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ESTIMATION OF DESIGN FLOODS USING UNIVARIATE AND MULTIVARIATE FLOOD FREQUENCY APPROACH WITH REGARD TO ONE WET YEAR

OCENA PROJEKTNIH PRETOKOV Z UPORABO UNIVARIATNIH TER MULTIVARIATNIH METOD S POUDARKOM NA VPLIVU NADPOVPREČNO MOKREGA LETA

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Abstract

The determination of design discharges and flood waves volumes is an important aspect of river engineering. The univariate annual maximum (AM), peaks-over-threshold (POT) and multivariate copula methods were used in this hydrologic study to investigate the impact of one wet year on the estimation of flood-related design variables. The flood frequency analyses (FFA) were performed using daily and hourly discharge data from three torrential streams in Slovenia where several flash floods occurred in the last decade. The results of the study indicate that the use of daily discharge data is inappropriate in case of torrential streams because the loss on information when compared to hourly hydrologic data is significant. The consideration of one wet year in the data sample has influence on the relationship between design variable and return period; however this influence is generally smaller than influence of the selected method to perform the FFA.

Keywords: flood frequency analyses, annual maximums, peaks-over-threshold, copulas, climate change

Izvleček

Določitev projektnih pretokov in poplavnih valov je pomemben korak pri načrtovanju hidrotehničnih objektov. Uporabili smo metodo letnih maksimumov (AM), metodo vrednosti nad izbranim pragom (POT) ter multivariatno metodo z uporabo funkcij kopula za določitev vpliva izrazito nadpovprečno mokrega leta na rezultate verjetnostnih analiz. Verjetnostne analize (FFA) so bile izvedene z uporabo podatkov o pretokih z urnim ter dnevnim časovnim korakom. Uporabljeni so bili podatki s treh hudourniških porečij v Sloveniji, kjer so se v preteklem desetletju zgodili številni ekstremni dogodki. Rezultati analiz so pokazali, da je uporaba podatkov z dnevnim časovnim korakom neprimerna za hudourniška območja, ker se veliko informacij o dejanskih konicah pretokov izgubi v primerjavi z urnimi podatki. Upoštevanje dodatnega nadpovprečno mokrega leta v analizah sicer ima vpliv na projektne pretoke, vendar je ta vpliv v večini primerov manjši kot vpliv izbire metode za izvedbo verjetnostnih analiz.

Ključne besede: verjetnostne analize, metoda letnih maksimumov, metoda vrednosti nad izbranim pragom, kopule, klimatske spremembe

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1. Introduction

Determination of the relationship between peak discharge values (*Q*) and return periods (*T*) is an important step in the design of river engineering and hydraulic structures. However, the discharge or water level observations are often relatively limited in time and therefore a great level of uncertainty, with a possible combination of bias due to the systematic measurements error, can be propagated in the estimated design discharge values. Therefore, appropriate methodologies should be selected to perform a flood frequency analysis (FFA) with an emphasis on reducing the model uncertainty (e.g., Xu et al., 2010).

Continuous discharge measurements in torrential streams are often insufficient (e.g. short series, gaps in the available data). However, flash floods can cause high economic damage or even endanger human lives. Several extreme events, i.e. flash floods, have occurred in Slovenia in the last 10 years. Probably the most severe one was the Železniki flash flood of the Selška Sora river in 2007 (Marchi et al., 2009; Rusjan et al., 2009; Zanon et al., 2010) when 6 people died. Likewise, the Gradaščica river played an important role in causing the 2010 Ljubljana floods (Kobold, 2011; Koler et al., 2012), when extreme meteorological conditions and extensive flooding caused 4 casualties. Furthermore, also the Zminec catchment (Poljanska Sora river), which is adjacent to the Železniki catchment, has torrential characteristics. Extreme hydrological conditions occurred in all three mentioned catchments in 2014, which can be regarded as extreme, because accumulated rainfall amounts (from 25 % to 60 %; on average 37 %), and air temperatures (on average 1.8°C) were significantly above the long-term average determined for the period 1971-2010 (ARSO, 2014). Therefore, these three catchments were selected to assess the influence of the year 2014 on the design discharge estimations. The data-based approach was selected to observe changes in the measured discharge series (Hall et al., 2014). Recently, Hall et al. (2014) summarised the observed flood changes in Europe. A positive trend can be observed in UK and part of the Western and Central Europe; on the other hand a negative trend is present in Eastern and Northern Europe and in part of the Western and Central Europe (Hall et al., 2014).

The measured continuous discharge series can be used to perform the FFA. In most practical cases the annual maximum series (AM) method is used to define the relationship between the return period and design discharge (e.g. Maidment, 1993). As an alternative, the peaks-over-threshold (POT) method can be used where more than one event per year can be considered in the analysis (e.g. Robson and Reed, 1999). However, in the last decade copula functions have been more frequently used to perform the multivariate flood frequency analysis where flood event volume (*V*) or (and) flood event duration (*D*) can be studied simultaneously with the peak discharge values (e.g., Salvadori et al., 2007). In this study, univariate and multivariate approaches were used to perform the FFA using continuous daily and hourly discharge data from the three Slovenian torrential streams.

The main objective of the study was to investigate the influence of one wet year on the flood frequency analyses results using the data-based approach, where the main interest was to analyse the impact of different aspect of FFA (e.g. sample definition, method selection,…) on the final FFA results, and not to determine the relationship between design variables and return period. The specific aims of this study were as follows: (i) to quantify the influence of the year 2014 on the estimated design discharges and flood event volumes using the annual maximum series method, peaks-over-threshold method and multivariate copula approach for three case studies in Slovenia, (ii) to compare the flood frequency analyses results using the daily and hourly discharge data as a basis for the analyses, (iii) and to investigate the changes in the relationship between the design discharge and return period.

2. Data

The daily and hourly discharge data from three Slovenian hydrological stations were used (ARSO, 2015). Fig. 1 shows the locations of the selected catchments, gauging stations and the topography map of Slovenia. All three catchments are located in the western part of Slovenia. Mean annual precipitation for three selected catchments are between 1600 and 2000 mm. Table 1 shows basic characteristics of the three case studies. The headwaters of all three rivers flow in the varied mountain relief with relatively steep slopes, which can be also seen from Table 1, meaning that all three streams can be characterised as flashy streams (Fig. 1). All three rivers have alpine pluvial–nival water regime, where this regime can be described with two fairly equal peaks, first one usually occurs in autumn and the other one in spring. Furthermore, the majority of the AM events occur in autumn. The coefficient of seasonality calculated based on the daily AM series, which was defined by Burn (1997), was 0.37, 0.56 and 0.38 for the Dvor, Železniki and Zminec gauging stations, respectively. If this coefficient is 1, seasonality is very explicit and all AM events occur in the same time of the year; if the coefficient is closer to 0, seasonality is more complex. Values between 0 and 1 indicate different strengths of seasonality. The calculated coefficient values (0.37, 0.56 and 0.38) indicate that seasonality for the three selected stations is not very explicit (moderate seasonality). We therefore cannot expect all maximum events in the same season. The seasonality characteristics should not have a significant impact on FFA results. For the Železniki station more AM events occurred in autumn as for the Dvor and Zminec gauging stations. Table 2 shows sample periods for the daily and hourly discharge data for the three selected gauging stations. Similarly, Fig. 2 shows average daily and hourly discharge data for the Dvor, Železniki and Zminec stations. The average daily discharge values were calculated based on the measured hourly discharge data (Fig. 2). For the Dvor gauging station limnigraph was used for the discharge measurements between the years 1981 and 2009; after the year 2010 a pressure probe is used for the discharge observations. Likewise, for the Železniki station the limnigraph was used between 1992 and 2009 and afterwards the pressure probe is used. Furthermore, for the Zminec gauging station from 1957 to 1990 water level observations were made once a day by an observer, from 1991 to 2011 measurements were performed using the limnigraph and after this year the pressure probe was used for the discharge measurements. The limnigraph data was digitized backwards until the year 1998 for the Dvor and Zminec stations and until the year 2005 for the Železniki station (Table 2). For all three stations the rating curves (Q = f(H)) were used to convert the measured stage values into discharge values. The rating curves were defined by measuring discharge at different stage levels (low and high conditions).

Fig. 3 shows the hydro-geological map and CLC Corine land use map for the three analysed catchments. Forest covers more than 65 % of area shown in Fig. 3 where mixed forest is the most frequent according to the CLC Corine land use map. Furthermore, agriculture land covers about 20 % of the three catchment areas.

Table 1: Basic characteristics of the selected case studies.

Preglednica 1: Osnovne značilnosti izbranih porečij.

Stream	Station name	Catchment area [km^2]	Station elevation [m.a.s.l.]	Mean elevation [m.a.s.l.]	Minimum elevation [m.a.s.l.]	Maximum elevation [m.a.s.l.]
Gradaščica	Dvor	79	341	616	341	1020
Selška Sora	Železniki	101	447	927	447	1664
Poljanska Sora	Zminec	306	343	676	343	1209

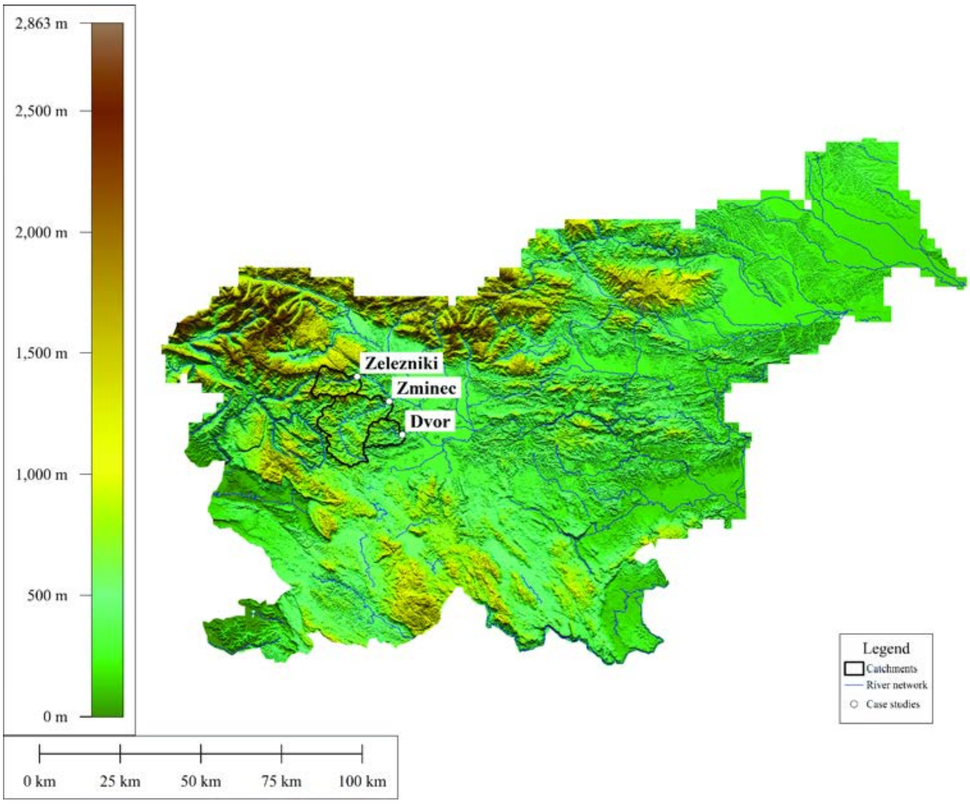

Figure 1: Location of the selected case studies on the topographic map of Slovenia.

Slika 1: Lokacija izbranih porečij na topografski karti Slovenije.

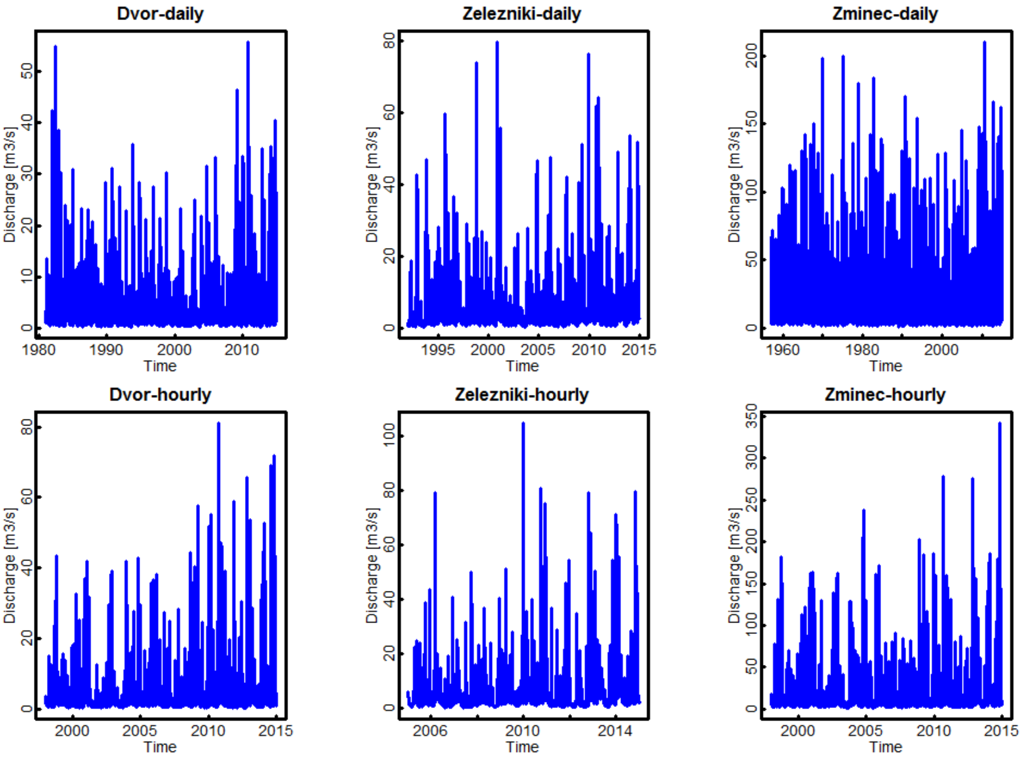

Figure 2: Presentation of average daily (upper three graphs) and hourly (lower three graphs) discharge data for the three selected case studies for the entire period of measurements.

Slika 2: Uporabljeni povprečni dnevni (zgoraj) in urni (spodaj) podatki o pretokih za izbrane vodomerne postaje za celotno obdobje meritev.

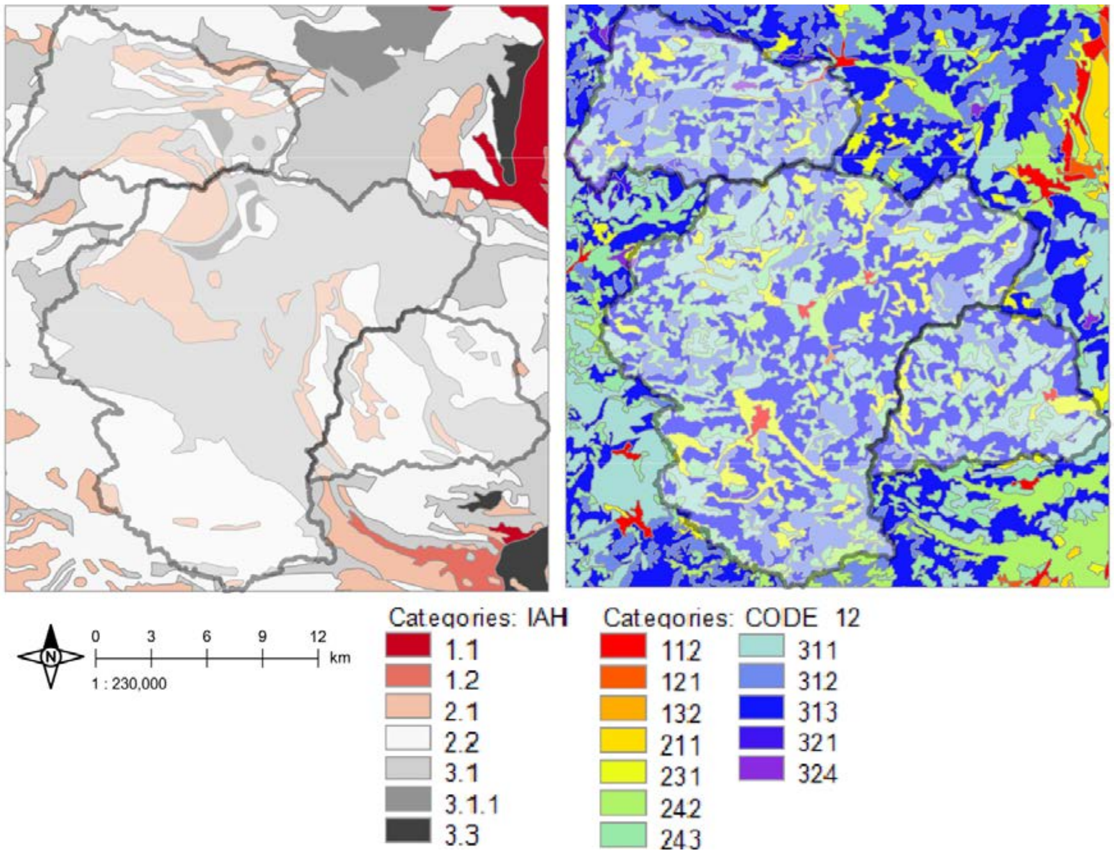

Figure 3: Hydro-geological map (left) and CLC Corine land use map (right) for the three selected catchments (*1.1*– Extensive aquifers and aquifers with medium to high water abundance; *1.2*– Local and non-continuous aquifers with high water abundance or extensive aquifers but with low to medium water abundance; *2.1*– Extensive aquifers; *2.2*–Local and non-continuous aquifers but with low to medium water abundance; *3.1* and *3.1.1*–Smaller aquifer with local and restricted ground water sources; *3.3*– Large aquifer under a thin cover; *112*–Urban fabric; *121*–Industrial, commercial and transport units; *132*–Mine, dump and construction sites; *211*–Arable land; *231*–Pastures; *242*, *243*–Heterogeneous agricultural areas; *311*–Broadleaf forest; *312*–Coniferous forest; *313*–Mixed forest; *321*, *324*–Shrubs).

Slika 3: Hidro-geološka karta (levo) in karta rabe tal CLC Corine (desno) za izbrana porečja (*1.1*–Obširni in srednje do visoko izdatni vodonosniki; *1.2*–Lokalni ali nezvezni izdatni vodonosniki ali obširni vendar nizko do srednje izdatni vodonosniki; *2.1*–Obširni in visoko do srednje izdatni vodonosniki; *2.2*–Lokalni ali nezvezni izdatni vodonosniki ali obširni vendar nizko do srednje izdatni vodonosniki; *3.1* in *3.1.1*–Manjši vodonosnik z lokalnimi in omejenimi viri podzemne vode; *3.3*–Kjer obsežen vodonosnik lezi pod tankim pokrovom; *112*–Urbane površine; *121*–Industrijske, trgovinske, transportne površine; *132*–Rudniki, odlagališča, gradbišča; *211*–Njivske površine; *231*–Pašniki; *242*, *243*–Mešane kmetijske površine; *311*–Listnati gozd; *312*–Iglasti gozd; *313*–Mešani gozd; *321*, *324*–Grmičevje).

Table 2: Sample periods for the daily and hourly discharge data.

Preglednica 2: Analizirana obdobja za urne in dnevne podatke o pretokih.

Stream	Station name	Daily data	Hourly data
Gradaščica	Dvor	1981-2014	1998-2014
Selška Sora	Železniki	1992-2014	2005-2014
Poljanska Sora	Zminec	1957-2014	1998-2014

3. Methods

Annual maximum series (AM), peaks-over-threshold method (POT) and multivariate copula approach were used in order to investigate the influence of one wet year on the FFA results, i.e. what is the impact of the year 2014 on the design discharge values.

The AM method is probably the most frequently used approach to define the relationship between the design discharge and the return period. The basic principles of the AM method are described in most hydrological textbooks (e.g., Maidment, 1993). Several distribution functions and parameter estimation methods are available (e.g., Hosking and Wallis, 1997; Bezak et al., 2014; Salinas et al., 2014). The Gumbel (G), generalized extreme value (GEV) and log-Pearson type 3 (LP3) distributions were used in this study and the distribution parameters were estimated with the method of L-moments (Hosking and Wallis, 1997). These three distributions (G, GEV and LP3) were selected because they are recommended for the FFA in many European counties (Salinas et al., 2014), including Slovenia (Bezak et al., 2014). Furthermore, the method of L-moments was given advantage over the method of moments or maximum likelihood method due to the higher robustness and smaller bias in the case of small samples (Salinas et al., 2014).

The POT method can be regarded as an alternative to the AM method. The main advantage is that on average more than one event per year can be selected in the POT sample, which is especially useful in small samples (e.g. Robson and Reed, 1999; Bezak et al., 2014). On the other hand, AM method can be more easily applied than the POT method, because in the latter case appropriate threshold has to be selected, the independence of consecutive peaks has to be ensured and appropriate distribution functions have to be defined (e.g., Lang et al., 1999; Önöz and Bayazit, 2001, Bezak et al., 2014). In this study the Poisson distribution was selected to model the annual number of exceedances and the exponential distribution was selected to deal with magnitudes of exceedances (Önöz and Bayazit, 2001, Bezak et al., 2014). Several thresholds were selected so that the samples on average contained 1, 3 and 5 peaks per year, which can be denoted as POT 1, POT 3 and POT 5 samples, respectively (Robson and Reed, 1999). The independence criteria suggested by the Water Resources Council was applied in order to ensure that consecutive events are independent (USWRC, 1982):

$$\theta < 5 \text{ days} + \log(A) \text{ or } x_{MIN} > \left(\frac{3}{4}\right)\min[x_{S1}, x_{S2}], \quad (1)$$

where x_{S1} and x_{S2} are consecutive peaks and A is basin area [square miles]. However, some other independence criteria could have been selected (e.g. Cunnane, 1979).

In contrast to the AM and POT methods where only one variable is used in the analysis, usually the peak discharge (Q), in the multivariate copula approach other variables can be considered in the analysis e.g. flood event volumes (V) and flood event durations (D). More theoretical information about copulas and their applications in geosciences can be found in textbooks, e.g. Joe (1997), Nelsen (1999) and Salvadori et al. (2007). In the present study the bivariate Gumbel-Hougaard copula, which is frequently used in hydrological applications (e.g., Zhang and Singh, 2006; Reddy and Ganguli, 2012; Šraj et al., 2015), from the Archimedean family was chosen to study the relationship between Q and V:

$$C_\theta(u,v) = \exp\left\{-\left((-\ln u)^\theta + (-\ln v)^\theta\right)^{1/\theta}\right\}, \quad (2)$$

where $u, v \in [0,1]$. θ is the Gumbel-Hougaard copula dependence parameter, which can be between 1 and ∞ and can be estimated based on the Kendall's correlation coefficient τ value (Salvadori et al., 2007):

$$\tau = \frac{\theta - 1}{\theta}. \quad (3)$$

Furthermore, the upper (λ_U) and lower (λ_L) tail dependence coefficients are $2\text{-}2^{1/\theta}$ and 0, respectively (Salvadori et al., 2007). The primary return period ($U > u$ or $V > v$) OR T^{OR} can be calculated as (Vandenberghe et al., 2011):

$$T^{OR} = \frac{\mu}{1 - C_\theta(u,v)}, \quad (4)$$

where μ is the mean inter-arrival time of two consecutive events.

4. Results and discussion

4.1 Influence of the year 2014 on the estimated design discharges and flood event volumes

First step of the study was to evaluate the influence of the year 2014 on the estimated design discharge and flood event volume values using daily discharge data. Table 2 shows sample periods for the daily discharge data used in this study. AM, POT and copula methods were used to assess the impact of the wet meteorological year 2014 on the design discharge values. Before performing the univariate and multivariate flood frequency analysis the Mann-Kendall test was used to identify trends in a time series (e.g. Kendall, 1975; Douglas et al., 2000). The computed trends in the AM and POT 1 series, which were defined based on the daily discharge data, were not statistically significant with selected significance level 0.01.

Fig. 4 shows the computed design discharge values for the return periods 10, 100 and 500 years using the AM, POT 1, POT 3 and POT 5 methods for the three selected case studies in Slovenia. For the Dvor and Zminec stations the design discharge values with the consideration of the year 2014 were larger than design discharge values without considering the year 2014 in the AM sample (Fig. 4). These results do not depend on the selected distribution function (G, GEV and LP3). However, the computed differences in the design discharge values using both samples (with and without 2014) did not exceed 2 % for the return period 100 years, which is often used in the design of hydraulic structures and objects (Fig. 4). On the other hand, when using the POT method (POT 1, POT 3 and POT 5) the calculated differences between both samples (with and without 2014) were from 0 to 7 % for the Dvor and Zminec stations. Also for the Železniki station the POT method yielded larger estimated design discharge values when considering the year 2014 than without year 2014; this does not apply for the AM method where opposite results were obtained, but differences were not significant (Fig. 4). Table 3 shows the estimated primary return period OR values for the three selected hydrological stations. Different procedure than in the univariate case was used in the copula methodology to connect the return period and design variables, because when using the multivariate flood frequency approach different combinations of *Q* and *V* can yield the same return period value (e.g., Zhang and Singh, 2006; Šraj et al., 2015). Therefore, in Table 3 the *Q* and *V* were fixed and corresponding return period values were calculated. The median and maximum values of the AM sample of *Q* and *V* variables were used to determine the return period OR values shown in Table 3. To define the flood event volumes for the AM events, which were selected based on the maximum peak discharge value, baseflow was separated from daily discharge series using the automatic baseflow filter, which is implemented in R package lfstat (Koffler and Laaha, 2012). The copula results shown in Table 3 are in agreement with the AM results shown in Fig. 4. For the Dvor and Zminec stations the consideration of year 2014 yielded smaller return period values for the same *Q* and *V* values. This means that higher design variables, for the same return period value, were obtained when considering the year 2014 in the analysis than in the opposite case. Different results were obtained for the Železniki station (Table 3). However, in none of the cases the differences in calculated return period values exceeded 6 %.

Univariate flood frequency results shown in Fig. 4 and multivariate flood frequency results shown in Table 3 indicate that consideration of one wet year in the sample can influence the estimated design discharges and flood event volumes; however, the selection of distribution function in the AM method, threshold determination in the POT method and copula selection (Šraj et al., 2015) can have an even more notable influence on the design variables. This can be seen from Fig. 4 where differences among different methods, e.g., POT 3 and LP3 distribution (AM) for the Zminec station can be as high as 25 %. Similar results were also obtained by Bezak et al. (2014) who compared AM and POT methods and also found that selection of method to perform the FFA can have a large influence on the estimated design discharge values.

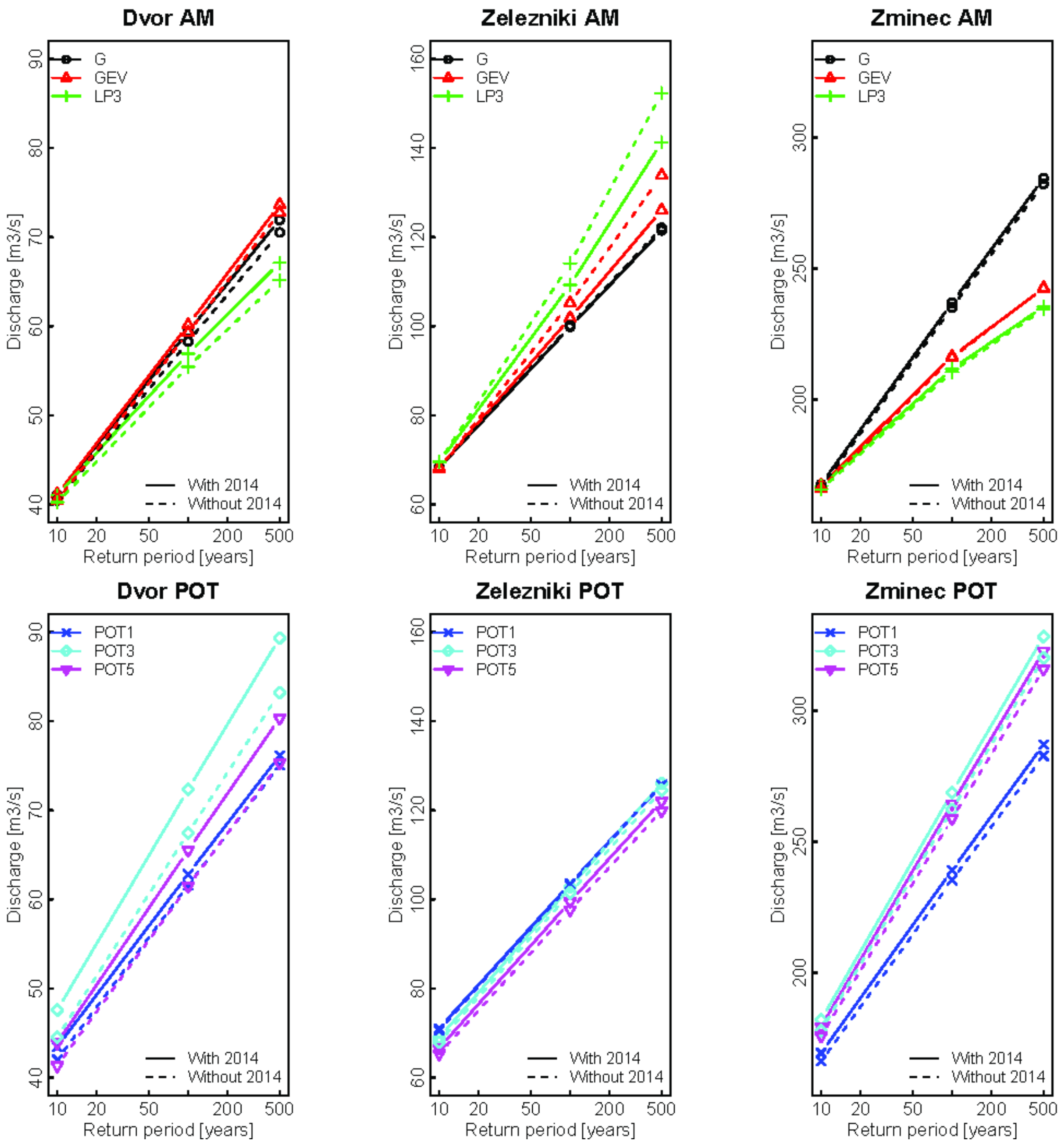

Figure 4: Estimated design discharge values for return periods 10, 100 and 500 years using the AM and POT series based on the daily discharge data.

Slika 4: Ocenjeni projektni pretoki za povratne dobe 10, 100 in 500 let z uporabo AM ter POT metod z uporabo dnevnih podatkov o pretokih.

Table 3: Estimated primary return period OR T^{OR} values for using the copula approach for three selected case studies.

Preglednica 3: Ocenjene povratne dobe OR T^{OR} z uporabo kopul za izbrana porečja.

	Dvor		Železniki		Zminec	
	With 2014	Without 2014	With 2014	Without 2014	With 2014	Without 2014
Median	1.51	1.53	1.43	1.42	1.51	1.52
Maximum	24.66	25.47	13.17	13.10	33.84	35.83

4.2 Comparison between daily and hourly discharge data

In the next step of the study the univariate FFA results using both daily and hourly discharge data were compared. To compare the daily and hourly discharge data the GEV distribution was selected for the AM method and POT 3 was chosen for the POT method. Fig. 5 shows the connection between estimated discharge values and the return period for the AM and POT series. Table 2 shows the hourly sample periods that were used to compute the values shown in Fig. 5. The daily discharge data (Table 2) that were used to perform the FFA shown in Fig. 5 were computed as average of the hourly data and have the same sample period as hourly data. The results show that differences in the estimated design discharge values when using daily or hourly data can be significant. These differences are especially notable for the Zminec and Dvor gauging stations where hourly discharge data yielded up to 80 % (for Zminec) and 50 % (for Dvor) larger estimated design discharge values for the return period 100 years than daily discharge data. This difference is smaller for the Železniki station (about 30 %). However, in this case only 10 years of data were used for the analysis (Table 2). The differences between daily and hourly discharge data are due to the flashy characteristics of the analysed streams which is also evident from the extreme flash floods which occurred in the previous decade in the analysed streams (e.g., Marchi et al., 2009; Rusjan et al., 2009; Zanon et al., 2010; Kobold, 2011). Furthermore, due to the complex topography, orographic precipitations are relatively common in the investigated area and therefore the hydrological conditions in these three adjacent catchments (Fig. 1) often depend on the local meteorological situation. Fig. 5 also shows the influence of the year 2014 on the estimated design discharge values. Differences between the sample including the year 2014 and the sample without year 2014 are generally larger than in the results shown in section 4.1, where longer daily discharge data were used (Table 2). This was expected because in shorter series one high discharge value in the sample can have a larger influence on the estimated parameters (AM or POT) and consequently also on the design discharge values than in the case of longer series, which are shown in section 4.1. However, using hourly data instead of daily data that is mostly done in practical cases, has larger influence on the estimated design discharge values than (non)consideration of one wet hydro-meteorological year in the sample (Fig. 5). Similarly, Bezak et al. (2015) found that not considering the local maxima in the AM sample and method selection (AM or POT) can have a significant influence on the statistical trend analysis results (Mann-Kendall test). However, this influence was smaller on the seasonality analysis results (Bezak et al., 2015). Therefore, the selection of data (daily or hourly) clearly has a significant impact on the design discharge values in case of flashy streams.

4.3 Changes in the relationship between design discharge and return period

In the next step of the study we investigated how adding an additional year to the sample influences the univariate FFA results. Fig. 6 shows changes in the estimated design discharge values with return period 100 years for the Dvor and Zminec stations. The results for the Železniki station are not shown in Fig. 6 because only 10 years of hourly data were available for this station (Table 2). The sample periods shown in Table 2 were used to calculate results in Fig. 6. Two wet years occurred (2010 and 2014) with several extreme hydrological conditions triggered by extreme precipitation conditions (ARSO, 2014; Kobold, 2011). These years have a notable influence on the design discharge values independently of the method and data selection (AM, POT, daily, hourly); e.g. for the Zminec station the difference in the FFA results when using AM daily data 1957-2009 or 1957-2010 was about 8 %. Similar conclusions can be made for the Dvor station and other methods shown in Fig. 6. However, these changes are not of the same order of magnitude as changes connected with sample selection (daily or hourly data). Table 4 and Table 5 show estimated return period values for 4 largest events, which occurred in 2014, for stations Dvor and Zminec. The results in Tables 4 and 5 were computed using hourly data. Again, method selection (AM or POT) had a larger influence on the estimated return periods than (non)consideration of one year in the sample.

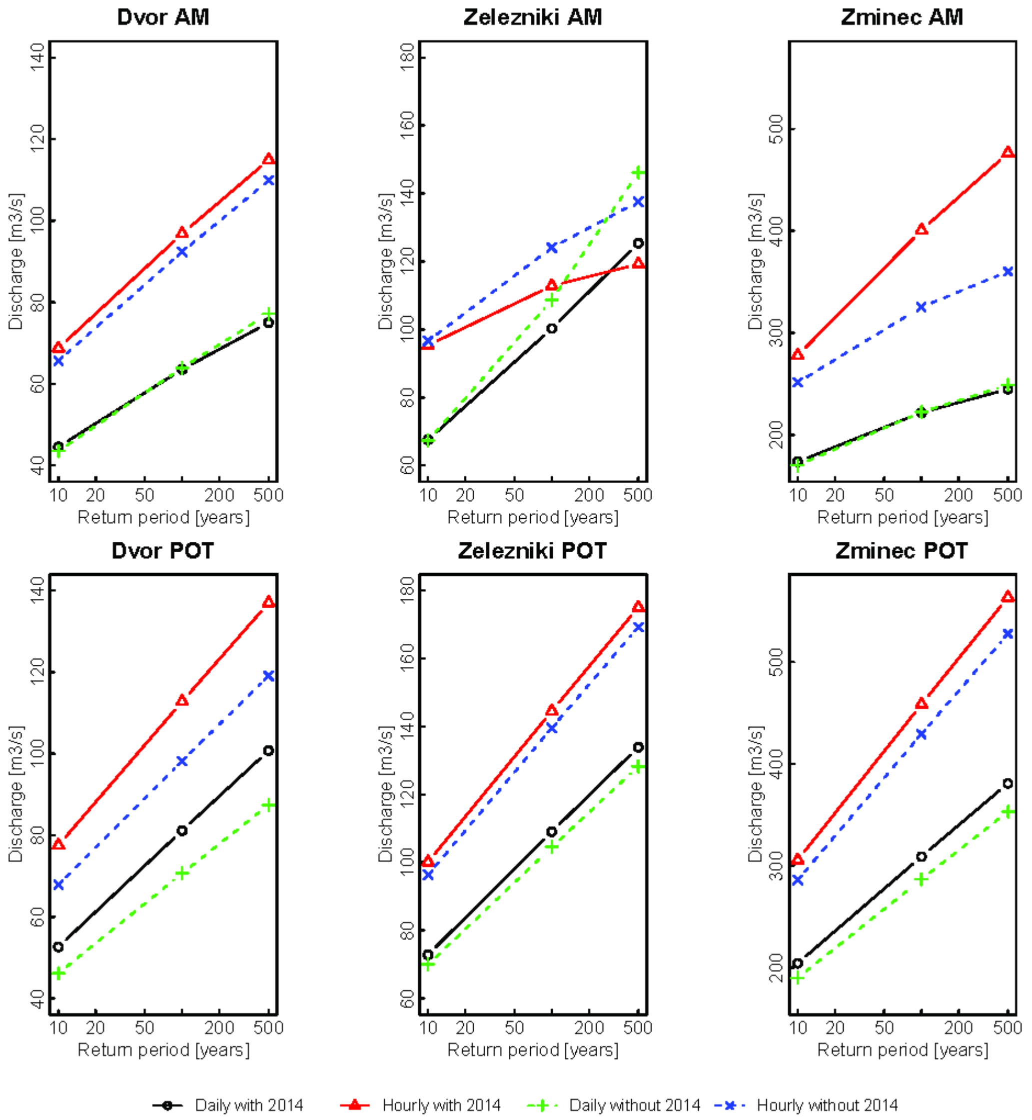

Figure 5: Estimated design discharge values for the daily and hourly discharge data using AM and POT methods for three case studies in Slovenia.

Slika 5: Ocenjeni projektni pretoki z uporabo dnevnih ter urnih podatkov z AM ter POT metodo za izbrana porečja v Sloveniji.

Table 4: Estimated return periods for some peak discharges that occurred in 2014 for the gauging station Dvor using hourly discharge data.

Preglednica 4: Ocenjene vrednosti povratnih dob za nekatere dogodke, ki so se zgodili v letu 2014, za postajo Dvor z uporabo urnih podatkov o pretokih.

Date	Peak discharge [m^3/s]	AM with 2014 [years]	AM without 2014 [years]	POT 3 with 2014 [years]	POT 3 without 2014 [years]
22.10.2014	71.8	12.7	16.6	7	13.3
5.8.2014	69	10.2	13.2	5.9	10.8
13.9.2014	62	6.1	7.5	3.9	6.5
21.8.2014	58.1	4.6	5.5	3.1	4.9

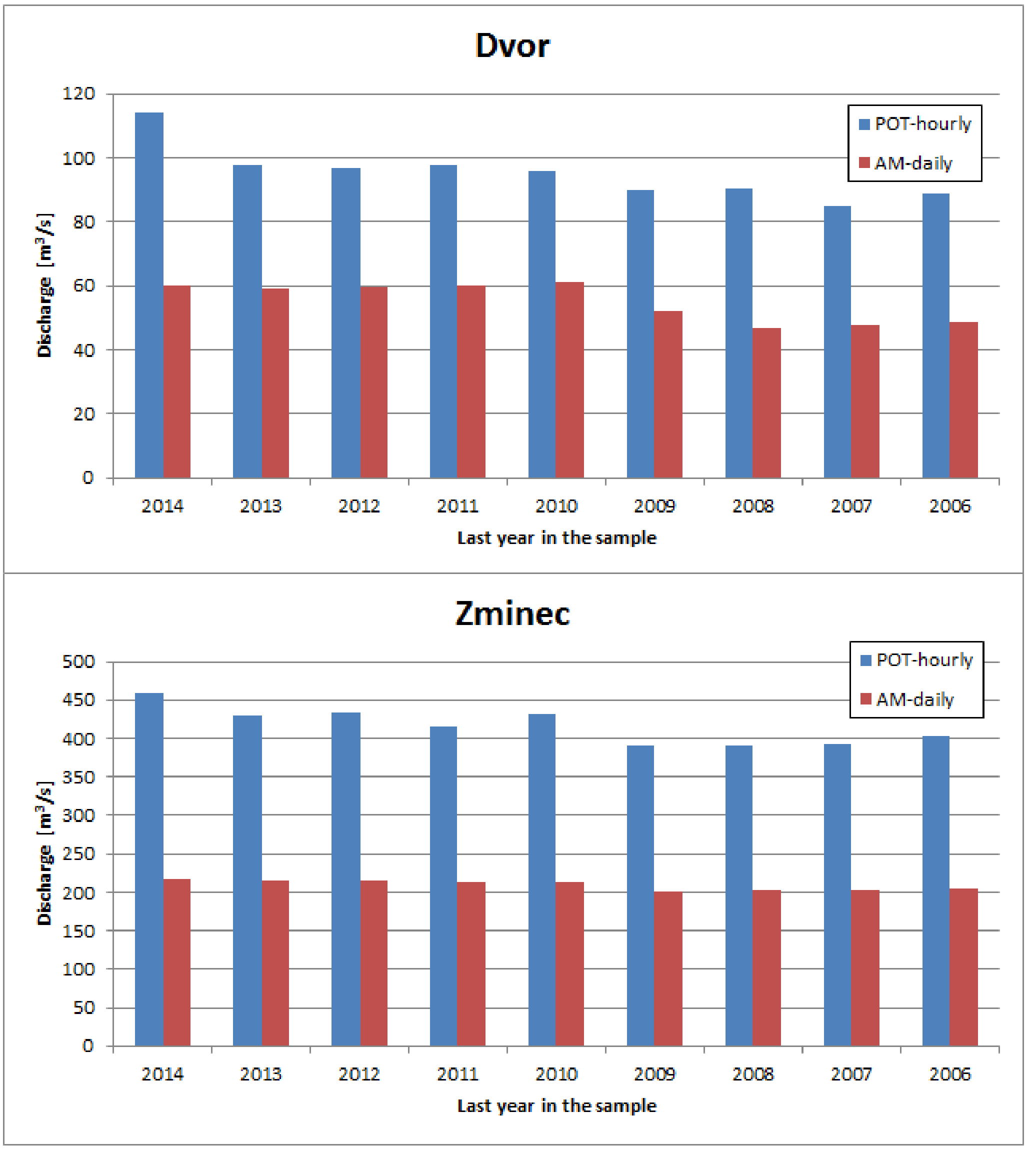

Figure 6: Changes in the estimated design discharge values with return period 100 years due to adding additional years in the analysis for the Dvor and Zminec stations using hourly and daily discharge data.

Slika 6: Spremembe v ocenjenih vrednostih pretokov s povratno dobo 100 let z dodajanjem dodatnega leta podatkov za postaji Dvor in Zminec (za urne in dnevne podatke).

Table 5: Estimated return periods for some peak discharges that occurred in 2014 for the gauging station Zminec using hourly discharge data.

Preglednica 5: Ocenjene vrednosti povratnih dob za nekatere dogodke, ki so se zgodili v letu 2014, za postajo Zminec z uporabo urnih podatkov o pretokih.

Date	Peak discharge [m^3/s]	AM with 2014 [years]	AM without 2014 [years]	POT 3 with 2014 [years]	POT 3 without 2014 [years]
22.10.2014	342	31.7	204	17.1	24.2
7.11.2014	196	2.8	3.2	2.3	2.7
11.2.2014	186	2.5	2.7	2.1	2.4
13.9.2014	179	2.3	2.5	1.9	2.2

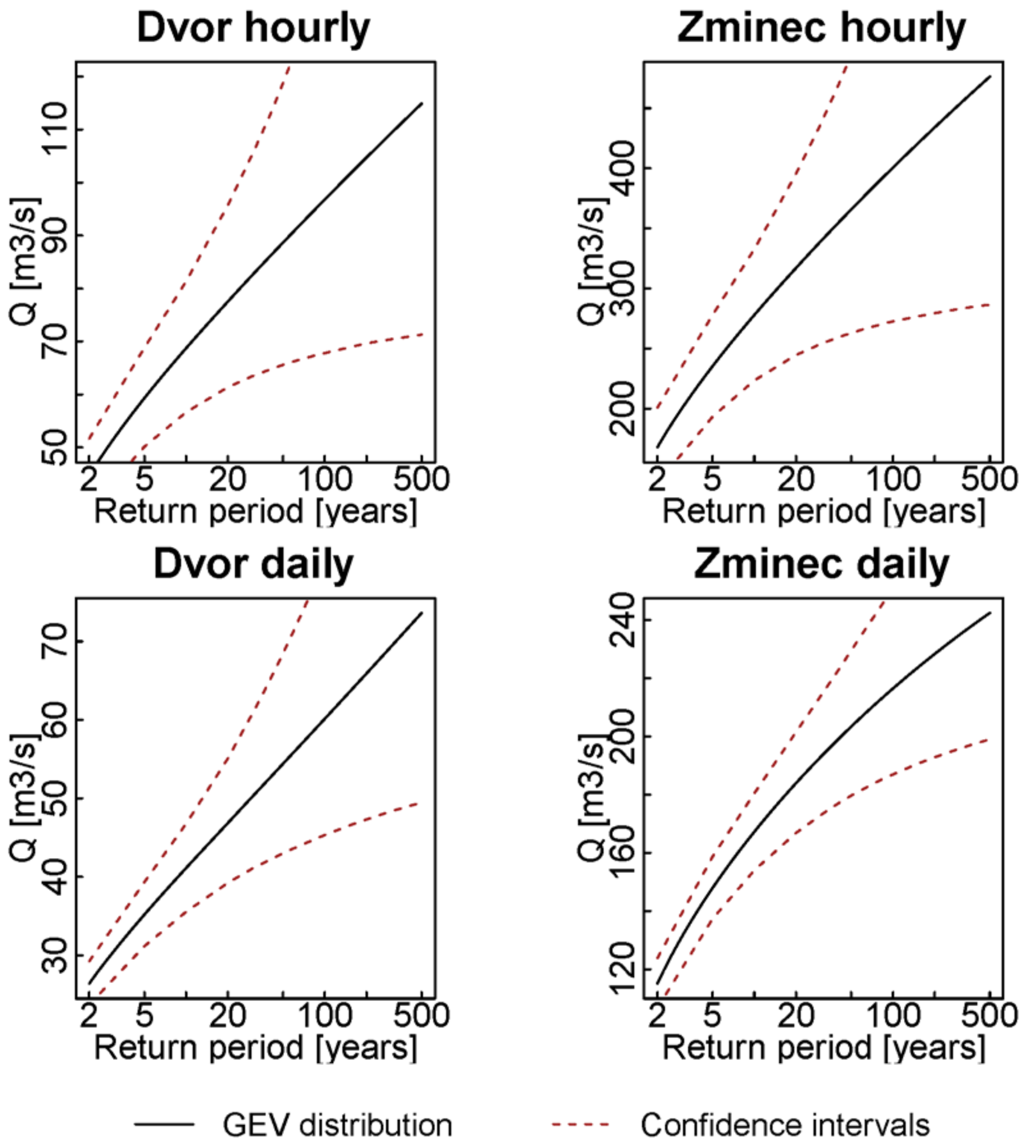

Figure 7: Flood frequency analysis results using GEV distribution and 90 % confidence intervals for the Dvor and Zminec gauging stations using hourly and daily discharge data.

Slika 7: Rezultati verjetnostnih analiz z uporabo GEV porazdelitve z intervali zaupanja (90 %) za postaji Dvor ter Zminec z uporabo urnih ter dnevnih podatkov o pretokih.

In the last step of the study the FFA was performed for the Dvor and Zminec stations using hourly and daily discharge data. The hourly and daily sample periods are shown in Table 2. The results for the Železniki station are not shown because only 10 years of hourly data were used in this study. Fig. 7 shows the FFA results using the GEV distribution where the method of L-moments was used to estimate the distribution parameters and 90 % confidence intervals for the Dvor and Zminec stations using hourly discharge data. Mann-Kendall test (e.g., Kendall, 1975; Douglas et al., 2000) was used to identify trends in the AM samples, which were defined based on the hourly discharge data before performing the FFA. For all three gauging stations (Dvor, Zminec, Železniki) statistical trends were positive; however, none of these trends was statistically significant with the chosen significance level 0.01. The parametric bootstrap procedure was used to define the confidence intervals. The algorithm (10,000 samples were generated for each case) defined in Meylan et al. (2012) was applied to construct the 90 % confidence intervals, which are shown in Fig. 7. One can notice that the sample period has an influence on the spread of the confidence intervals. The sample periods for hourly data are shorter than the periods for daily data, which also reflects in larger spread of the confidence intervals shown in Fig. 7. However, difference between using daily and hourly data has a larger influence on the relation between design discharge values and return period than the sample period.

5. Conclusions

Daily and hourly discharge data from three Slovenian torrential streams were used in this study to investigate the influence of one wet meteorological year on the design discharges and flood event volumes estimations. The data-based approach was selected and design discharge and flood event volumes were determined using the univariate and multivariate flood frequency procedures, where AM, POT and copula methods were selected. The aim of the study was to evaluate the influence of several FFA aspects, such as sample selection (hourly or daily) and method used (AM, POT or copula), on the relationship between design variable and return period. The conclusions of this study are:

i. The consideration of meteorologically wet year 2014 in the sample caused an increase in the design discharge values; however, these changes were generally smaller than changes connected with selection of method to perform FFA. For the Dvor and Zminec stations the AM, POT and copula results are in agreement, which is not the case for the Železniki station where different results were obtained using AM and POT methods.

ii. In case of flashy streams the use of daily discharge data to perform FFA is inappropriate due to the significant loss of information compared with hourly data. Again, data time step selection has a significantly larger influence on the design discharge values than (non)consideration of one year in the sample.

iii. Sample period affects the computed confidence intervals that were determined using parametric bootstrap procedure.

Based on this, we can draw a general conclusion regarding the FFA for torrential streams: the FFA should be performed using hourly discharge data and the final FFA results should include confidence intervals to capture the uncertainty in the relationship between design value and return period.

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