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Development of the Methodology for the Design Hydrograph Estimation in Slovenia, Europe

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Abstract

Design peak discharge and hydrograph estimation are one of the most frequently needed tasks in engineering hydrology. Therefore, numerous options and methods are available, from most simple empirical equations or more sophisticated flood frequency analysis to very complex rainfall-runoff models including stochastic rainfall generators. Engineers that are dealing with river engineering and the design of hydro-technical structures such as culverts, dams, and levees or preparation of flood risk maps are often applying relatively simple methods that do not account for the uncertainty related to the design peak discharge and hydrograph calculation. Moreover, in some cases not all available discharge data is used for the engineering design. Non-optimal selection of the methodological steps can lead to over- or under-estimation of the design peak discharge, hydrograph volume and duration. This can lead to higher costs of construction or questionable safety of the designed and constructed hydro-technical structures. Thus, a robust state-of-the-art methodology is needed to guide engineers in the process of the design peak discharge or hydrograph estimation. Such methodology is still lacking in Slovenia (central Europe) where river engineers often apply very simple empirical equations for the estimation of the design peak discharges without any consideration of uncertainty, especially in case of small torrential watersheds. At the same time, they use very complex 2D hydraulic models for flood simulations or design. This contribution will present recent developments in relation to the definition of the methodology for the design peak discharge and hydrograph calculation in case of gauged and ungauged watersheds in Slovenia.

Keywords: Design flood; Design hydrograph; Design peak discharge; Methodology; Slovenia

1. INTRODUCTION

Design peak discharge and hydrograph estimations are one of the most frequently needed tasks in engineering hydrology (Bezak et al., 2018). Numerous options and methods are available, from relatively simple empirical equations or more sophisticated flood frequency analysis using peak discharge data (Sraj et al., 2015) to very complex rainfall-runoff models including stochastic rainfall generators (Pushpalatha et al., 2011; Kossieris et al., 2018; Sezen et al., 2019). Selection of suitable method(s) mostly depends on availability of measured discharge data. In case that discharge data is available one can apply the multivariate or univariate flood frequency analysis (Bezak et al., 2014; Sraj et al., 2015) or set-up, calibrate, and evaluate the rainfall-runoff model (Coron et al., 2017; Addor and Melsen, 2019; Lavtar et al., 2020). In case that discharge data is not available, alternative methods (Blöschl et al., 2011) should be applied taking into consideration regionalization concepts, empirical approaches, etc.

Engineers that are dealing with river engineering and the design of hydro-technical structures such as culverts, dams, and levees or preparation of flood risk maps are often applying relatively simple methods that do not account for the uncertainty related to the design peak discharge and hydrograph calculation. Moreover, in some cases not all available discharge data is used for the engineering design (Meylan et al., 2012). Non-optimal selection of the methodological steps can lead to over- or under-estimation of the design peak discharge, hydrograph volume and duration. This can lead to higher costs of construction or questionable safety of the designed and constructed hydro-technical structures (Kryžanowski et al., 2014). Thus, a robust state-of-the-art methodology is needed to guide engineers in the process of the design peak discharge or hydrograph estimation. Such methodology is still lacking in Slovenia (central Europe) where river engineers often apply very simple empirical equations for the estimation of the design peak discharges without any consideration of uncertainty and at the same time use very complex hydraulic models for flood simulations or design.

This contribution will present recent developments in relation to the definition of the methodology for the design peak discharge and hydrograph calculation in case of gauged and ungauged catchments in Slovenia. The methodology will consider state-of-the-art methods developed and applied throughout the globe and adopt them based on the characteristics of Slovenia (e.g., climate, topography). The methodology will make use of recently developed regional empirical curves (for Slovenia) for the peak discharge estimation including uncertainty (Piry, 2020). Additionally, the methodology for the design hydrograph estimation will be based on the application of copula functions that simultaneously consider peak discharge and hydrograph volume (Brunner et al., 2017) in case that measured discharge data is available. In case that discharge data is limited or not available, a methodology using the rainfall-runoff models will be presented.

The main aim of this contribution is to present recent methodological development done in Slovenia and raise awareness among engineers about possible uncertainties related to the design peak discharge and hydrograph definition.

2. PROPOSED METHODOLOGY

Table 1 shows overview of the proposed methodology for the design hydrograph estimation in Slovenia using different approaches for gauged and ungauged catchments. Additionally, the methodology is divided into simple and more sophisticated approach where the first one should be used for less important applications such as culvert design in case of roads with the design vehicle speed less than 60 km/h or design of river cross-sections in places without major infrastructure. The more sophisticated approach should be used in case of design of hydro-power plants, larger flood protection works such as design of dry retention reservoirs, etc. Detailed description of the methodology is provided in the following two subsections.

Table 1. Overview of the proposed methodology for the design hydrograph estimation.

	GAUGED CATCHMENTS	UNGAUGED CATCHMENTS
SIMPLE APPROACH	Univariate flood frequency analysis (FFA) with the consideration of the uncertainty	Regional empirical curves that relate specific discharge (e.g., q_{100}) and catchment area or application of event based rainfall-runoff model and design rainfall events as shown for example by Bezak et al. (2018)
SOPHISTICATED APPROACH	Multivariate flood frequency approach using copula functions as suggested by Brunner et al. (2017)	Application of rainfall-runoff model and multiple design rainfall scenarios defined either using stochastic rainfall generators (using the FFA based on the simulated flow data) or based on different scenarios of design rainfall events (e.g., different spatial extent, different duration)

2.1 Gauged catchments

In case that measured discharge data is available, construction of the design hydrograph based on the results of the univariate flood frequency analysis (FFA) is suggested (Bezak et al., 2014). In such analysis the largest peak discharge in each year is selected (i.e. annual maximum method) to form a sample for the FFA (Bezak et al., 2014). Different distribution functions can be used to model the relationship between the peak discharges and return period (e.g., Pearson type 3, generalized extreme value (GEV)) and parameters can be estimated using the method of L-moments, method of moments, etc. (Bezak et al., 2014). Uncertainty can be estimated using the parametric bootstrap approach (Meylan et al., 2012). Figure 1 shows an example of such analysis for the gauging station Litija on the Sava River. In this case the GEV distribution was selected to perform the FFA and method of L-moments was used for parameter estimation. The design hydrograph was then constructed using the typical flood hydrograph (TFH) method that is commonly used in engineering practice as mentioned by Yue et al. (2002). In the TFH method, a typical flood hydrograph is selected to define the design hydrograph (Figure 1). Multiple hydrographs can be selected (e.g., short- and long-duration hydrographs) to construct multiple design hydrographs.

In case of more important hydro-technical structures, a more complex method should be applied. This is the method that was proposed by Brunner et al. (2017) and it is based on the multivariate flood frequency analysis using copula functions. Multiple steps should be conducted in order to define the design hydrograph such as: sample definition (e.g., annual maximum method or peaks over threshold), classification of events based on the type of event (e.g., rain on snow, flash flood, etc.), baseflow separation, data normalization, selection of the typical flood hydrograph, use of probability density of function for the description of the hydrograph shape, modelling of the relationship between hydrograph volume and peak discharge using copulas, definition of the multivariate return period (Figure 2), definition of the design hydrograph with the consideration of the uncertainty. Detailed description can be found in Brunner et al. (2017). Two examples of such design hydrographs are shown in Figure 3 for the gauging station Dravograd on the Drava River in Slovenia.

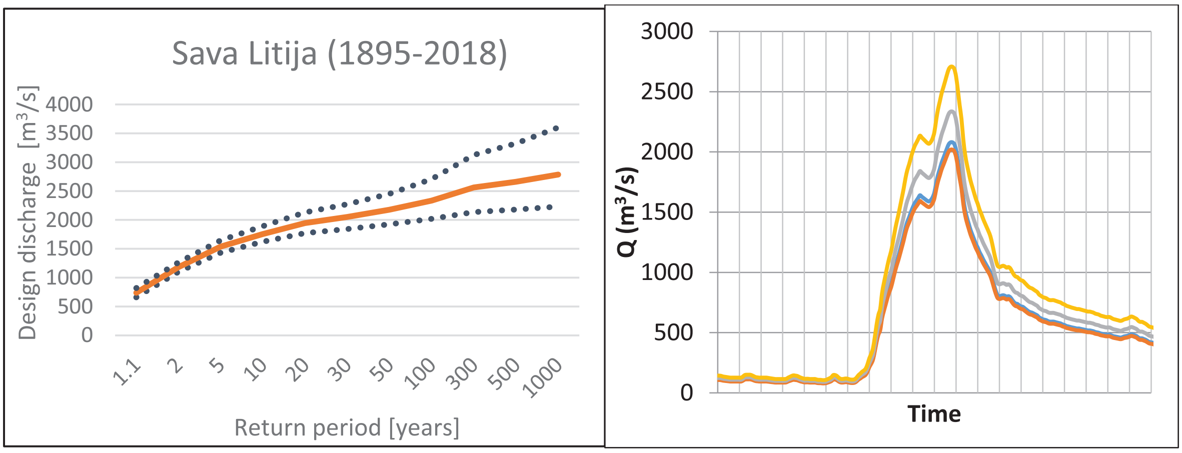

Figure 1. Left figure: flood frequency analysis (FFA) results (orange line) for the gauging station Litija on the Sava River using the annual maximum peak discharge data for the period 1895–2018 with the consideration of the 95% confidence intervals (dotted lines). Right figure: design flood hydrograph based on the upper (yellow line), lower (red line) confidence intervals, and based on the FFA results (grey line) for the 100-year return period. Measured hydrograph used to construct the design hydrograph is shown with blue line.

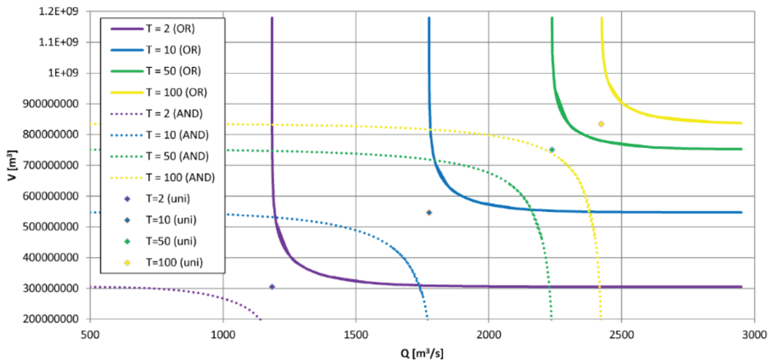

Figure 2. Comparison between the multivariate return periods (AND and OR) and univariate return period (uni). Figure is adapted after Šraj et al. (2013).

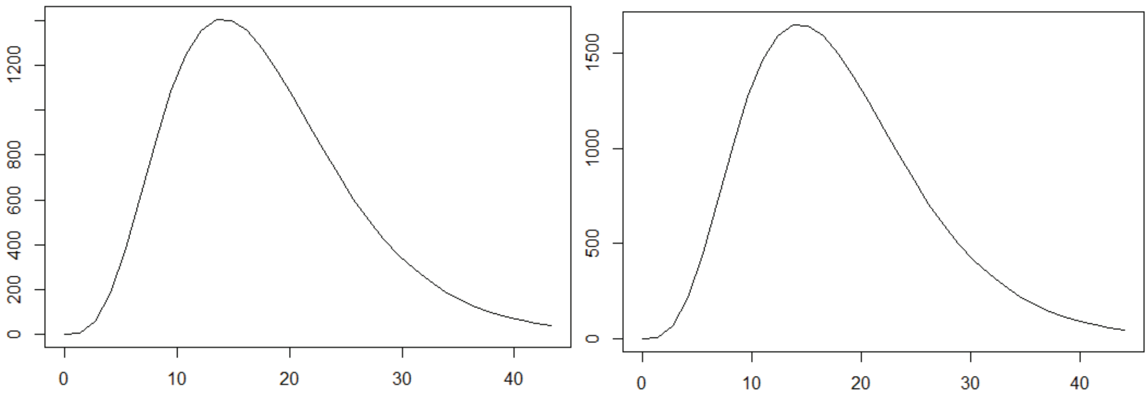

Figure 3. Example of the design hydrographs for the AND 10-years return period (left figure) and OR 10-years return period (right figure) according to the methodology proposed by Brunner et al. (2017). X-axis shows time in hours and y-axis discharge in m^3/s. Design hydrographs for the gauging station Dravograd on the Drava river in Slovenia are shown. Hourly data from 1996 until 2019 was used to construct the design hydrographs. Please note that graphs have different y-axis scale.

2.2 Ungauged catchments

In case of ungauged catchments, one can use simple regionalized empirical threshold curves that were developed for nine sub-regions in Slovenia (Figure 4) based on the results of the flood frequency analysis (Piry, 2020). Figure 5 shows example of such thresholds for one of the regions in Slovenia (Figure 4). This kind of thresholds can be used to obtain estimate of the design discharge values together with the consideration of uncertainty. It should be noted that very small catchments (less than 5 km^2) are not included in these thresholds since this kind of catchments in Slovenia are mostly ungauged. Thus, there are no discharge data available to perform the FFA. The smallest catchments with some measured data available have size of around 8–10 km^2 (Figure 6). Thus, it is clear that the specific discharge for very small catchments (i.e. around 1 km^2) in Slovenia can be in the range of 5-15 m^3/s/km^2 (Figure 6).

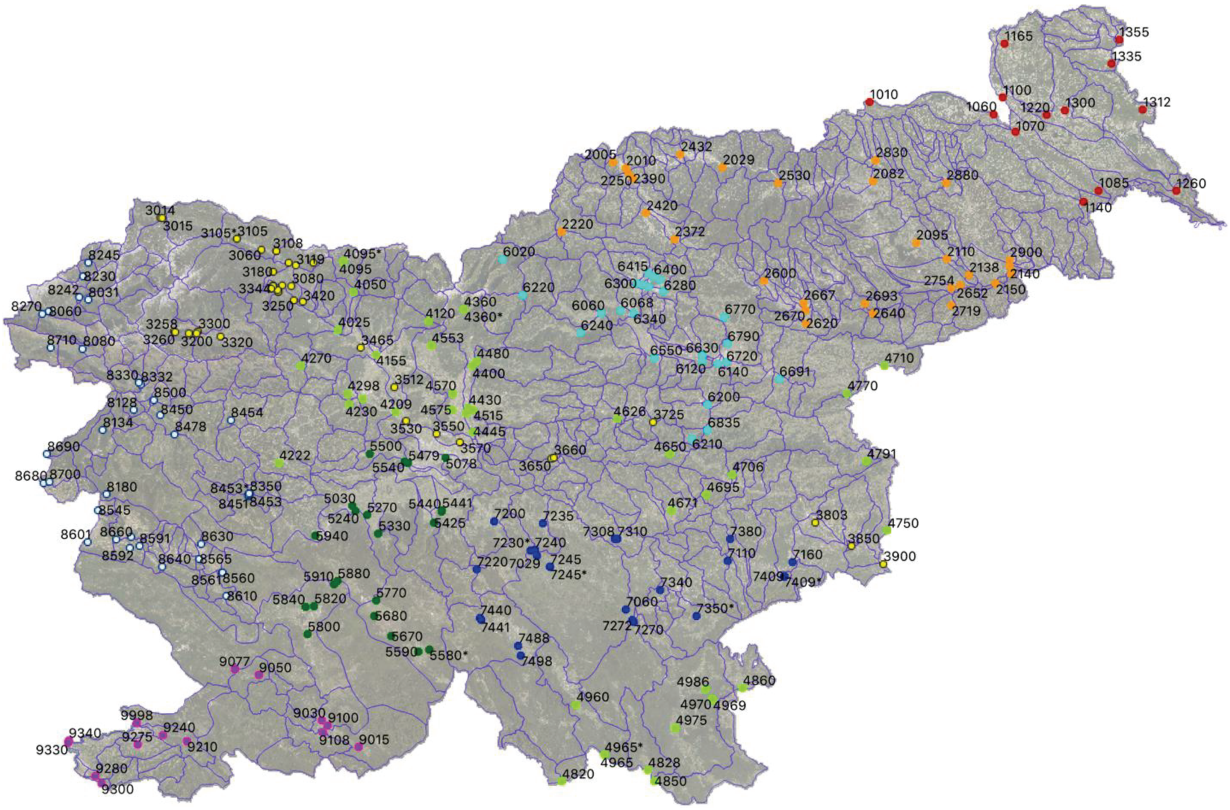

Figure 4. Nine sub-regions for which regionalized empirical thresholds were prepared. Regions are shown with different colors. Adapted after Piry (2020).

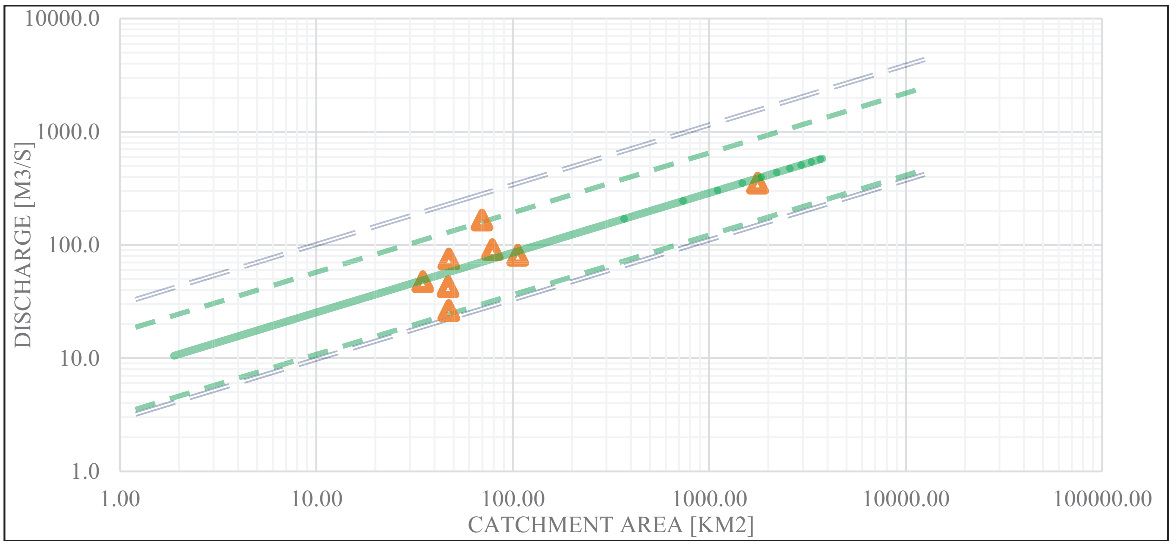

Figure 5. Example of regional empirical thresholds for the 100-year floods that were developed based on the FFA analysis for one of the sub-regions in Slovenia. Orange triangles show FFA results for gauged

catchments. Full green line shows regionalized empirical threshold and dashed green lines show confidence levels. Dashed blue lines show maximum and minimum values of the 95% confidence limits related to the FFA. Adapted after Piry (2020).

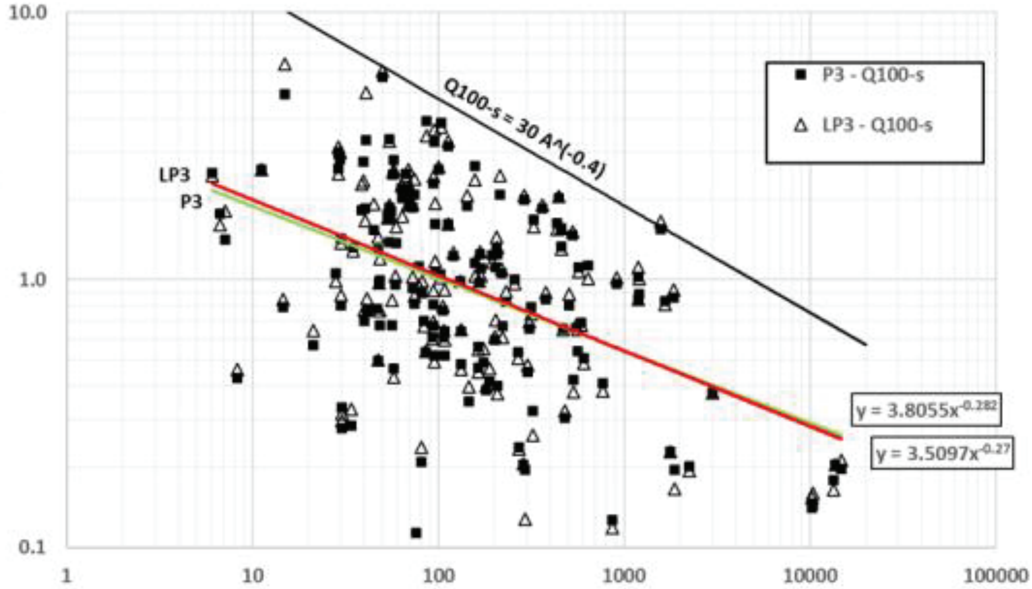

Figure 6. Empirical threshold curves (red and green line) for the return period of 100 years for all the gauging stations in Slovenia based on the FFA results using Pearson type 3 and log-Pearson type 3 distributions. Additionally, maximum envelope curve is shown (black line). Results are adapted after Mikoš (2020).

In case that one needs to define the design hydrograph, a different approach is needed (Table 1) where simple rainfall-runoff models such as HEC-HMS can be used together with the design rainfall events (Bezak et al., 2018). Such methodology involves the following steps. The first step is an estimation of model parameters such as curve number (CN) and lag time based on the catchment properties such as land use, soil characteristics, slope, river length, etc. (e.g., Bezak et al., 2018). The second step is a definition of the design rainfall event with the assumption that the rainfall duration should be roughly equal to the catchment time of concentration (Šraj et al., 2010). This is followed by a description of the temporal rainfall distribution for example using the Huff curves (Dolšak et al., 2016; Bezak et al., 2018). Such methodology assumes that the return periods of the design rainfall event and design hydrograph are the same. Example of such calculations for one of the catchments in Slovenia with 12.5 km^2 (river Draščica) is shown in Figure 7. For bit larger catchments (e.g., from 10 to 100–150 km^2) a combination of interpolated intensity-duration-frequency (IDF) values (Figure 8) and interpolated Huff values (Figure 9) can be used to define the design rainfall event using the catchment boundary.

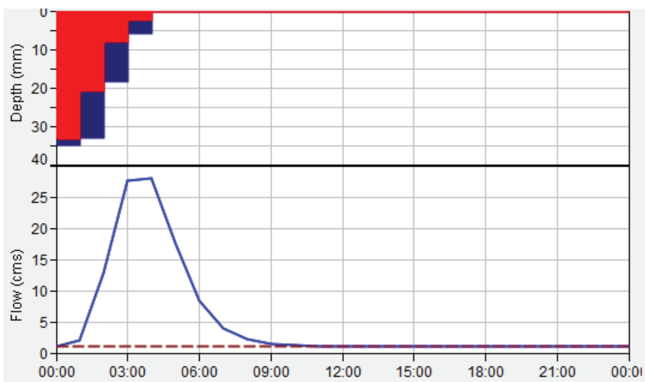

Figure 7. Example of the design hydrograph calculation (blue line) based on the design rainfall event (upper panel) for the Draščica River (12.5 km^2) in Slovenia. Results for the 100-year return period are shown. The temporal rainfall distribution was described using the Huff curves.

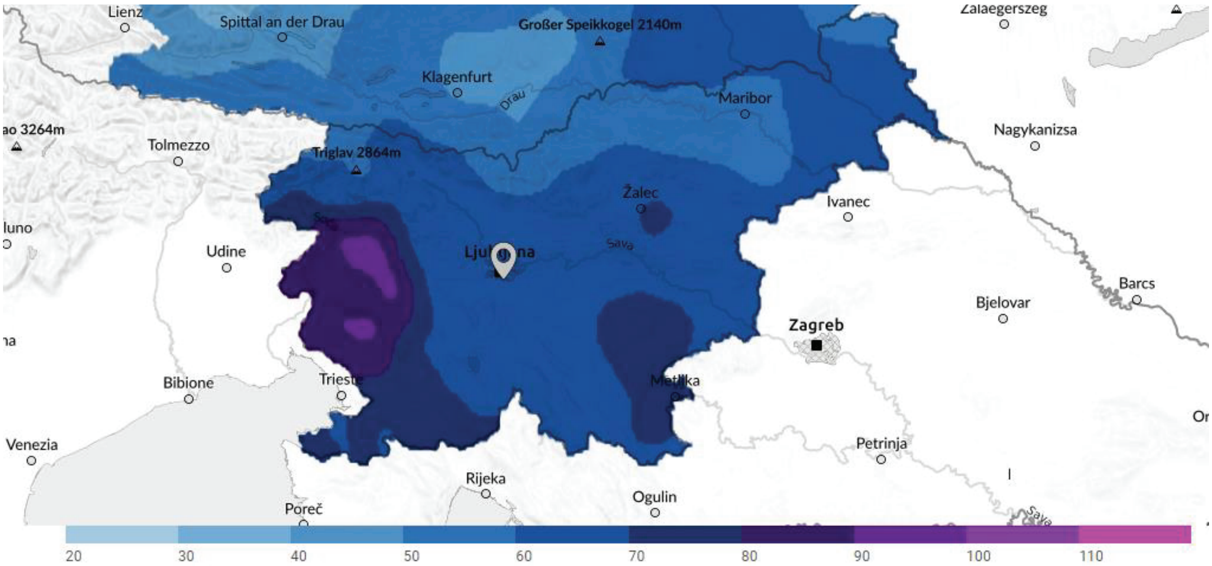

Figure 8. Example of the spatial map for the 100-year design rainfall event with the duration of one hour for the area of Slovenia. Maps and design rainfall values for other rainfall durations are available at https://www.crossrisk.eu/. A legend shows rainfall amount in mm.

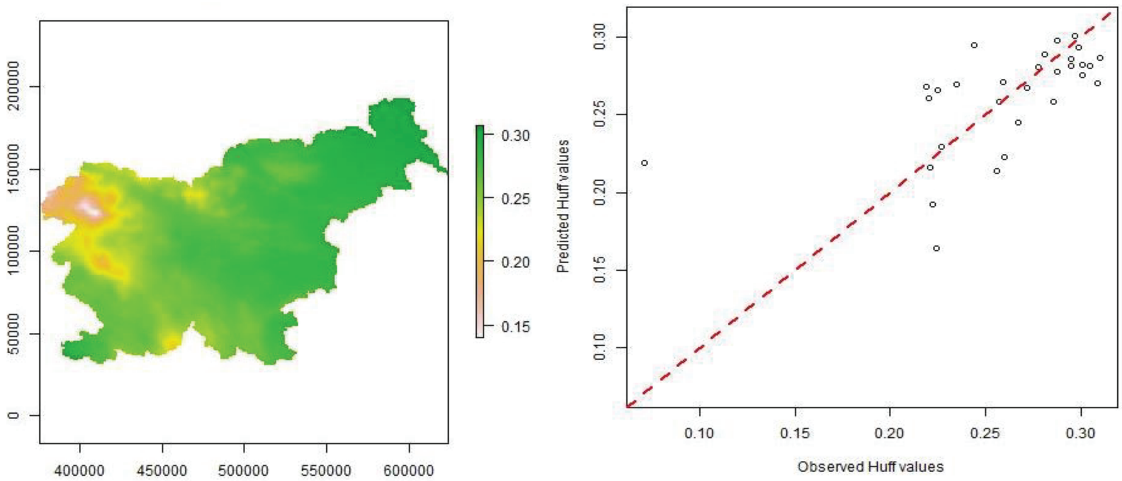

Figure 9. Left figure: example spatially interpolated maps (normalized rainfall amount at 0.3 normalized time for rainfall events longer than 24 hours) that can be used to define the Huff curves for a random catchment in Slovenia. Right figure: leave-one-out cross validation results for the external drift kriging that was used to prepare the interpolated maps.

In case of very important hydro-technical structures even more sophisticated methods should be used with a combination of the stochastic rainfall simulators and rainfall-runoff models. Model parameters can be estimated based on different methods (Blöschl et al., 2011) such as a-priori estimation of model parameters, transfer of calibrated parameters from gauged catchments, constraining model parameters by dynamic proxy data, etc. One such example is shown in Figure 10 where the lumped conceptual rainfall-runoff model GR4H (Coron et al., 2017, 2018) was calibrated for more than 15 catchments in Slovenia. Such regionalized relationships can be used to estimate model parameters in case of ungauged catchments. It should be noted that such relationships are site specific, meaning that are valid only for specific region. For example, in Slovenia forest covers almost 60% of the entire area. Therefore, a reliable estimate can be obtained for most of the catchments but for the catchments with limited forest cover a negative parameter value would be obtained, which is of course not a meaningful result. Then stochastic rainfall and air temperature simulators (Evin et al., 2018; Kossieris et al., 2018; Evin, 2019) can be used to generate multiple time series of rainfall and air temperature data to be used as an input to the rainfall-runoff model. Simulated discharge data can then be used to perform the FFA and to define the design discharge values and hydrographs as in the case of the gauged catchments. Example of two random realizations of stochastic rainfall simulators is shown in Figure 11. This kind of data can then be used as input to the rainfall-runoff model (e.g., Figure 12). The procedure can be repeated multiple times to obtain estimate of the potential uncertainty due to model parameters (e.g., uniform distribution can be used to generate parameters within the range of confidence intervals as shown in Figure 10) and natural variability (e.g., stochastic simulators) (Figure 12). Example of the design hydrograph for one of the catchments in Slovenia is shown in Figure 13.

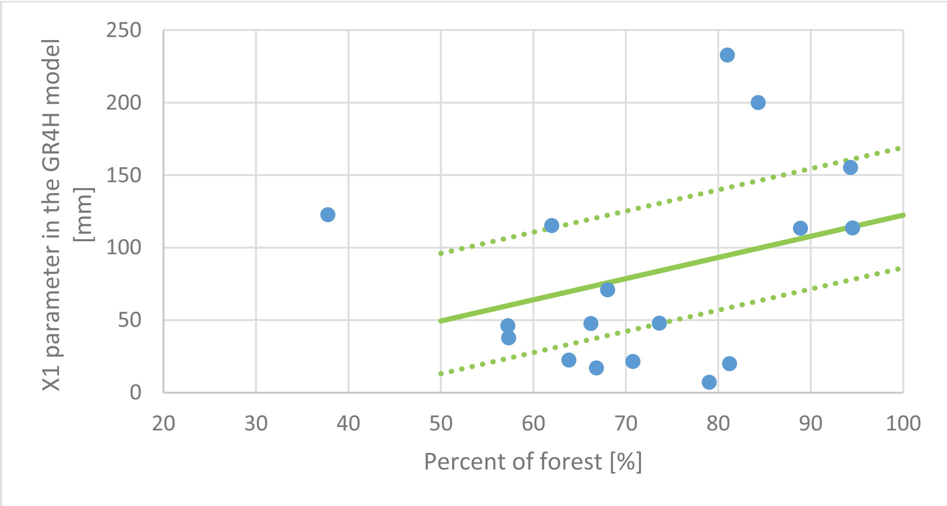

Figure 10. Example of regionalized model parameters for the GR4H model (Coron et al., 2017, 2018) and percent of forest cover. Full green line shows best fitted trend line and dotted green lines indicate confidence intervals.

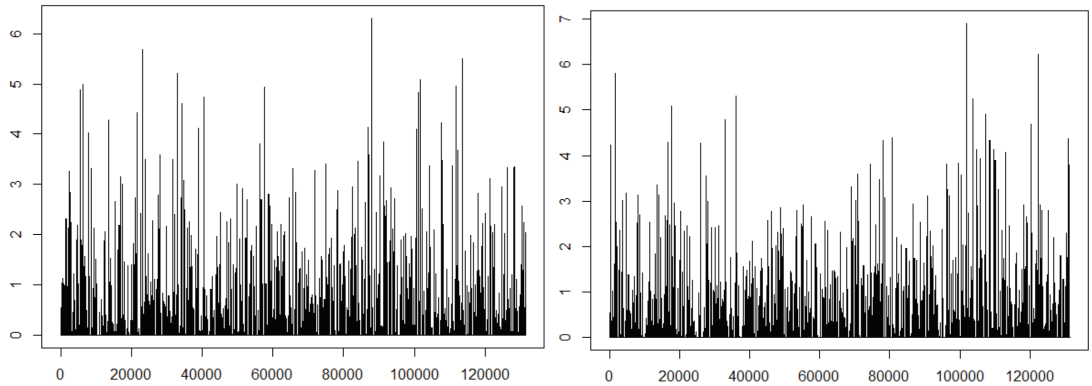

Figure 11. Stochastically simulated hourly rainfall data (in mm) for the location of the Hrastnik rainfall station in Slovenia using the model described by Kossieris et al. (2018).

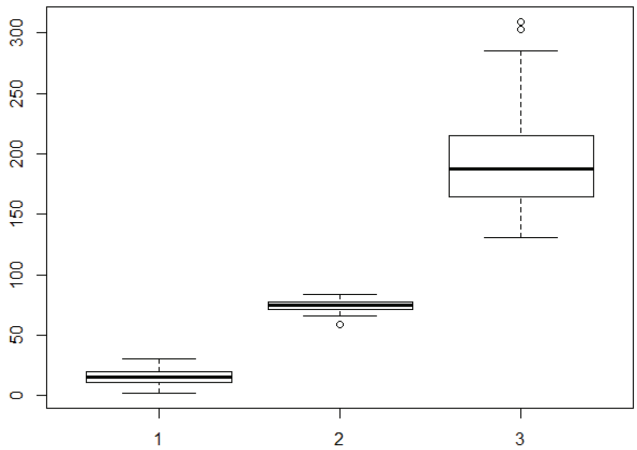

Figure 12. Boxplots of minimum (1), mean (2) and maximum (3) annual peak discharge values based on simulations of 60-years of data 100-times. Y-axis shows discharge values in m^3/s. Results for the Zagorje station on the Medija River in Slovenia (catchment area of 98 km^2) are shown. GR4H model was used for model simulations and stochastically generated precipitation and air temperature data was used as an input.

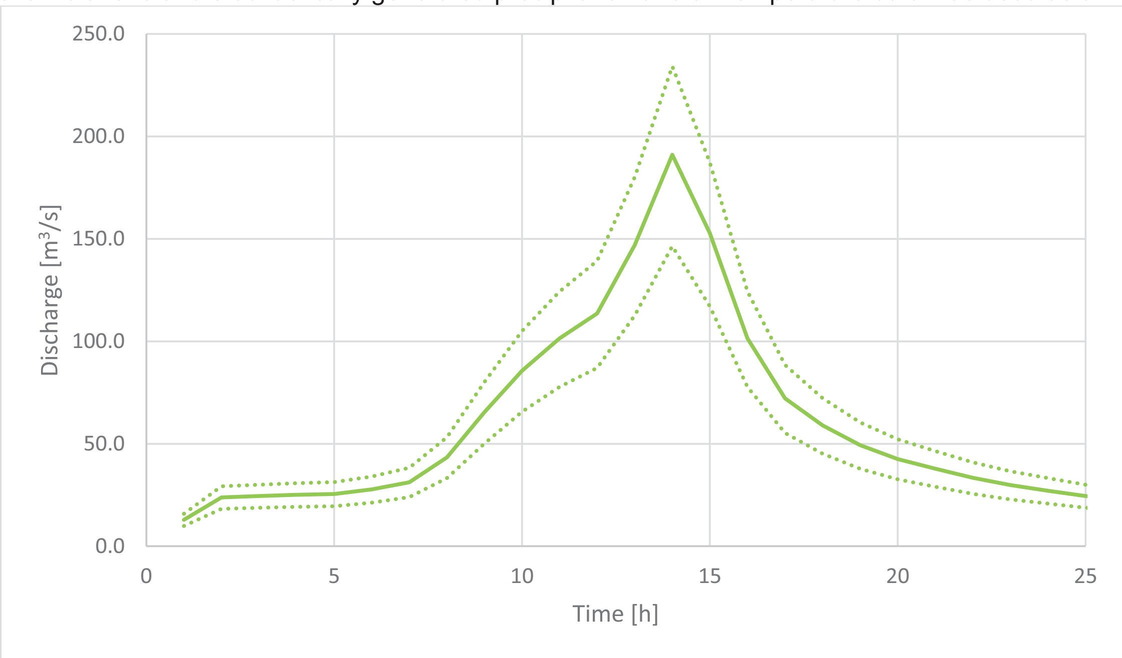

Figure 13. Example of the design hydrograph with the 100-year return period (full green line) with the consideration of the 95% confidence intervals (dotted green lines) for the Zagorje station on the Medija River. The stochastic rainfall and air temperature simulators were used to generate 100-times 60-years of hourly data that was used as an input to the GR4H rainfall-runoff model. A FFA approach and TFH were used to define the design hydrograph together with confidence intervals.

3. CONCLUSIONS

This contribution represents overview of the proposed methodology that should be used for the design hydrograph definition in Slovenia where such methodology is currently not available. The methodology uses multiple state-of-the-art steps and methods that should reduce the uncertainty in the hydrological assessments. The methodology distinguishes between gauged and ungagged catchments and between simple and complex methods. Thus, it can cover the variety of different needs and suitable method should be selected based on the discharge data availability, purpose of use, precipitation data availability, etc.

4. ACKNOWLEDGEMENTS

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5. REFERENCES

Addor, N., and Melsen, L. A. (2019). Legacy, Rather Than Adequacy, Drives the Selection of Hydrological Models. *Water Resour. Res.* 55, 378–390. doi:10.1029/2018WR022958.

Bezak, N., Brilly, M., and Šraj, M. (2014). Comparison between the peaks-over-threshold method and the annual maximum method for flood frequency analysis | Comparaison entre les méthodes de dépassement de seuil et du maximum annuel pour les analyses de fréquence des crues. *Hydrol. Sci. J.* 59. doi:10.1080/02626667.2013.831174.

Bezak, N., Šraj, M., Rusjan, S., and Mikoš, M. (2018). Impact of the rainfall duration and temporal rainfall distribution defined using the Huff curves on the hydraulic flood modelling results. *Geosci.* 8. doi:10.3390/geosciences8020069.

Blöschl, G., Sivapalan, M., Wagener, T., Viglione, A., and Savenije, H. (2011). *Runoff prediction in ungauged basins: Synthesis across processes, places and scales*. doi:10.1017/CBO9781139235761.

Brunner, M. I., Viviroli, D., Sikorska, A. E., Vannier, O., Favre, A.-C., and Seibert, J. (2017). Flood type specific construction of synthetic design hydrographs. *Water Resour. Res.* 53, 1390–1406.

doi:10.1002/2016WR019535.

Coron, L., Perrin, C., Delaigue, O., Thirel, G., and Michel, C. (2018). airGR: Suite of GR Hydrological Models for Precipitation-Runoff Modelling. Available at: https://webgr.irstea.fr/en/airGR/.

Coron, L., Thirel, G., Delaigue, O., Perrin, C., and Andréassian, V. (2017). The suite of lumped GR hydrological models in an R package. *Environ. Model. Softw.* 94, 166–171. doi:10.1016/j.envsoft.2017.05.002.

Dolšak, D., Bezak, N., and Šraj, M. (2016). Temporal characteristics of rainfall events under three climate types in Slovenia. *J. Hydrol.* 541. doi:10.1016/j.jhydrol.2016.08.047.

Evin, G. (2019). GWEX: Multi-Site Stochastic Models for Daily Precipitation and Temperature. Available at: https://cran.r-project.org/web/packages/GWEX/index.html.

Evin, G., Favre, A.-C., and Hingray, B. (2018). Stochastic generation of multi-site daily precipitation focusing on extreme events. *Hydrol. Earth Syst. Sci.* 22, 655–672. doi:10.5194/hess-22-655-2018.

Kossieris, P., Makropoulos, C., Onof, C., and Koutsoyiannis, D. (2018). A rainfall disaggregation scheme for sub-hourly time scales: Coupling a Bartlett-Lewis based model with adjusting procedures. *J. Hydrol.* 556, 980–992. doi:10.1016/j.jhydrol.2016.07.015.

Kryžanowski, A., Brilly, M., Rusjan, S., and Schnabl, S. (2014). Review Article: Structural flood-protection measures referring to several European case studies. *Nat. Hazards Earth Syst. Sci.* 14, 135–142. doi:10.5194/nhess-14-135-2014.

Lavtar, K., Bezak, N., and Šraj, M. (2020). Rainfall-runoff modeling of the nested non-homogeneous sava river sub-catchments in Slovenia. *Water (Switzerland)* 12. doi:10.3390/w12010128.

Meylan, P., Favre, A.-C., and Musy, A. (2012). *Predictive Hydrology: A Frequency Analysis Approach*. CRC Press.

Mikoš, M. (2020). Flood hazard in Slovenia and assessment of extreme design floods | Poplavna nevarnost v sloveniji in ocena ekstremnih projektnih poplavnih pretokov. *Acta Hydrotechnica* 33, 43–59. doi:10.15292/acta.hydro.2020.04.

Piry, M. (2020). Analiza projektnih pretokov z upoštevanjem negotovosti. Available at: https://repozitorij.uni-lj.si/IzpisGradiva.php?id=123334&lang=slv.

Pushpalatha, R., Perrin, C., Le Moine, N., Mathevet, T., and Andréassian, V. (2011). A downward structural sensitivity analysis of hydrological models to improve low-flow simulation. *J. Hydrol.* 411, 66–76. doi:10.1016/j.jhydrol.2011.09.034.

Sezen, C., Bezak, N., Bai, Y., and Šraj, M. (2019). Hydrological modelling of karst catchment using lumped conceptual and data mining models. *J. Hydrol.* 576. doi:10.1016/j.jhydrol.2019.06.036.

Sraj, M., Bezak, N., and Brilly, M. (2015). Bivariate flood frequency analysis using the copula function: A case study of the Litija station on the Sava River. *Hydrol. Process.* 29. doi:10.1002/hyp.10145.

Šraj, M., Bezak, N., and Brilly, M. (2013). Primerjava med klasičnimi univariatnimi verjetnostnimi analizami in bivariatnimi z uporabo funkcije kopula. *Acta hydrotechnica* 26, 37–48. Available at: https://actahydrotechnica.fgg.uni-lj.si/si/paper/a44ms.

Šraj, M., Dirnbek, L., and Brilly, M. (2010). The influence of effective rainfall on modeled runoff hydrograph | Vplyv efektívnych zrážok na modelovaný hydrograf odtoku. *J. Hydrol. Hydromechanics* 58, 3–14. doi:10.2478/v10098-010-0001-5.

Yue, S., Ouarda, T. B. M. J., Bobée, B., Legendre, P., and Bruneau, P. (2002). Approach for describing statistical properties of flood hydrograph. *J. Hydrol. Eng.* 7, 147–153. doi:10.1061/(ASCE)1084-0699(2002)7:2(147).

