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A methodology for the estimation of control flood wave hydrographs for the Horné Orešany reservoir

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Recent changes in climatic characteristics and consequent changes in the discharges and in the hydrological response of watersheds raise questions about the safety of water structures. Changes in flood wave characteristics (shape, volume, peak flow) may significantly affect the functionality of these structures. The study proposes a methodology for constructing design wave and flood hydrographs using discharge time series. A case study was carried out in the Little Carpathians watershed of the Parná River, above the profile of the Horné Orešany reservoir in Slovakia. The volumes and characteristic shapes of the flood waves with the maximum annual and seasonal discharges were determined using the Floodsep software. Subsequently, the *T*-year annual and seasonal discharges were estimated. Then, for pairs of the *T*-year discharges and the associated volumes of flood waves, a joint probability distribution was constructed by copula functions. The associated volume of the *T*-year peak discharges was selected from the copula, and the probability of exceeding it was determined. Based on this analysis, a set of annual and seasonal control flood waves with the design maximum discharge, the associated volume with the selected probability, and the typical shape of the flood wave was constructed. This research provides satisfactory results for designing control waves necessary for assessing water structures with extreme loads and establishing a functional methodology for assessing other water structures in the region.

KEY WORDS: design flood hydrograph, Horné Orešany reservoir, separation of discharge wave

Introduction

Discharge time series are essential for various hydrology and water resources management activities. They are used to provide valuable information about long-term flow characteristics as well as, to a partial extent, when the analysis of individual extreme events are essential for solving many problems. In the case of floods, flood peak discharges are often sufficient to perform a traditional flood frequency analysis, the results of which can be used to design many engineering structures such as levees, bridges or flood control channels. However, it is sometimes critical to use whole flood hydrographs, as they provide other essential flood characteristics such as volume, duration, gradient, course, etc. These characteristics can be affect by the recent hydrological time series changes (Ďurigová et al., 2020; Mohammadzadeh et al., 2019; Yonus and Hassan, 2022). In practice, these hydrographs are often referred to as design flood hydrographs (DFH), which are often associated with an estimated return period. Hence, the physical properties of a flood event and statistical information about the event's rarity must be united (Serinaldi and Grimaldi, 2011). Design flood hydrographs are used as input for hydraulic simulations that are necessary for the design and safety assessments of critical hydraulic structures, such as dams or retention basins, as well as for the preparation of operational rules and management strategies of existing flood mitigation measures (Goswami, 2020; Yue et al., 2002).

The design of a hydraulic structure is sensitive to all the characteristics of a DFH, which means that it has to be estimated as close to reality as possible (Paquet, 2019). Even slight differences in any characteristic of the DFH may cause significant changes in the cost and efficiency of these structures (Yue et al., 2002). An excellent example of the importance of characteristics other than the flood peak, volume, and duration on the efficiency of retention basins in flood protection is given by Chow et al. (1988). They describe a situation in which two flood waves, differing only in their shapes, result in significant differences in the retention basin's flood peak reduction efficiency. To define a complete DFH, one has to estimate the following characteristics: 1) its peak discharge, 2) hydrograph volume or duration, and 3) the shape of the hydrograph. Estimating the first two characteristics is a traditional task in hydrology. It is backed up by many well-established methods, which are thoroughly described in an extensive literature describing the individual methods and their practical application.

Unfortunately, most of these methods are dedicated to a univariate flood frequency analysis (FFA), which communicates the difficulties of estimating hydrological variables (mostly peak discharges) with very large return periods that are far beyond the range of an available historical dataset (Paquet, 2019). However, the characteristics of flood hydrographs cannot be described by a single variable but must be described by a set of interdependent random variables usually consisting of a flood´s peak, volume and duration (Brunner et al., 2016). This means that the univariate framework of the FFA is not applicable and that a bi- or multivariate approach has to be considered instead of accounting for the dependency between, e.g., flood peaks and flood volumes or flood peaks and flood durations (Gräler et al., 2013; Salvadori and Michale, 2004; Szolgay et al., 2016).

Flood hydrographs often come in different shapes. They differ not only between catchments but also between the individual events influenced by various hydroclimatic factors (e.g., rainfall depths, wetness of a catchment), including the governing processes that determine the flood type (Brunner et al., 2017; Merz and Blöschl, 2003). Yue et al. (2002) summarize the existing methods of constructing unit hydrographs, which can be used to represent the shape of the constructed DFH and group them into the following four classes: traditional unit hydrograph (TUH), synthetic unit hydrograph (SUH), typical hydrograph (TH) and statistical methods (SM). While the TUH methods (Dooge, 1959; Yue and Hashino, 2000) utilize rainfall data and rely on simple rainfall-runoff modelling, the SUH methods (Jena and Tiwari, 2006; Snyder, 1938) try to relate the unit hydrographs to the physiographic descriptors of the catchments and enable their estimation in ungauged catchments as well. The TH methods (Paquet, 2019; Xiao et al., 2009) select the unit hydrograph from the observed flood hydrographs and scale it accordingly, as opposed to the SM methods (Brunner et al., 2018a; Goswami, 2020; Serinaldi and Grimaldi, 2011), which use probability density functions (pdf) of known flexible distributions to model the shape of the unit hydrograph with the significant advantage of the area under the curve being one (1). When constructing a DFH, Brunner et al. (2017) also emphasize the importance of limiting the analysis to the individual flood types such as flash floods, short-precipitation and long-precipitation floods, or snowmelt floods. The authors state that such a flood type-specific design is also advantageous from a statistical point of view as it avoids mixing very different events, which also justifies the assumption made in the FFA that the variables are independent and are randomly and identically distributed. Moreover, the flood type-specific design can also help to identify seasons with different types of flood risks (e.g., large peaks in the summer vs. large volumes in the spring), which can help adjust the existing flood control policies and operational rules of the reservoirs (Gaál et al., 2015; Merz and Blöschl, 2008).

Particular problems in constructing a DFH include developing a sampling strategy and identifying the individual flood events. The sampling strategy influences the sample size used in the analysis, which can often lead to different characteristics of the constructed DFH. Brunner et al. (2018b) investigated annual maxima (AM) and peaks over threshold (POT) sampling strategies and concluded that the latter seems to be a better choice for the estimation of a DFH. However, one should consider that the selection of the sampling strategy influences the apparatus of the methods that can be used in the FFA. Moreover, the automatic selection of the events can extend the flood sample by outliers (man-made floods that should be excluded from the FFA, or multimodal floods that should not be used to estimate the shape of the flood), which have to be manually removed.

Besides selecting the sampling strategy, one must also identify the individual flood events in terms of finding their beginning and end and separating their direct and base runoffs. Thiessen et al. (2019), who developed a method for identifying rainfall-runoff events in discharge time series, states that even though this process might be straightforward for a trained hydrologist, it is complicated to formulate rigid criteria that would enable the reliable identification of flood events. Currently, there is no single accepted method for automating this process, even though it has been the subject of substantial scientific efforts (Oppel and Mewes, 2020).

As the beginning and end of a flood event are often associated with the intersection of baseflow and direct runoff curves, most methods try to separate the baseflow from the discharge time series. The first methods date back to the 1930s (Chow et al., 1988), with the most recent ones utilizing digital filtering techniques, which are currently considered to provide the best results (Gonzales et al., 2009), as the most reliable tracer-based methods often lack input data. To mention a few of these methods, Paquet (2019) identified flood hydrographs by fixing a time from the flood peak (0 h) to the beginning (-24 h) and end (+48 h) of the event. Merz et al. (2006) proposed an iterative approach in which using a digital filter of Chapman and Maxwell (1996), the baseflow was separated from the direct runoff. The event's beginning and end were set at points where the direct runoff became lower than a certain threshold given by the direct runoff at the time of the peak flow. Thiesen et al. (2019) proposed a data-driven approach with different predictors to identify a flood hydrograph at the beginning, peak and end. They found that models using discharges as predictors returned the best results, making them even more attractive, as no additional data is required except for the discharge time series. Finally, Oppel and Mewes (2020) trained several machine learning algorithms to identify the beginning and end of a flood event as given by the position of its peak discharge. Despite the fact that their methods were able to reproduce manually-identified flood hydrographs very well, the process of building, training, and testing the algorithms is far beyond the capabilities of ordinary practitioners. Therefore, multiple authors have often suggested performing some sort of manual control to pick incorrectly identified flood events and exclude oddly-shape events from a flood sample dataset (Gaál et al., 2012; Merz et al., 2006; Paquet, 2019).

This study presents a complete methodology that can be used to build design flood hydrographs using only discharge time series. Within the methodology, a simple semi-automatic procedure was developed to identify the beginning and end of the pre-selected flood events, thereby enabling any type of sampling strategy. The flood event characteristics such as flood peaks, volumes, and durations are also a subject of a bivariate FFA using copulas to derive a joint probability distribution for dependent variables (either flood peaks and volumes or flood peaks and durations). The shape of the DFH is derived from the identified flood events, which are simplified to maintain the monotonicity of their rising and falling limbs (multimodal to unimodal hydrographs) and smoothed using a smoothed function composed of several normal distributions pdfs. The method enables the DFH construction using a flood´s peak, volume or duration and shape.

Materials and methods

Study area

The design flood hydrograph estimation for the safety assessment of the waterworks was processed for the Horné Orešany reservoir dam in Slovakia, which is located on the Parná river at rkm 25.00. The Parná river, with a length of 38.5 km, is the right-handed tributary of the Trnávka river. The spring of the Parná river is located in the Little Carpathians on the southeastern slopes of the Vápenná hill at an altitude of 560 m a.s.l. The catchment area in the reservoir profile is 45.59 km^2; the catchment is fan-shaped; and the average slope of the catchment is 2.5 %. The water structure is classified in II category of water structures, according to the amount of damage that would result from the sudden release of the water held. The dam was built for the purpose of land irrigation, mitigation of peak flows, improvement of minimum flows, sport fishing, and electricity generation. The water reservoir volume is 3.8 mil. m^3 and the flooded area is 0.496 km^2.
As the input data were used the discharge time series in hourly time steps and the maximum annual discharges. Data used in the analysis were provided by the Slovak Hydrometeorological Institute (SHMI) for the 5250 Parná – Horné Orešany gauging station for the period 1.11.1988–31.12.2019. The gauging station is located above the reservoir on the Parná river at rkm 26.8, and has a catchment area of 37.86 km^2. Precipitation and air temperature data were used for a better determination of the flood wave durations. The precipitation in the daily time step was collected from the Dolné Orešany rainfall station for the period 1.11.1988–31.12.2013. The air temperature data in the daily time step were taken from the SHMI Modra – Piesok climatological station for the period 1.11.1988–31.12.2013.

Methodology

Selection of discharge waves based on their seasonal occurrence

To determine the design flood hydrographs, it was necessary to correctly select the discharge waves and identify their volume and shape characteristics. The discharge waves analysed differed significantly not only in their duration but also in their shape and volume. Spring discharge waves are associated with melting snow or a combination of melting snow and rain. A similar wave formation may occur in the winter period. Therefore, these waves have a longer duration and greater volume than summer discharge waves, which often arise from storm events. Summer waves are slimmer in shape with a shorter duration.
For this reason, flood waves were analysed for annual and seasonal maximum discharges for the period 1989–2019, i.e.:

- Seasonal maximum discharges, April to May – Spring season;
- Seasonal maximum discharges, June to October – Summer season;
- Seasonal maximum discharges, November to March – Winter season;
- Annual maximum discharges.

Separation of discharge waves

A discharge wave is characterised by a rising limp, culmination, and subsequent falling limp. The separation of these waves and the calculation of the base flow have been processed by methods used in the FloodSep software (Valent, 2019). An example of separation is shown in Figure 1. The main task o f FloodSep is to

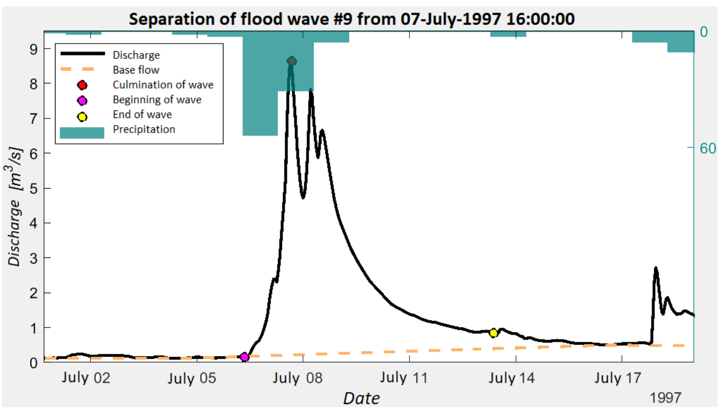

Fig. 1. Example of a flood wave separation in the FloodSep programme (Valent, 2019).

identify individual flood events from a time series of discharges and then analyse their characteristics. Subsequently, it was necessary to determine the flood peaks from a series of hourly discharges for each year. In each group of floods, the peak discharges were manually determined. The separation of the waves then took place in the following steps in each group according to the methods that were programmed in FloodSep:

1 Separation of the base flow: the beginning and end of the wave are determined subjectively.
2 Allocation of the beginning and end of the wave using precipitation and air temperature data.

Selection of the representative shape of the wave

The shape of the flood wave used in the design flood hydrographs was determined using the methods programmed in FloodSep as follows: In the first step, the discharge waves selected were simplified and scaled to an interval <0.1>. Then the multimodal flow hydrographs were transformed into a simple modal form. In the second step, a representative hydrograph was constructed from a set of scaled waves. The hydrographs were centred on the peak position so that the x-axis coordinate at this point was equal to 0. When flood hydrographs are constructed, the important parameter is the percentile, which affects the shape of the representative hydrograph. In this study, the 50%, 70% and 90% percentiles were applied, which resulted in three different shapes of flood hydrographs.

Local estimation of T – year discharges from available measurements

The estimation of the annual and seasonal floods, the selection of the theoretical probability distribution, and the parameters of the method for estimating the theoretical probability distribution were made according to the DVWK (1999) methodology. The following theoretical probability distribution and methods for estimating the parameters were selected according to statistical tests proposed in the DVWK:

- Spring season – 3-parameter lognormal distribution (LN3), the maximum likelihood method;
- Summer season – The Generalized Extreme Value distribution (GEV), the maximum likelihood method;
- Winter season – Pearson type III distribution (P3), the method of probability weighted moments;
- $Q_{an,max}$ – log-Pearson type III distribution (LP3), the moments method.

Volume of flood waves derived by an analysis of the relationship between the culmination and volumes

A joint probability distribution using a copula function was constructed for the pairs of peak discharges and their associated volumes. In this paper, we use the following types of copulas, chosen according to the smallest distance:

- Spring season – Frank copula;
- Summer season – Gumbel copula;
- Winter season – Gumbel copula;
- $Q_{an,max}$ – T copula.

For this study, we used a selected discharge with a probability of exceeding 0.01 and a conditional probability of non-exceedance of 0.5, 0.7, and 0.9.

Results and discussion

Separation of discharge waves

Figures 2 to 4 show the separation of the discharge waves in the spring, summer, and winter seasons. We can see that during the initial separation, some waves had prolonged durations and thus increased their volume. Attention was particularly paid to waves that were outside the range of the majority of the separated waves after the first step of the separation. When determining the duration of waves with more extreme values, whether it involved the peak discharge or volume, the beginning and end of the flow waves were incorrectly determined in the first step using the base flow. After an adjustment in the second step, their volumes decreased.
The results of the separation of the annual maximum discharge waves are shown in Figure 5.
We can see that the wave layout is not homogeneous and consists of several groupings of waves. While winter and spring waves rank towards waves with larger volumes and lower peak discharges, summer waves stand out from this trend and are characterised by a higher discharge and smaller volume, i.e., shorter durations. This redistribution of the waves points to the fact that the selection of waves in each season was an appropriate procedure for the solution and should be taken into account in the design of the design flood hydrographs.

Representative shape of control flood waves

As already mentioned in the previous section, waves with a percentile value of 50, 70 and 90% were selected for each group of floods. Figures 6 to 9 show the separated waves scaled for each group; as an example, only the percentile value of 50% is presented here. The highlighted shape is the representative one, see Figs. 6 to 9 (left). The next step produces a representative smoothed hydrograph using the Gauss composite function. The representative hydrograph defines the shape of the design wave, which is necessary for the correct determination of design flood hydrographs Figs 6 to 9 (right).

Construction of the flood control waves

When the design flood hydrographs were constructed, the design discharge values of the selected probability of exceedance and the corresponding volume and duration of the wave were estimated.
The results of the local estimation of the *T* – year discharges and conditional volumes of a given 100-year

discharge for each group are shown in the following Tables 1 to 3. As already mentioned in the previous sections, we used the following data for the design flood estimation: the 100-year design discharge, conditional probability of non-exceedance of the volume 0.5, 0.7 and 0.9, and wave duration, which we determined by assigning the conditional volume to the wave shape, using the 50, 70, and 90% percentile shapes.

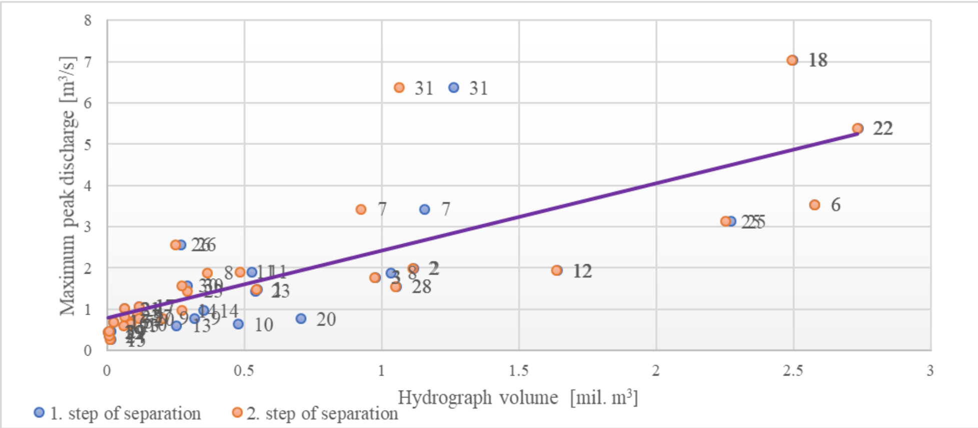

Fig. 2. Relationship between a flood´s volume and peak discharge: results of discharge-wave separation in the Spring season.

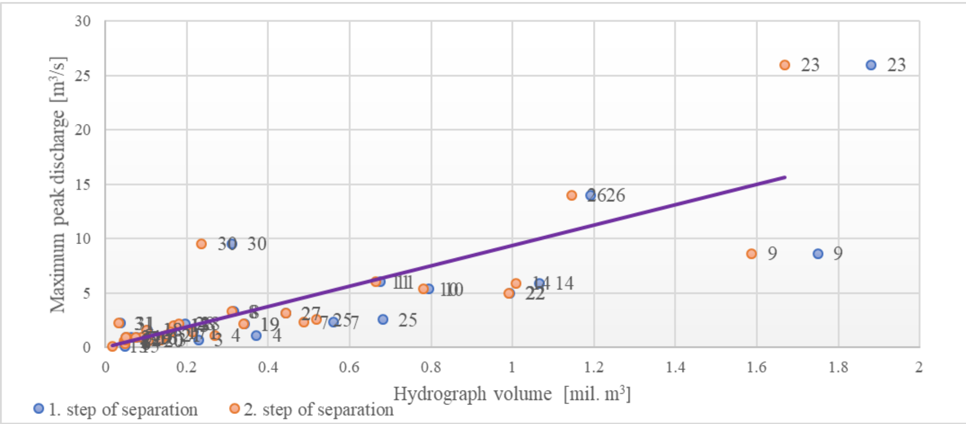

Fig. 3. Relationship between a flood´s volume and peak discharge: results of discharge-wave separation in the Summer season.

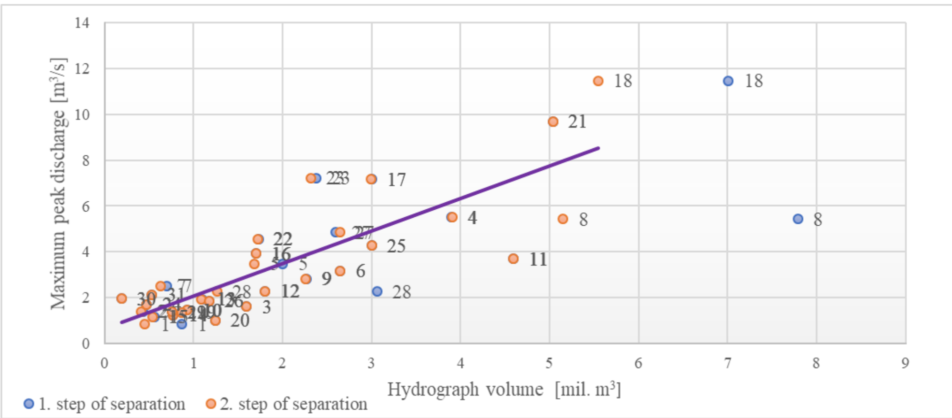

Fig. 4. Relationship between a flood´s volume and peak discharge: results of discharge-wave separation in the Winter season.

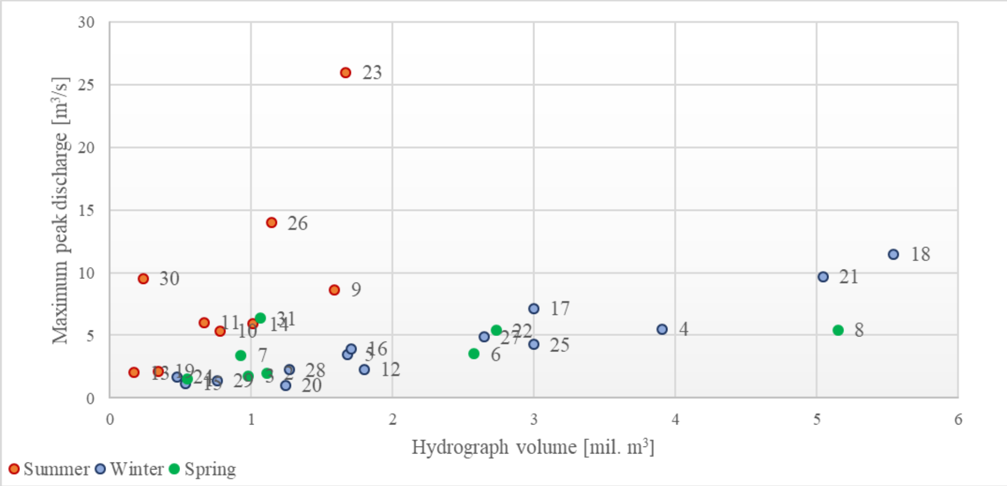

Fig. 5. Relationship between a flood´s volume and peak discharge – annual maximum discharges.

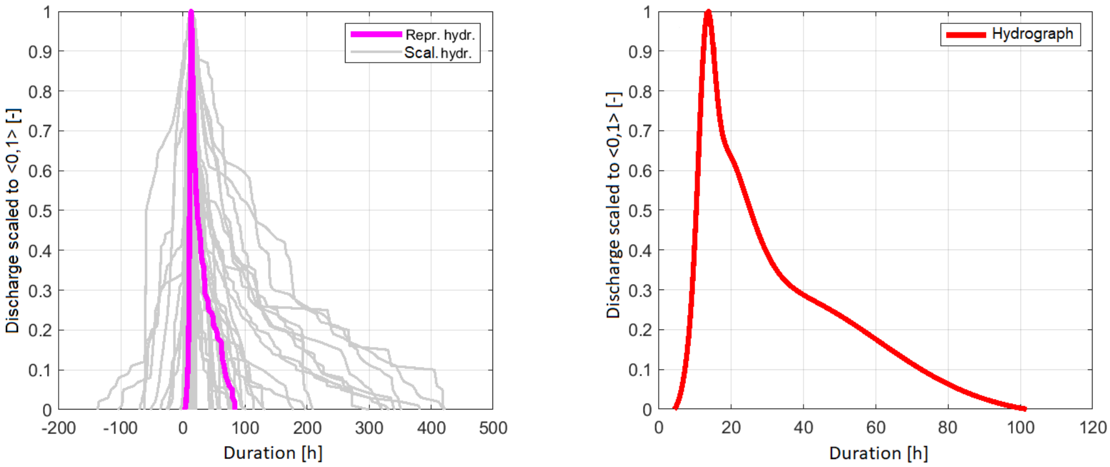

Fig. 6. Representative hydrograph of scaled waves (left) and smoothed representative hydrograph for the spring season (right).

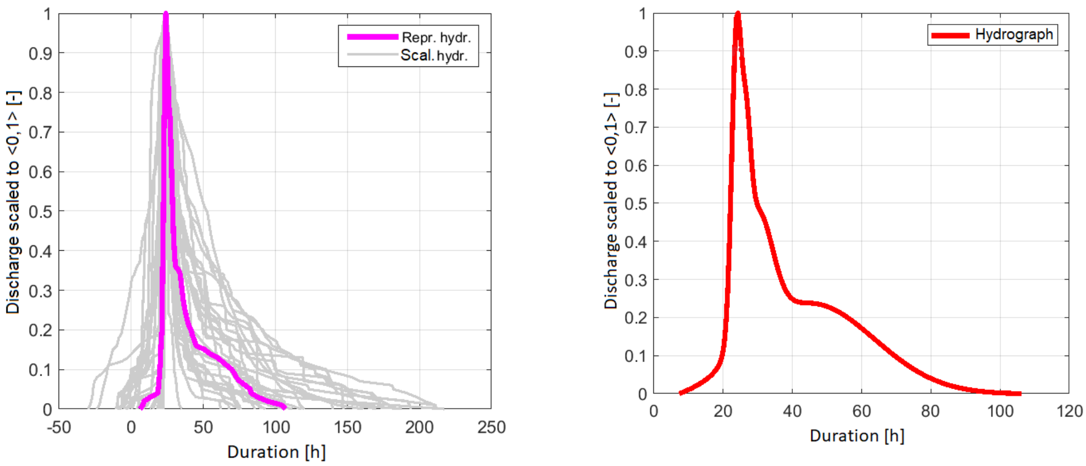

Fig. 7. Representative hydrograph of scaled waves (left) and smoothed representative hydrograph for the summer season (right).

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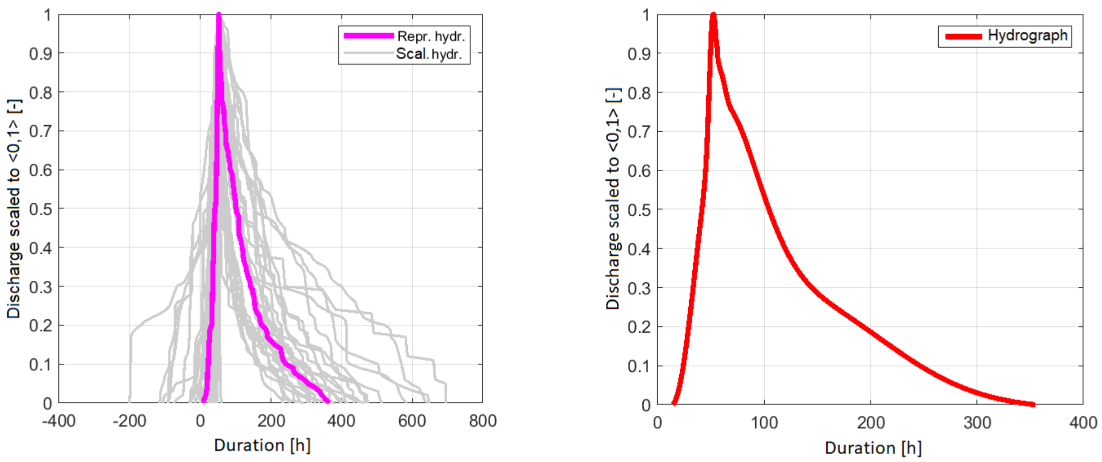

Fig. 8. Representative hydrograph of scaled waves (left) and smoothed representative hydrograph for the winter season (right).

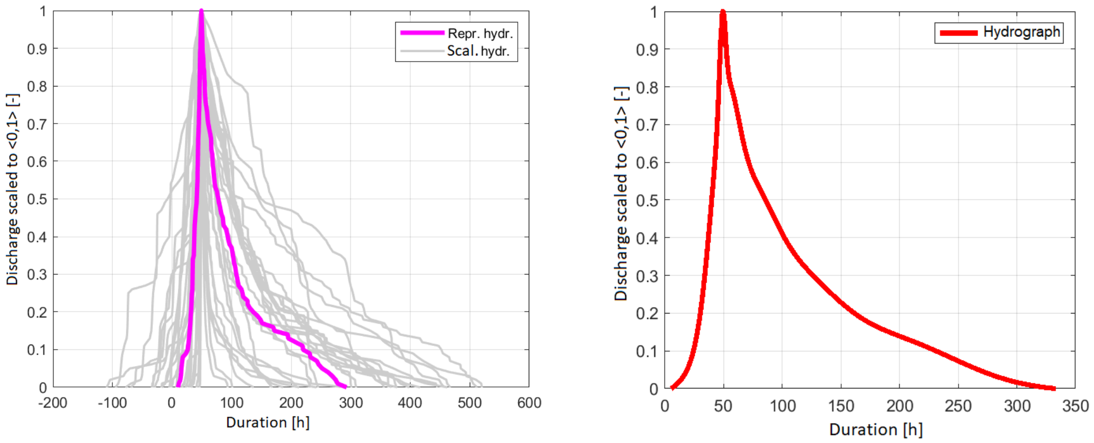

Fig. 9. Representative hydrograph of scaled waves (left) and smoothed representative hydrograph for the annual culminative discharge group (right).

Table 1. *T*-year maximum discharges [m^3 s^{-1}]

N [years]	2	5	10	20	25	50	100	200	500	1000
Spring season	1.2	2.6	4.0	5.6	6.2	8.2	10.7	13.6	18.2	22.3
Summer season	1.8	4.6	8.1	13.7	16.1	26.7	43.7	71.3	135.7	220.5
Winter season	2.5	5.0	6.9	9.0	9.6	11.7	13.7	15.8	18.5	20.6
Annual	3.9	7.7	11.2	15.4	17.0	22.4	28.8	36.5	48.9	60.2

Table 2. Conditional volumes with various non-exceedance probabilities to a given 100-year discharge [million m^3]

P [-]	0.4	0.5	0.6	0.7	0.8	0.9	0.99
Spring season	2.117	2.405	2.724	3.110	3.621	4.460	7.207
Summer season	2.194	2.271	2.345	2.432	2.525	2.671	3.090
Winter season	6.840	7.109	7.374	7.642	7.958	8.415	9.711
Annual	2.713	3.253	3.900	4.736	5.944	8.146	17.219

Table 3. **Values of the design flood hydrographs**

Group	Q_{100} [m^3.s^{-1}]	V [mil. m^3]			t_c [h]		
		0.5	0.7	0.9	0.5	0.7	0.9
Annual maximum	28.80	3.253	4.736	8.146	132.8	184.8	269.2
Spring season	10.69	2.405	3.11	4.46	222.9	343.1	397.1
Summer season	43.70	2.271	2.432	2.671	82.0	89.2	92.4
Winter season	13.72	7.109	7.642	8.415	506.0	511.2	540.7

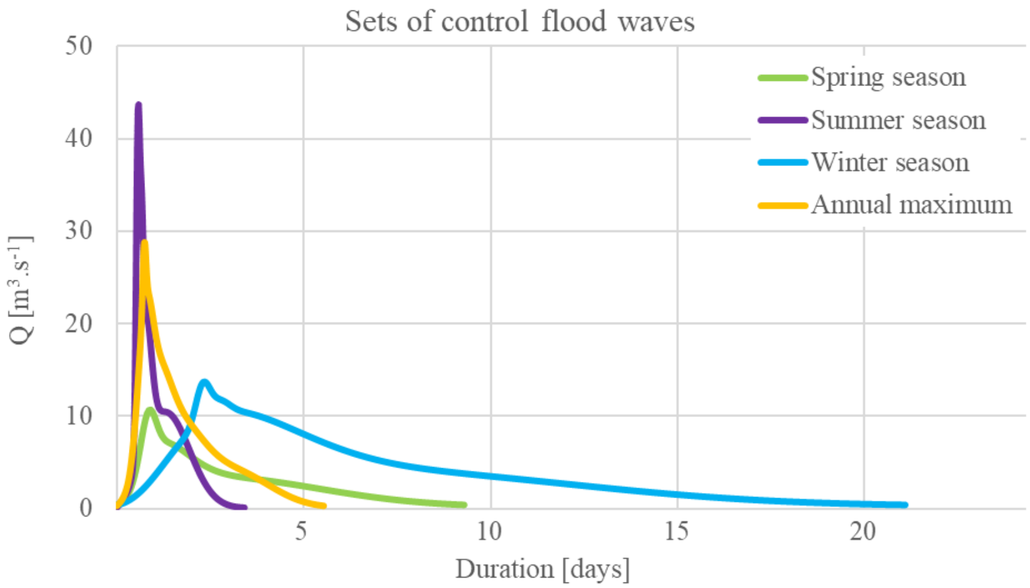

Fig. 10. Design control flood waves for all the seasons analysed.

Conclusion

We have addressed the construction of a set of design flood hydrographs. The design of the flood hydrographs was based on an analysis of the relationship between the culmination, volume, and shape of the flood waves. The project was processed for the Parná River basin in the profile of the Horné Orešany dam. The findings and results can be summarised as follows:
As the discharge waves differ significantly due to their seasonal occurrence, the first step needed to analyse the individual discharge waves in separate groups was to select a group of annual maximum discharges and three seasonal groups i.e., spring, summer, and winter. The next step was the separation of the individual discharge waves, where we took into account the antecedent climatic conditions, i.e., the precipitation and air temperature to determine the beginning and end of each discharge wave. The precipitation data were essential in deciding upon the duration and shape of the rising and falling limp of the flood hydrograph. The temperature data were mainly used in the winter season to estimate the start of the melting snow. The separation resulted in the dataset of the volume and duration of all the flood events identified. Representative shapes of the flood hydrographs were constructed from the separate discharge waves. Finally, we identified the design flood hydrographs with the selected probability of exceedance. In this paper we have shown the results for discharges with the probability of exceeding 0.01. The relationship between the peak discharge and the volumes of the individual flood events has been analysed, and a joint probability distribution was constructed using a copula function. Finally, we calculated the conditional probability of non-exceeding the volume of a given 100-year discharge.

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