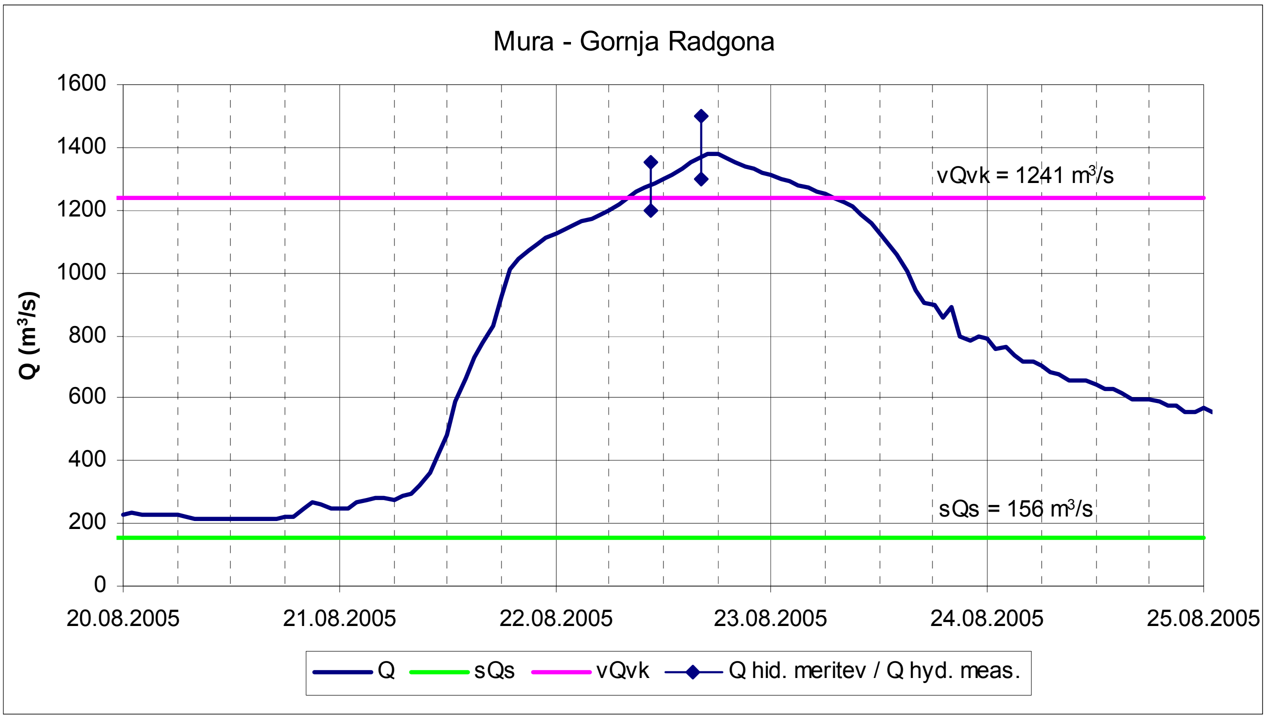
Slika 13. Na gradbenem objektu vidna sled najvišje vode Sevnične v Sevnici dne 21. avgusta 2005 ob 12:38 (foto: Jože Uhan).
Figure 13. The trace of the highest water on a building in Sevnica on August 21, 2005, at 12:38 (photo: Jože Uhan).

Na rekah, ki so poplavljale, je bila dejavnost hidrometrije v času visokih voda usmerjena na meritve pretoka visokih voda z akustičnim Dopplerjevim merilnikom ADCP (Kobold et al., 2005). Na območju Posavja so poplavljali tudi manjši potoki in hudourniki ter povzročili ogromno škodo, vendar se na njih hidrološke meritve ne izvajajo.

Mura je zaradi obilnega deževja v Avstriji preplavila poplavne površine znotraj visokovodnih nasipov. V Gornji Radgoni je bil 22. avgusta izmerjen dotlej največji pretok v opazovalnem obdobju, ki je od leta 1946 naprej, in sicer okrog 1380 m^3/s, kar je skoraj 100-letna povratna doba. Maksimalni pretok je bil za 140 m^3/s večji v primerjavi z dotlej največjim izmerjenim pretokom iz leta 1954 (slika 14). V Gornji Radgoni sta bila 22. avgusta izvedena dva niza hidrometričnih meritev z akustičnim Dopplerjevim merilnikom. Zaradi visoke in deroče Mure je bila izvedba meritev izredno težavna.

Some hydrometric measurements were done with the Acoustic Doppler Current Profiler on the rivers which were flooding (Kobold et al., 2005). Smaller streams and torrents also flooded in the Posavje region and caused severe damage, however, these are not covered with measurements and hydrological stations.

The Mura River flooded the inundation areas along the river because of heavy rains in Austria. On 22 August the highest discharge in Gornja Radgona since 1946 was measured. The maximal discharge was about 1380 m^3/s, what is nearly 100-year event. The peak discharge was 140 m^3/s larger compared with flood peak registered in the year 1954 (Fig. 14). Two sets of hydrometric measurements were done with Acoustic Doppler Current Profiler in Gornja Radgona during the flood in August 22. The realization of hydrometric measurements was very difficult because of high and rapid flow.



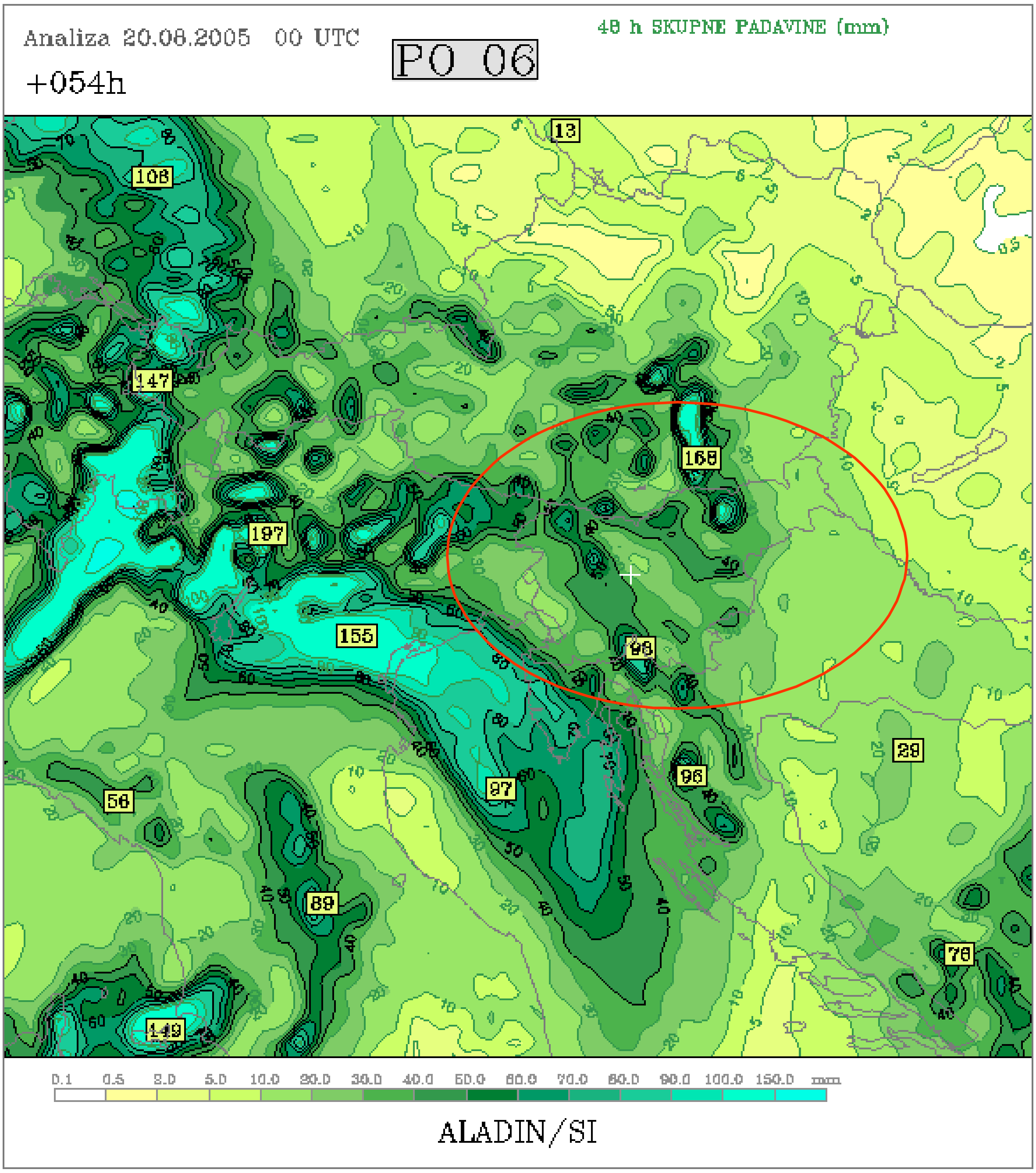
Slika 14. Hidrogram Mure v Gornji Radgoni od 20. do 25.08.2005, obdobni srednji pretok (sQs) in obdobni veliki pretok (vQvk) ter območje hidrometričnih meritev.
Figure 14. Hydrograph of the Mura River in Gornja Radgona between 20 and 25 August 2005, mean periodic discharge (sQs) and maximal periodic discharge (vQvk), and the range of hydrometric measurements.

Za slovenske reke so, z izjemo Mure in Drave, značilne hudourniške poplave. Hudourniške poplave nastanejo zaradi intenzivnih, običajno lokalnih padavin, ki jih je skoraj nemogoče napovedati. Napovedi meteoroloških modelov so osnova za hidrološke napovedi. Prostorska ločljivost globalnih modelov kot je ECMWF je premajhna, da bi modeli omogočali napoved lokalnih in intenzivnih padavin na območju Slovenije (Kobold in Sušelj, 2005). Lokalni meteorološki model ALADIN/SI ima večjo ločljivost. Nekateri avtorji (Brilly et al., 2000; Kobold, 2007), ki so se v svojih študijah ukvarjali z uporabnostjo napovedi modela ALADIN/SI za hidrološke napovedi, so prišli do precej dobre korelacije napovedanih dnevnih padavin in padavin s padavinskih postaj. Korelacija je slabša za gorata in hribovita območja.

Za hudourniške poplave, ki so 20. avgusta 2005 prizadele vzhodni del Slovenije in Posavje, je model ALADIN/SI precej podcenil padavine (slika 15) in tako tudi ni bilo mogoče predvideti hudourniških poplav na območju Posavja.

Except for the Mura and Drava rivers the flash floods are characteristic for the Slovenian rivers. Flash floods are result of local and usually intense precipitation, which is almost unable to predict. The forecasts of meteorological models are the basis for flood prediction. The space resolution of global models like ECMWF is not high enough to predict local and intense precipitation on the territory of Slovenia (Kobold and Sušelj, 2005). The limited area meteorological ALADIN/SI model has a higher resolution. Some authors (Brilly et al., 2000; Kobold, 2007), who studied the applicability of forecasts of the ALADIN/SI model for hydrological forecasts, have obtained a rather good correlation of predicted daily precipitation with the data from raingauges. The correlation is less satisfactory for mountainous and hilly areas.

For flash floods which affected the eastern part of Slovenia and the Posavje region on 20 August 2005, the predicted precipitation of the ALADIN/SI model was underestimated (Fig. 15) and it was impossible to predict flash floods in the Posavje region.



Slika 15. Skupne dvodnevne padavine modela *ALADIN/SI* z začetkom 20 avgusta 2005.
Figure 15. Two-day cumulative ALADIN/SI predicted precipitation starting 20 August 2005.

5. ZAKLJUČEK

Za hidrološko modeliranje in izdelavo operativnih hidroloških napovedi in količinskih ocen pretoka so pomembni razpoložljivi podatki, poleg meteoroloških napovedi tudi meteorološki in hidrološki podatki v realnem času. Napovedovanje poplav in zagotavljanje pravočasnih opozoril je osnova za dovolj zgodnje ukrepanje pred

5. CONCLUSION

Hydrological modelling and operational hydrological forecasting giving quantity estimation of runoff depend on the data available, that is, not only on the meteorological forecast but also real-time meteorological and hydrological data. Flood forecasting and timely warning issues provide a basis for early measures and acceptance of nastopom pojava in sprejemanje odločitev. Pomanjkanje podatkov meritev in nezanesljivost padavinskih napovedi sta poglavitni vir nezanesljivosti v modelih padavine–odtok in v napovedovanju hudourniških poplav. Pri modeliranju s kratkim časovnim korakom je pomanjkanje podatkov glavna ovira za umerjanje modela in kasneje za njegovo operativno uporabo. Padavinskih postaj je premalo, zlasti na povodjih z izrazito topografijo, kjer je variabilnost padavin velika in je pomembno poznavanje prostorske in časovne porazdelitve padavin. Gostota padavinske mreže z zveznim beleženjem intenzitete padavin v Sloveniji (ena postaja na približno 500 km^2) nikakor ne zadošča za pravilno oceno ploskovnih padavin, ki je nujna za hidrološko modeliranje in napovedovanje.

Radarske padavine so pomemben vir podatkov, ki bi lahko nadomestil izračun ploskovnih padavin iz padavinskih postaj. Toda izvedene analize na povodju Savinje z razpoložljivimi radarskimi padavinami kažejo potrebo po korekciji radarskih podatkov z meritvami na tleh.

Pri napovedovanju poplav z modeli padavine–odtok je primarni vir nezanesljivosti hidrološke napovedi nezanesljivost padavinske napovedi in zato tudi glavni razlog za omejeno rabo modelov. Napovedi modela ALADIN/SI kažejo na veliko nezanesljivost količine padavin na povodju Savinje. Model dobro predvidi padavinske dogodke, količina padavin pa je podcenjena ali precenjena. Kljub temu predstavlja model ALADIN/SI dobro osnovo za hidrološko napoved.

operational decisions before the flood. Deficiency of precipitation measurements and the uncertainty of precipitation forecast are the main source of uncertainty in rainfall-runoff models and flash flood forecasting. The main obstacle in modelling with a short time step is the lack of data needed for model calibration and later for operational use. The number of raingauges is not enough, especially on the catchments with complex topography, where the variability of precipitation is high and therefore the knowledge about the spatial and temporal distribution of precipitation is very important. The density of recording raingauges in Slovenia (one station per approximately 500 km^2) is not enough for the accurate areal estimation of precipitation which is necessary for hydrological modelling and forecasting.

The radar precipitation is aa great source of data which could replace the areal precipitation calculated from raingauges. But the analyses performed for the Savinja catchment with available radar data have shown that radar data need to be corrected with ground rainfall measurements.

The uncertainty of precipitation forecast is the primary source of uncertainty in flood forecasting and also a major reason for a limited use of rainfall-runoff models. The forecasts of ALADIN/SI model show great uncertainty in amount of precipitation on the Savinja catchment. The model predicts the rainfall event well, but the amount of precipitation is underestimated or overestimated. In spite of that, the ALADIN/SI model represents a good basis for hydrological forecasting.

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