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Statistična analiza gospodarsko enakovrednih nalivov

Statistical Analysis of the Equivalent Design Rainfall

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Statistično analizo padavinskih podatkov uporabljamo za oblikovanje kanalizacijskega omrežja in črpališč, ugotovitev trajanja in pogostosti prelivanja razbremenilnikov in zadrževalnikov oziroma za določitev kritičnega dotoka na komunalno čistilno napravo ali izpust v vodotok (npr. iz avtocest). Pri tem sta osnovna podatka jakost in trajanje naliva pri izbrani povratni dobi.

Opisani so postopki, ki se uporabljajo za analizo gospodarsko enakovrednih nalivov (GEN) pri nas in v tujini. Natančneje je prikazana metoda stohastičnega modeliranja, ki je uporabna predvsem za ugotovitev verjetnosti pojava delnih nalivov višjih pogostosti in za določitev spodnje meje vrednotenja nalivov. Prikazani so rezultati izračunov za vrednotenje padavin na podlagi statistične analize opazovanih nalivov na območju Ljubljane.

(Ključne besede: statistika nalivov, jakost nalivov, pogostost nalivov, trajanje nalivov, analize regresijske)

Statistical analyses of rainfall data are used for the design of sewerage systems and pump-stations, for the evaluation of the duration and the frequency of overflow in runoff detention facilities, for the determination of the critical influence on a municipal wastewater-treatment plant or for the protection of watercourses from storm-water runoff (e.g., from highways). The basic data in this calculation are the intensity and the duration of a rainstorm.

Different procedures used in the analysis of Equivalent Design Rainfall (EDR) in Slovenia and abroad are described. The stochastic model used is presented in more detail because of its applicability for the determination of the probability of the occurrence of partial rainfalls of higher frequencies and the determination of the lower limit of rainfall evaluation. Computation procedures and the results of the evaluation of rainfall data according to the stochastic model are presented for Ljubljana.

(Keywords: rainfall statistics, rainfall intensity, rainfall frequency, rainfall duration, regression analysis)

0 UVOD

Pri dimenzioniranju odvodnje so osnovni podatki za določitev količin odtoka padavinske vode s površin v naseljih in odvodnji avtocest, posamezni, statistično ovrednoteni nalivi ali deževja določenega časovnega trajanja t_r (npr. t_r = 5, 10, 15, 30 min …) in pogostosti n, ki pove, kolikokrat se naliv pojavi v enem letu (n = 1 pomeni, da se pojavi enkrat na leto, n = 0,5 pa enkrat v dveh letih itn.), oziroma kakšna je njegova povprečna povratna doba T=1/n. Za njihovo vrednotenje se uporabljajo različne statistične metode. Z ovrednotenjem padavinskih podatkov za oblikovanje kanalizacijskih sistemov se je v Sloveniji

0 INTRODUCTION

The basic data for the design of rainfall-runoff drainage from urban areas and highways are individual, statistically evaluated storms and rainfalls of a certain duration, t_r, (e.g., t_r = 5, 10, 15, 30 min …) and their frequency, n, which tells us how many times the rainfall phenomena occurs in one year (n = 1 means that it appears once per year, n = 0.5 once in two years etc.), or what is its average return period, T=1/n. Different statistical methods are used for their evaluation. In Slovenia, Sketelj [1] from the University of Ljubljana, Faculty of Civil and Geodetic Engineering, Institute of Sanitary Engineering, was največ ukvarjal Sketelj [1] na UL, Fakulteta za gradbeništvo in geodezijo, Inštitut za zdravstveno hidrotehniko, pred več ko 40 leti. Vse analize so potekale "peš". Temeljni problemi, ki se pri tem pojavijo, so, kako natančni naj bodo padavinski podatki (mm/h), kakšen naj bo najmanjši časovni korak opazovanja nalivov iz zapisanih časov merjenja in v kakšnem časovnem koraku naj bodo podani preprosti in sestavljeni nalivi. Zato smo preverili, kako se lotevajo teh problemov v tujini.

V zadnjih 36 letih (od 1964 do 2000) v Sloveniji padavine niso bile statistično vrednotene za oblikovanje sistemov odvodnje. Pridobili smo podatke z Ministrstva za okolje, prostor in energijo (MOPE), Agencije za okolje (ARSO), Urada za meteorologijo (prej Hidrometeorološki zavod Republike Slovenije - HMZ). Podatki so shranjeni v digitalni obliki za Ljubljano od leta 1965 do vključno 1996, skupaj 32 let.

Posredovali so lahko digitalne meritve za nalive v časovnem koraku Δt = 5 minut. Intenzivnost padavin je bila zajeta z natančnostjo 0,1 mm/h, kar so, tako za naše vrednotenje kakor tudi v primerjavi z mednarodnimi dosežki, dobri podatki.

Svetovna meteorološka organizacija (WMO) priporoča, naj analize vremenskih pojavov temeljijo na časovni vrsti vsaj za 30 let teh pojavov, za potrebe načrtovanja kanalskih sistemov pa zadoščajo tudi časovne vrste iz 10 do 15 letnih opazovanj, če ni drugih podatkov.

Zelo podrobno se s to problematiko ukvarjajo na Danskem [2], kjer so potekale celovite raziskave o osnovah oblikovanja in analize sistemov urbane odvodnje glede na lokalne in regionalne točkovne padavinske podatke. Pri tem so uporabili enominutni osnovni časovni korak.

Švicarska meteorološka služba [3] zajema podatke z ločljivostjo 10 minut. Zato je švicarski Zvezni inštitut za okoljske znanosti in tehnologijo razvil metodo (1998), s katero je 10-minutne padavinske podatke mogoče razdeliti v podatke z enominutno ločljivostjo in natačnostjo 0,1 mm/h.

Meteorološka služba nemške dežele Vestfalije je za celotno območje uvedla standardno metodo za simulacijo padavinskega dogajanja in odtoka. V delu Maul-Koetterja in Einfalta [4] so uporabljeni različni matematični modeli za simulacijo razmer padavine – odtok.

V Franciji s podatki za območje Seine Saint Denise [5] preučujejo izvedljivost izgradnje

involved in the processing and evaluation of rainfall data for the design of sewerage systems more than 40 years ago. All the calculations had to be carried out by hand in those times. The basic problems that emerged in such an analysis are how accurate the precipitation data (mm/h) should be, what should be the minimum time interval for the observation of rainstorms, and at what intervals should elementary and composed rainfalls be given. For this reason we explored how these problems are tackled abroad.

In Slovenia, the recorded precipitation data have not been statistically evaluated for the design of runoff drainage systems in the last 36 years (from 1964 to 2000). The digitally processed data saved for Ljubljana since 1965 to 1996 have been provided by the Ministry of the Environment, Spatial Planning and Energy, the Nature Protection Authority, the Office for Meteorology (formerly the Hydrometeorological Institute). Therefore, our evaluation extends over the years 1965 to 1996 inclusive, which means a total of 32 years.

We received the measurements for rainfalls with a time step Δt = 5 min as digital data. The intensity of rainfalls is accurate to 0.1 mm/h, which is high-quality data for our application, and, as will be seen, also in the world-wide comparison.

The World Meteorological Organisation (WMO) recommends that analyses of meteorological phenomena should be carried out on data extending over at least 30 years, but for the purpose of the sewage-system designs, data extending over 10 to 15 years suffices if no other data is available.

In Denmark [2] researchers have studied this question in depth, where comprehensive research on the fundamentals of the design and analyses of urban drainage systems with respect to local and regional point precipitation data has been performed. The basic time step is one minute.

The Swiss Meteorological Service [3] measures data with a resolution of 10 minutes. Therefore, The Swiss Federal Institute of Environmental Sciences and Technology developed a method in 1998 that makes it possible to divide 10-minute precipitation data into data with 1-minute resolution and 0.1 mm/h accuracy.

The meteorological service in the German federal land of Westphalia introduced a standard method for the simulation of precipitation events and drainage for the whole region. In the work of Maul-Koetter and Einfalt [4] different mathematical models are used for the simulation of precipitation-drainage conditions.

In France, using data for the region Seine Saint Denis [5], the feasibility to construct a naključnostnega modela, združljivega s potrebami urbane odvodnje, kjer so podatki nanizani po 5-minutnih korakih. Ločnica med suhim in deževnim obdobjem je na robu koraka, na katerem je skupna količina padavin 2 mm, ali kjer je mejna jakost 0,2 mm/h.

V Kanadi [6] so določili jakosti in ustrezne povratne dobe na podlagi mesečnih skrajnosti (največjih nalivov) za obdobje 35 oz. 50 let.

1 NAKLJUČNOSTNO MODELIRANJE NALIVOV

Temeljne značilnosti obnašanja padavin lahko opišemo in analiziramo s stohastičnim modeliranjem.

Jakost padavin lahko razumemo kot naključno spremenljivko *Q*, ki lahko zavzame eno od diskretnih vrednosti $q_1, q_2, \dots, q_m$ oziroma poljubno vrednost na nekem koraku pozitivne realne osi $0 < q < q_{max}$. Porazdelitev naključne spremenljivke opišemo s porazdelitveno funkcijo $F(q) = P(Q \le q)$ in v njej podamo njene parametre. Ker nas pri oblikovanju zanimajo predvsem porazdelitve skrajnih vrednosti jakosti nalivov, te opišemo z logaritmično normalno porazdelitvijo, za katero velja, da se njihov logaritem *Y*:

stochastic model with a time step compatible with the needs of urban drainage (5 minutes time step) is explored. The dividing line between the dry and the rainy periods is a total amount of precipitation of 2 mm or the limit intensity of 0.2 mm/h.

In Canada [6] the intensities and corresponding return periods were determined on the basis of the monthly maxima (maximum rainfall) for periods of 35 and 50 years respectively.

1 STOCHASTIC MODELLING OF RAINFALL

The fundamental characteristics of rainfall behaviour can be described and analysed with stochastic models.

The precipitation intensity can be described with a random variable *Q*, which can take over one of the discrete values $q_1, q_2, \dots, q_m$, or an arbitrary value in the interval $0 < q < q_{max}$. The distribution of random variables are described by their cumulative distribution function, defined by $F(q) = P(Q \le q)$, where its parameters have to be given. As we are analysing the extreme values of the rainfall intensities, the variable *Q* is most suitably described by a lognormal distribution. The probability density function *Y* of the lognormal distribution:

$$Y = \ln Q \tag{1}$$

porazdeljuje standardizirano normalno. Splošna formula za logaritmično normalno porazdelitev je:

is normally distributed. The general formula for the probability density function of the lognormal distribution is:

$$f_Q(q) = \begin{cases} \dfrac{1}{q\sigma(\ln q)\sqrt{2\pi}} e^{\frac{-1}{2}(\ln(q/Me(Q))/\sigma(\ln q))^2} & \Leftarrow q > 0 \\ 0 & \Leftarrow q \le 0 \end{cases} \tag{2}$$

Z vstavitvijo standardizirane normalno porazdeljene spremenljivke *z*, ki je dobro poznana in tabelirana:

Let us introduce a standardized normally distributed variable Z, which is widely tabulated:

$$z = (\ln(q / Me(Q)) / \sigma(\ln q)) \tag{3}$$

dobimo preprostejši izraz za porazdelitveno funkcijo jakosti nalivov, ki omogoča brati iskane vrednosti porazdelitvene funkcije prek preglednic za standardizirano normalno porazdelitev:

in this case one gets a simpler equation for the density function of the rainfall intensities, which can be easily evaluated using tables of the standardized normal distribution, since:

$$F_Q(q) = P(Q \ge q) = F_Z(\ln(q / Me(Q)) / \sigma(\ln q)) \tag{4}$$

kjer je *Me(Q)* povprečje porazdelitve *Q*. Za aritmetično povprečje $M_y = \ln q'$ smo v (4) namreč upoštevali zvezo (5):

Here, *Me(Q)* is the median of the distribution of *Q*. For the asymmetric mean $M_y = \ln q'$ we used in Eq. (4) the equality (5):

$$\ln q - M_Y = \ln q - \ln MeQ = \ln \frac{q}{MeQ} \tag{5}$$

V enačbi (4) zapis $F_z(.)$ označuje porazdelitveno funkcijo standardizirane normalne porazdelitve, za katero imamo preglednice vrednosti želene natančnosti.

Pri tem zapisu je varianca jakosti padavin pri matematičnem upanju jakosti:

In (4) $F_z(.)$ is the CDF of the standardised normally distributed variable, and is also widely tabulated and given with the desired precision.

Following this description the variance of the rainfall intensities by mathematical expectation of a certain intensity:

$$M_Q = q' = q'(t, T_p) \qquad (6),$$

naslednja:

is as follows:

$$\sigma^2(Q) = (q')^2 (e^{\sigma^2(\ln q)} - 1) \qquad (7).$$

Varianco lahko ocenimo iz eksperimentalnih podatkov. Od tod izhaja koeficient variacije:

The variance can be estimated from the experimental data. Subsequently, the coefficient of variation follows:

$$C_v = \sqrt{(e^{\sigma^2(\ln q)} - 1)} \qquad (8).$$

Vrednotenje opravimo za vsako enoto opazovalnega časovnega območja, za korak vnaprej določene dolžine, v vsem obravnavanem obdobju (N let). Izračunati moramo vse statistike empirične porazdelitve: aritmetično povprečje *q'*, standardni odmik *S*(*Q*), koeficient asimetrije *Cs*(*Q*), koeficient variacije *Cv*(*Q*).

Rezultati postopkov vrednotenja so nizi GEN (Gospodarsko Enakovrednih Nalivov) določene pogostosti (*n*), jakosti odtoka (*q*) in trajanja (*t*), ki jih v koordinatnem sistemu predstavimo kot točke *q* = *q* (*t, n*) razpršene okrog ploskve *q'* = *q'* (*t, n*), ki ji pravimo ploskev JTP (jakost, trajanje, pogostost). Točke z enako pogostostjo določajo v linearnem merilu regresijsko krivuljo hiperbolične oblike $q' = C / t^\alpha$ (v logaritmičnem merilu pa točke enake pogostosti določajo regresijsko premico) oziroma črtni grafikon, dokler se ne lotimo obdelave podtakov analitično in dokler ostajamo na opisni ravni. Na ravni opisne statistike imamo opravka s t.i. neizravnanimi točkami. Za nadaljnjo analizo je treba uporabiti metodo, s katero krivuljo "izravnamo" in dobimo t.i. izravnane krivulje. Obstaja kar nekaj metod, s katerimi je mogoče analitično izraziti izravnane krivulje GEN.

Do sedaj izvedene enačbe v tuji literaturi imajo praktični pomen le na območjih, od koder izhajajo podatkovne zbirke, zato so za Slovenijo praktično neuporabne (uporabna je struktura enačbe, ne pa tudi parametri). Zato je treba za padavine v naši državi ali natančneje na posameznih območjih Slovenije (za vsako posebej) z regresijsko analizo

The evaluation for each unit of the observed time interval for the whole data set (N years) was performed. All the statistical parameters of the empirical distribution: arithmetic mean *q'*, standard deviation *S*(*Q*), coefficient of asymmetry *Cs*(*Q*), coefficient of variation *Cv*(*Q*) have been calculated.

The results of the evaluation procedures are sets of EDR (Equivalent Design Rainfall) of a certain frequency (*n*), runoff intensity (*q*) and duration (*t*), which are presented in the coordinate system as points *q* = *q* (*t, n*) scattered around the surface *q'* = *q'*(*t, n*) or the IDF plane (Intensity, Duration, Frequency). The points with equal frequency, represented on a linear scale, constitute a regression curve with a hyperbolic shape, $q' = C / t^\alpha$ (the same points constitute a regression line on the logarithmic scale) or line graph, as long as the data are analytically treated and as long as one stays on a descriptive level. On the level of descriptive statistics one speaks about non-straightened data and curves. For a further analysis it is necessary to use a method by which the data or the curve is straightened to obtain a straightened curve. There exist several equations with which it is possible to express analytically the straightened EDR curves.

Equations, derived till now in other countries, have practical meaning only for the region where they come from. Therefore, they are more or less useless for Slovenia (the structure can be used, but not the specific parameter values). That is why it is necessary in our country, or even for smaller areas of Slovenia, to find the values of parameters *C* and poiskati parametra C in α regresijske krivulje (hiperbole) oziroma njene linearizacije:

α of the regression curve (of hyperbole) and of its linearization:

$$\log q' = \log C - \alpha \cdot \log t \quad (9).$$

Vrednosti parametrov določimo z metodo najmanjših kvadratov napake (MNK) ([8] in [10]). Zaradi popačenega merila je treba pri uporabi logaritemskega koordinatnega sistema upoštevati v vsaki točki tudi njeno utež, ki je sorazmerna vrednosti ordinate y. Tako dobimo regresijsko premico $\log q' = \log q'$ ($\log t$, n = konst) v logaritmičnem koordinatnem sistemu. Če v zgornji logaritmični enačbi izrazimo: $y' = \log q'$, $B = \log C$, $-A = \alpha$ in $x = \log t$, preide enačba v splošen izraz za premico. Vrednosti y_k pri posameznih meritvah (k = 1, 2, …) odstopajo od pričakovane vrednosti na premici za napako v_k. Zato pri danih parih vrednosti (x_k,y_k) iščemo parametra A in B tako, da bo vsota kvadratov odmikov posameznih točk od premice, ki jo neznana parametra A in B določata, najmanjša.

Tako dobimo sistem linearnih enačb, za katere pa moramo zaradi loma premice v (T_k) upoštevati napako z $b_k = (B - f_k)$. Zaradi popačenega merila pa upoštevamo še utež (p) premice, ki je sorazmerna vrednosti njene ordinate.

Z dobljenimi rezultati iz splošne enačbe za izenačevalno premico izračunamo še vrednost konstante C za obravnavani odsek: $\log C = B - A \log t(T_k)$. Postopek ponovimo za vse odseke GEN.

Parameter values are determined with the Least Square Error (LSE) method ([8] and [10]). Due to the distorted scale, it is necessary in an application of the logarithmic coordinate system to take into account, for each point, also its weight, which is proportional to the ordinate value. The result is a straight line, $\log q' = \log q'$ ($\log t$, n = const), in the logarithmic coordinate system. When we set in the above logarithmic equation: $y' = \log q'$, $B = \log C$, $-A = \alpha$ and $x = \log t$, we obtain a general expression for a straight line. The values of y_k of the distinct measurements (k = 1, 2, …) deviate from the expected value on the straight line for the error v_k. Thus, our task is to find parameters A and B in such a way as to minimise the sum of the squared errors for all pairs of (x_k, y_k).

So, we get a system of linear equations. Still, we have to take into account breaks of the straight line in T_k, i.e., to account for the correction of $b_k = (B - f_k)$. Owing to the distorted scale of the logarithmic coordinate system used for straightening, a weight (p) proportional to the ordinate value must be applied, too.

Then, the value of the constant C can be obtained from the general equation for the regression line at the investigated section: $\log C = B - A \log t(T_k)$. This procedure is repeated for all sections of the EDR.

2 RAČUNALNIŠKI MODELI ZA NAPOVEDOVANJE GEN

Iz časovne vrste za 32 let za padavine na območju Ljubljane je bilo treba pregledati okoli 3,4 milijona podatkov. Za branje in vrednotenje podatkov smo izdelali več programov v C++ in Excelu. Po ovrednotenju smo poiskali analitični izraz (parametra 10^A in 10^B) za krivulje konstantne pogostosti, ki se jim dobljene točke (t_k, q_k), k = 1, 2, … $m(n)$ kar se da dobro prilegajo.

Osnovna oblika arhiviranih digitalnih padavinskih podatkov je podana v preglednici 1. Vsaka vrstica je sestavljena iz 50 mest (znakov); vsebuje (1) - šifro opazovalne postaje (5 mest), (2) - leto (3 mesta), (3) - mesec (2 mesti), (4) - dan (2 mesti) in (5) - uro (2 mesti) pojava padavin ter (6) – (17) - 12 podatkov za 5-minutno količino padavin (12×3 mesta).

2 COMPUTER MODELS FOR THE PREDICTION THE EDR

From the precipitation time series for 32 years for Ljubljana it was necessary to manipulate about 3.4 million data points. Several programs in C++ and Excel were written for data preparation and evaluation. After that, an analytical expression was sought for the parameters (10^A and 10^B) of the lines (curves) for the given frequencies, which the points (t_k, q_k), k = 1, 2, … $m(n)$ should fit as well as possible.

The basic form of archived digital precipitation data is given in table 1. Every row consists of 50 places (characters). It contains (1) - the code of the measuring station (5 places), (2) - the year (3 places), (3) - the month (2 places), (4) - the day (2 places) and (5) - the hour of beginning of precipitation and (6) – (17) - 12 data points for 5-minute rainfalls (12×3 places).

Preglednica 1. *Prikaz podatkov za 28.12. do 30.12.1979, kakor so zapisani v elektronskem arhivu [9]*
Table 1. *Presentation of the data for 28.12. to 30.12.1979 as they are written in electronic form [9]*

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]
192	979	12	28	19	0	0	0	0	1	1	2	5	5	1	1	0
192	979	12	28	20	0	1	0	0	1	0	1	1	1	1	1	0
192	979	12	28	21	0	1	0	1	0	0	1	0	0	1	0	0
192	979	12	28	22	1	0	1	1	1	0	1	1	1	1	1	1
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
192	979	12	29	11	0	0	0	0	1	0	0	0	0	0	0	0
192	979	12	30	8	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88

Pomen šifer: -88 sneg; Meaning of codes: -88 snow

Zaradi nepreglednosti tako zapisanih podatkov bi bilo pri vrednotenju trajanja in poteka posameznega deževja zelo težko izhajati iz podane osnovne oblike zapisa.

Zato sta bila v Excelu izdelana algoritem in računalniški program SURED. Kot primer rezultatov programa so v preglednici 2 prikazani obdelani podatki za isto obdobje kakor v preglednici 1.

Za določitev največjih mesečnih vrednosti smo izdelali program SORTMAX. Z vpeljavo sestavljenih deževij, ki imajo prekinitev dežja krajšo od 5 minut, dobimo deževja, ki trajajo dlje in zato zmanjšamo njihovo skupno število. Za primer: v letu 1996 dobimo namesto 2 396 enostavnih deževij le 1 476 sestavljenih deževij, za celotno obdobje pa se povprečno število 1 589 deževij zmanjša na 1 011 sestavljenih deževij na leto.

Za časovne korake naliva, ki so daljši od 5 minut, lahko dobimo tudi informacijo o povečani

Because of the lack of clarity of such coded data in view of the duration and evolution of rainfall it would have been a very difficult task to start the evaluation from the given basic form of the data.

Thus, an algorithm *SURED* was derived and programmed in Excel. An example of the result using this program is shown in Table 2 for the same period as in the previous Table 1.

The SORTMAX program was developed to determine the maximum monthly values. With the introduction of composite rains, which have a break in rainfall shorter than 5 minutes, one can obtain longer rainfalls and thus reduce their total number. As an example, 1 476 composite rainfalls instead of 2 396 elementary rainfalls were obtained for the year 1996, while an average of 1 589 rainfalls per year for the whole period is reduced to 1 011 composite rainfalls per year.

A higher intensity of runoff for the time intervals higher than 5 minutes can also be obtained.

Preglednica 2. *Primer preureditve podatkov s programom SURED*
Table 2. *An example of the data rearrangement with the program SURED*

Zap. št. deževja Consec. no. of rainfall	Začetek Beginning		Konec End		Skupni čas trajanja Total duration of rainfall	Skupna višina padavin Total rainfall depth	Intenzivnost padavin po 5 minut Intensity of 5 minute rain
	datum date	ura hour	datum date	ura hour	[min]	[mm]	[mm]
1777/79	28.12.	18:20	28.12.	18:55	35	1,6	0,1 0,1 0,2 0,5 0,5 0,1 0,1
1778/79	28.12.	19:05	28.12.	19:10	5	0,1	0,1
1779/79	28.12.	19:20	28.12.	19:25	5	0,1	0,1
1780/79	28.12.	19:30	28.12.	19:55	25	0,5	0,1 0,1 0,1 0,1 0,1
…	…	…	…	…	…	…	…
1786/79	28.12.	21:10	28.12.	21:25	15	0,3	0,1 0,1 0,1
1787/79	28.12.	21:30	28.12.	22:40	70	1,7	0,1 0,1 0,1 0,1 0,1 0,1 0,2 0,1 0,1 0,2 0,1 0,1 0,2 0,1

potrebni jakosti odtoka. Višine padavin v mm zapišemo v enorazsežno matriko. Za vsako določeno trajanje izberemo samo en delni naliv, in sicer tistega, ki od vseh z enakim trajanjem izkazuje največjo jakost (q_{max}).

Dobljenim rezultatom mesečnih skrajnosti (največjih jakosti odtoka q_{max}) za posamezne časovne korake nalivov je treba poiskati ustrezne verjetnosti pojava oz. njihovo relativno pogostost, kar smo storili z uporabo Hazenove empirične in teoretične porazdelitvene funkcije. Pri izračunu upoštevamo vse rezultate (nalivov po jakosti navzdol ne omejimo) za vsa možna trajanja, to je do 1 080 minut (18 ur). Izračun poteka po celicah preglednice za vsak časovni korak posebej (t = 5, 10, 15, 20, 30, ..., 1 080 minut). Delne nalive enakega trajanja razvrstimo od največje vrednosti q_{max} proti najmanjši in po empirični enačbi [7] za vsako razmerje q_{max}/q'_p (q'_p…srednja vrednost podatkov) posebej. Iščemo, kakšna je verjetnost P_e, da se bo pojavila večja ali enaka vrednost od m-te v nizu, če je m rang podatka v ranžirni vrsti. P_e je dejansko kvantilni rang pojava in ga v odstotkih zapišemo:

Rainfall depths [mm] are recorded in a one-dimensional matrix. For each fixed duration of observation only one partial rainfall is chosen, namely that which shows the maximum intensity (q_{max}) from all the rainfalls with the same duration.

Then it is necessary to find out the probability of the occurrence or the frequencies corresponding to the obtained results of the monthly maximal intensities of runoff (q_{max}), which can be done by means of Hazen‘s empirical and theoretical distribution function. In this computation all the results (there is no lower limit for rainfall intensities) for all possible duration times with the same time intervals up to 1080 minutes (18 hours) were taken into account. The computation runs in the cells of the table for each time interval separately (t = 5, 10, 15, 20, 30, ..., 1 080 minutes). The partial rainfalls of the same duration are arranged from the highest q_{max} to the lowest value, and by means of the empirical equation [7] it is sought for each ratio q'_{max}/q'_p (q'_p… mean value of data). It is sought the probability of the occurrence P_e of a higher or equal value than the m-th in a set, provided that m is the rank of the datum in the ranking list, while P_e is indeed the quantile rank of the event and is written as:

$$P_e[\%] = \frac{m-0,5}{n} \cdot 100 \quad (10).$$

Iz urejenega niza podatkov izračunamo empirične statistike. Ker je koeficient asimetrije bistveno odvisen od števila statističnih podatkov, so lahko zaradi majhnega števila podatkov ocene povprečja netočne. Da bi se izognili podcenjevanju asimetrije zaradi majhnega števila istovrstnih podatkov (n), smo upoštevali popravni faktor:

Experimental values of the parameters are computed from the ordered set of data. The coefficient of asymmetry is very dependent on the number of data, i.e., a low number of data can result in inaccurate estimations of the median or other quantiles. To avoid underestimations of the asymmetry due to a small number of data (n) of the same rank we used the correction factor:

$$F = 1 + \frac{8,5}{n} \quad (11).$$

Tako dobimo prirejeni koeficient asimetrije, ki je definiran kot:

In this way, we obtain an adjusted asymmetry coefficient which is defined as:

$$C_{s(prir)} = C_s \cdot F \quad (12).$$

Na podlagi empirično dobljenih parametrov porazdelitve poiščemo tako teoretično porazdelitev, ki najbolj ustreza našim empiričnim podatkom. Uporabili smo zopet Hazenovo porazdelitev. Ta temelji na predpostavki, da se ekstremni pojavi porazdeljujejo zelo asimetrično, zato normalna aproksimacija nikakor ni primerna, pač pa logaritmična normalna krivulja verjetnostne gostote ustrezneje opiše pojav. Izhajamo iz splošne enačbe za hidrološko frekvenčno analizo:

On the basis of the empirically obtained distribution parameters, a theoretical distribution that best fits the empirical data is sought. Hazen‘s distribution was applied here. It is based on the assumption that extreme events, which usually form an asymmetric curve, better fit to the log-normal curve, which is a result of the logarithmic distribution, than to the normal distribution function. We are starting from the general equation for the hydrologic frequency analysis:

$$x = \mu + \Delta x \quad (13),$$

kjer je $\Delta x = \sigma \cdot K_H$ (σ je standardni odklon in K_H je frekvenčni faktor po Hazen-u), ter dobimo:

where $\Delta x = \sigma \cdot K_H$ (σ is the standard deviation, and K_H is the frequency factor according to Hazen), we obtain:

$$x = \mu + \sigma \cdot K_H \quad (14).$$

Po deljenju s povprečno vrednostjo preide enačba v obliko:

After division with the mean value this equation has the following form:

$$\frac{x}{\mu} = 1 + C_v \cdot K_H \quad (15),$$

kjer je $C_V = \sigma / \mu$ ustrezni koeficient variacije pojava. S statistikami empirične porazdelitve zapišemo pričakovano razmerje med največjo in srednjo jakostjo nalivov nespremenljive frekvence:

where $C_V = \sigma / \mu$ corresponds to the coefficient of variation. Using the statistics of an empirical distribution, the expected ratio between the maximum and mean rainfall intensity by selected frequency is:

$$\frac{x}{\bar{x}} = \frac{q'_{\max}}{q'_p} = 1 + C_v \cdot K_H \quad (16)$$

$$C_v = \frac{S}{\bar{x}} \quad (17).$$

Pri vrednotenju nalivov na ljubljanskem območju smo si delo poenostavili z računalniškim programom STEVP, ki določi odločujoče delne nalive in njihove jakosti ter nalive še prešteje. Pri pisanju programa se je izkazalo, da je zagotavljanje pogojev, da se zaporedja enojnih nalivov, ki jih upoštevamo v eni kombinaciji, ne smejo prekrivati, zelo težavno. Na sliki 1 je prikazan alogaritem iskanja in zapisa delnih nalivov iz sestavljenega naliva.

Further work on the evaluation of rainfall data has been simplified with the computer program *STEVP,* which determines the relevant partial rainfalls, their intensities and counts their number. At the time of writing the program it turned out that it is difficult to satisfy the condition that groups of single rainfalls, considered in one combination, should not overlap. In Figure 1 is the algorithm for searching and recording partial rainfalls from combined rainfalls.

3 REZULTATI IN RAZPRAVA

Končno vrednotenje je opravljeno s programom KONPAD v C++, ki je rezultate predhodnih treh programov uporabil kot vhodne podatke.

Program rezultate izpiše v tri datoteke, in sicer v prvo preglednico prikaze ovrednotenih nalivov, v drugo preglednico preštete delne nalive po času trajanja in velikosti jakosti odtoka in v preglednico 3 vsa deževja.

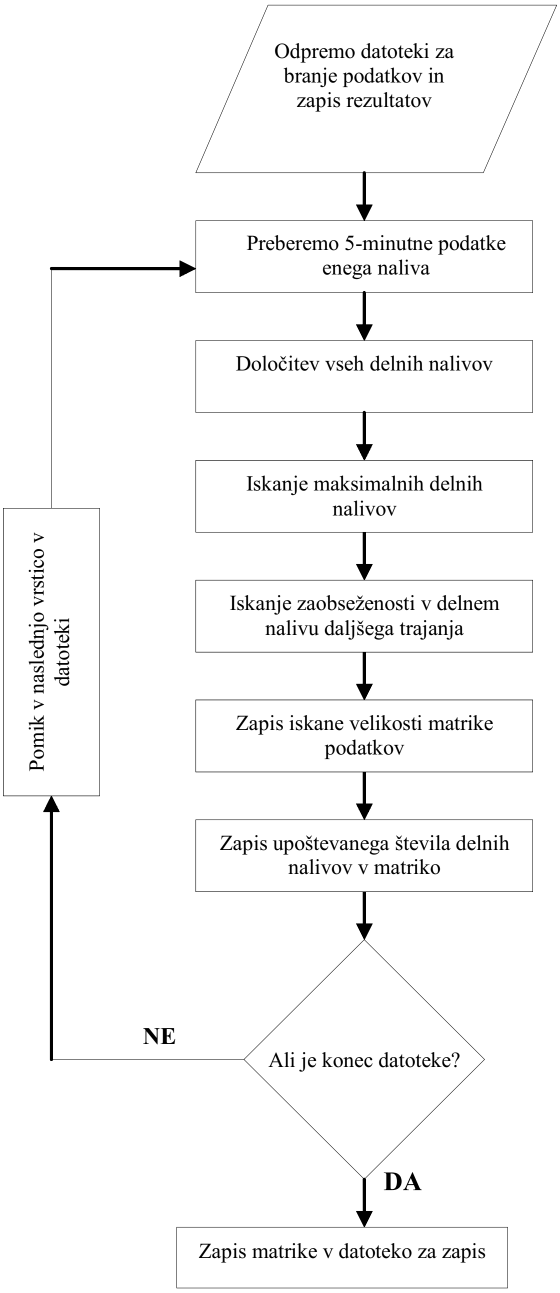
Na sliki 2 je prikazana primerjava našega (IZH2) stohastičnega modeliranja za obdobje (1965 do 1996) s predhodno analizo Sketlja [1] (IZH1) za obdobje (1921 do 1946) ter dveh izračunih Agencije RS za okolje, Urada za meteorologijo (HMZ) za Bežigrad (HMZ1: 1948 do 1998) in Kleče (HMZ2: 1979 do 1989), ki ne upošteva delnih nalivov znotraj sestavljenega naliva. Vidimo, da so njihove vrednosti jakosti nalivov nižje, kar je bilo seveda treba pričakovati.

3 RESULTS AND DISCUSSION

The final evaluation was carried out with the program KONPAD in C++, which used results of the former three programs as input data.

This program writes the results in three files, namely, in the first table is a presentation of the individual evaluated rainfalls, in the second table are counted partial rainfalls according to their duration and intensity of runoffs, and in Table 3 are all the rainfalls.

Figure 2 shows a comparison of our stochastic model (IZH2) for the period (1965 to 1996) with previous computations of Sketelj [1] (IZH1) period (1921 to 1946) and two analyses of the Environmental Agency of Slovenia, (HMZ) for station Bežigrad (HMZ1: 1948 to 1998) and Kleče (HMZ2: 1979 to 1989), which does not consider elementary rainfalls inside the composite rainfalls. Their values of intensity are lower, which is to be expected.



Sl. 1. *Algoritem za določanje delnih nalivov iz sestavljenih nalivov*

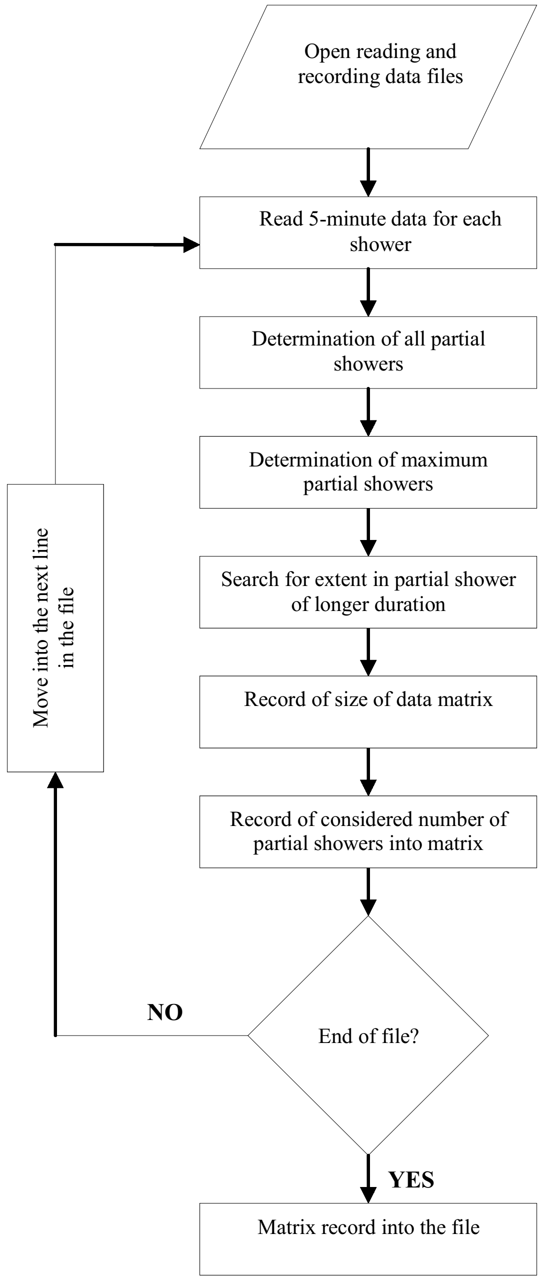


Fig. 1. *Algorithm for establishing partial rainfalls from combined rainfalls*

4 SKLEPI

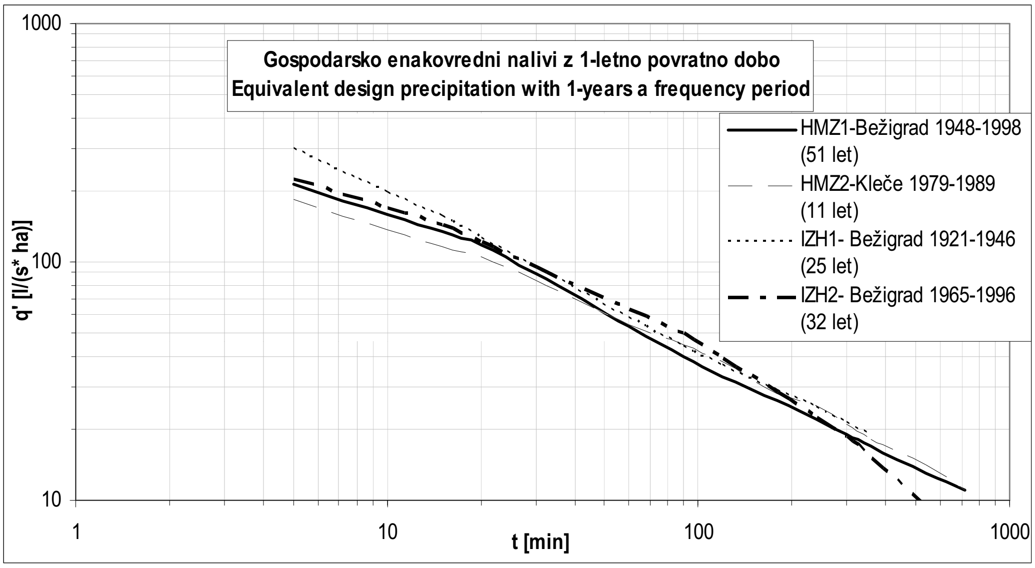
Izdelali smo računalniško ovrednotenje padavinskih podatkov in ga uporabili na primeru Ljubljane za obdobje let 1965 do 1996. Z računalniškimi programi v C++ in Excelu (SURED, SORT-MAX, STEVP in KONPAD), smo ugotavljali

4 CONCLUSIONS

A computer evaluation of precipitation data was developed and applied in the case of Ljubljana for the period 1965 to 1996. Using computer programs in C++ and Excel (SURED, SORTMAX, STEVP, and KONPAD) the maximum intensities of all rainfalls,

Preglednica 3. *Prikaz jakosti padavin po naključnostnem modelu*
Table 3. *Presentation of the intensities of rainfalls according to the stochastic models*

IZH2- naključnostni model IZH2-stochastic analysis		Jakost padavin [l/(s.ha)] Intensity of rainfall [l/(s.ha)]											
1965-1996 (32 let/years)		Trajanje naliva / Rainfall duration Minute/Minutes											
Povratna doba Return period	Pogostost Frequency	**5**	**10**	**15**	**20**	**30**	**60**	**90**	**120**	**180**	**240**	**300**	**360**
100 let/ years	**0,01**	633,3	486,5	416,9	373,7	320,3	213,3	168,2	142,1	112,0	67,3	45,3	32,8
25 let/ years	**0,04**	504,5	381,9	324,5	289,1	245,6	168,2	134,7	115,1	78,3	51,6	37,4	28,7
20 let/ years	**0,05**	484,1	365,3	309,9	275,7	233,8	158,9	126,8	108,0	73,7	49,2	35,9	27,8
10 let/ years	**0,1**	420,6	313,8	264,4	234,1	197,3	130,1	101,9	85,7	59,6	41,6	31,4	25,0
5 let/ years	**0,2**	361,8	267,7	224,5	198,1	166,1	107,8	83,8	70,0	49,4	35,5	27,4	22,2
2 leti/ years	**0,5**	280,3	211,1	178,8	151,9	120,6	81,3	64,6	50,5	35,8	28,0	23,1	18,8
1,5 let/ years	**0,67**	256,5	193,3	163,9	138,8	109,8	73,6	58,2	45,8	32,7	25,7	21,3	16,9
1 leto/ year	**1**	223,9	168,9	143,3	121,1	95,5	63,6	50,1	39,6	28,4	22,4	18,7	15,1
8 mes./ months	**1,5**	192,8	143,2	120,4	106,4	81,2	51,1	38,9	32,1	24,5	20,2	17,4	13,3
6 mes./ months	**2**	169,5	126,0	105,9	93,7	71,2	44,6	33,9	27,9	21,2	17,5	15,0	11,3
4 mes./ months	**3**	135,3	100,8	84,9	75,1	57,3	36,1	27,5	22,7	17,3	14,3	12,3	8,6
3 mes./ months	**4**	110,6	82,7	69,7	61,8	47,1	29,7	22,6	18,7	14,2	11,7	10,1	8,9
2 mes./ months	**6**	74,6	56,1	47,5	42,2	32,7	21,1	16,4	13,6	10,6	8,8	7,7	



Sl. 2. *Grafična primerjava različnih obdelav GEN za Ljubljano z enoletno povratno dobo (IZH2 je rezultat te študije)*
Fig. 2. *Graphical comparison of different EDR evaluations for Ljubljana for a frequency of 1 year (IZH2 is result of present study)*

največje jakosti vseh nalivov, vključno z delnimi nalivi znotraj sestavljenih nalivov do trajanja 18 ur. Kot rezultat so podani gospodarsko enakovredni nalivi - GEN $q' = q'(t, n)$ v pregledniči in grafični obliki (diskretne vrednosti na ploskvi enakovrednih nalivov). Poiskali smo parametre splošne hiperbole

including partial rainfalls within composite rainfalls up to 18 hours, were determined. Equivalent Design Rainfalls (EDRs) $q' = q'(t, n)$ are given as results in tabular and graphical forms (discrete values on the plain of equivalent rainfalls). The parameters of the general hyperbola were sought for each frequency za vsako frekvenco n prek lineariziranega zapisa odnosov med obravnavanimi kazalci, ki opisujejo naliv. Parametre smo določili po metodi najmanjših kvadratov z upoštevanjem uteži zaradi logaritemskega merila. Rezultati statističnega vrednotenja tega stohastičnega obnašanja padavin IZH2 so primerjani s prejšnjimi izračuni IZH1 in HMZ1 ter HMZ2 (sl. 2).

V povprečju so rezultati le malo nižji od prejšnjih izsledkov IZH1. Za celoten niz GEN smo povzeli, da so ujemanja naših rezultatov zelo dobra, predvsem še v časovnem odseku 30 do 60 minut. Rezultati jakosti nalivov so za te časovne korake celo višji, in to pri nižjih pogostostih (od n = 1 do n = 0,1), kar se ujema z izkušnjami zadnjih let (manj povprečnih letnih padavin in več močnejših nalivov kratkega trajanja). Tako so npr. nalivi na območju Ljubljane, ki so trajali 60 minut pogostosti n = 1 po IZH2 jakosti 63,6 l/(s.ha), po IZH1 62,5 l/(s.ha) in po HMZ1 54 l/(s.ha). Vidimo, da se razlikujejo le malo. Za naliv t = 15 min, n = 1, ki se najpogosteje uporablja za oblikovanje, pa je po IZH2 143,3 l/(s.ha), po IZH1 160,6 l/(s.ha) in po HMZ1 135 l/(s.ha). Spodnja meja vrednotenja, ki za mejne vrednosti upošteva jakosti odtoka pogostosti več ko n = 6, pa se ujema na 1 l/(s.ha) natančno.

Z manjšimi popravki so programi uporabni tudi za obdelavo podatkov za katerekoli druge postaje v Sloveniji ali druga obdobja.

n, using linearized relationships among the functions that describe a rainfall. Parameters values were determined by the least square error method taking into account weights due to a logarithmic scale. The results of our evaluation IZH2 by means of the stochastic models are compared with previous calculations IZH1 and HMZ1, HMZ2 (Fig. 2).

On average the results are only slightly lower than previous computations IZH1. For the complete set of EDRs it was concluded that the agreement is good, especially for the time interval of 30–60 minutes. The results of the rainfall intensities are even higher for these time intervals at lower frequencies (from n = 1 to n = 0,1), which is in agreement with experiences over the last few years (lower average annual rainfall and more rainfalls of higher intensities and short duration). The rainfalls of 15 minutes duration and frequency n = 1 by IZH2 are 63.6 l/(s. ha), by IZH1 62.5 l/(s.ha) and by HMZ 1 54 l/(s.ha). The differences are minimal. For the rainfall of t = 15 min. and n = 1, which is frequently used in drainage design the intensity by IZH2 is 143.3 l/(s.ha), by IZH1 160.6 l/(s.ha) and by HMZ1 135 l/(s.ha). The lower limit of evaluation, which takes into account runoff intensities with a frequency greater than n = 6, is in accordance within 1 l/(s·ha) precision.

With minor changes, the computer programs are also applicable for data processing for other stations in Slovenia or for other periods.

5 OZNAKE
5 NOMENCLATURE

konstanta	C		constant
porazdelitvena funkcija	CDF		Cumulative Distribution Function
Gospodarsko Enakovredni Nalivi	GEN/EDR		Equivalent Design Rainfall
višina padavin	h	mm	depth of rainfall
intenziteta padavin	i	mm/h	rainfall intensity
JTP ploskev (jakost, trajanje, pogostost)	IDF		plane (Intensity, Duration, Frequency)
zaporedna številka podatka q'_{max}	m		consecutive number of data q'_{max}
pogostost	n		frequency
število let	N		number of years
verjetnost pojava višje ali enake vrednosti	P		probability of occurrence of a higher or equal value
izmerjena vrednost padavin	q	mm/h	measured unit intensity of a runoff
vrednost spremenljivke za pojav, ki ima v hidrološki seriji povratno dobo T	q_i		value of the variable for the event having a return period T in a hydrological series
enotska jakost padavin	q'	l/(s.ha)	expected unit intensity of a runoff at f(n,t)
opazovani pojav	Q		an observed event
povratna doba	T		return period
trajanje naliva	t, t_r	min	duration of a rainfall
smerni koeficient premice	α		slope of the line
pričakovana vrednost (matematično upanje)	μ		mean value (mathematical expectation)

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