Design Criteria for Levees

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Abstract
Flood development in complex flow conditions where significant influence of backwater effect is present is not straightforward from the standpoint of flood generators and selection of the design flood flow. Design principles applied for levees within the flood risk management are frequently challenged. Research focus of this paper is Sava River reach in Croatia, where high flow water regime is heavily influenced by the construction of the flood retention system. Methodology used for flood hazard assessment combined application of flow routing, flood frequency analysis and numerical model computations on analysed 4 gauging station records. In this paper design criteria for levees is determined combining information from gauging station monitoring and available data records on historical floods on Sava River reach where significant backwater effect is present. Based on hydrological events during which coincide high water flows both on Sava and Kupa River, stage-discharge curve was constructed for use in levee design analysis. Water levels are calculated using 1D numerical model HEC-RAS calibrated on gauging station recordings. Final verification of proposed methodology for levee design places emphasis on the observation of flood situations that occurred in the past in order to further the current flood management practice.

Keywords
Levee; flood hazard; Sava River

INTRODUCTION

Levees are important structures for flood risk management and therefore design principles applied to them are frequently challenged because no matter how safe a flood defence system is, there will always exist a possibility of its failure (Meyer, 2013). Practical approach to flood hazard assessment requires calculation of flood event magnitude for design exceedance probability on a specific river reach to be determined. For an unknown distribution of flood events over a period of time, the flood hazard can be estimated using probability of flow exceedance in a year (CEIWR-HEC, 1989) by applying common univariate flood frequency analysis on annual maximum flows (Tanaka et al., 2016). Flows calculated on basis of the recorded water levels and discharges at the gauging stations are only part of flow regime information required in flood management. Most often long-term recordings from gauging stations are not covering long enough time span to reflect flow regime accurately enough to reliably determine discharge for a given return period (Kuspilić et al., 2015). More frequent occurrence of the flood events in the Sava River basin results in the increase of the flood risk due to positioning of large cities in the lowland zones protected by levees that are frequently exposed to the threat of overflowing. Flood development in complex flow conditions where significant influence of backwater effect is present is complicated to describe for practical purposes from the standpoint of the design flow selection of the main river and its tributary (Ilić & Prohaska, 2013), so numerical computations of hydraulic parameters are required for analysed river reach in order to define relevant water levels for flood protection along the river.

Objective

The objective of this paper is to determine design criteria for levees on the Sava River reach downstream of Zagreb combining information from gauging station monitoring with available data records of historical floods. Focus of analysis is mainly the reach at Martinska Ves, where existing levees are proven to be inadequately designed and are under a frequent danger of overflowing.

Based on hydrological events during which high flows both on Sava and Kupa River coincide, stage-discharge curve of flow data relevant for the high flows was constructed for use in levee design analysis verified on the observation of flood situations that occurred in the past.

STUDY REACH

Research focus of this paper is the Sava River reach in Croatia, downstream of its capital Zagreb, until Kupa River confluence in Sisak. During the flood event of 2010, in September and December, levees along the analysed river reach were required to be temporarily additionally heightened up to 1 m in order to prevent flooding. There are 4 gauging stations that record data covering this river reach: GS Dubrovčak Lijevi (rkm 613+000), GS Strelečko (rkm 586+000) and GS Crnac (rkm 575+000) on Sava River, and GS Farkašić (rkm 47+150) on Kupa River that has confluence into Sava River upstream of the GS Crnac (Figure 1). Significant influence on the high flow water regime is construction of flood retention system Srednje Posavlje, used to relief excess flow into the preserved alluvial wetlands upstream of the gauging station GS Dubrovčak Lijevi, which in turn affects flow measurement and additionally restrict information acquired from long-term monitoring (Bonacci & Ljubenkov, 2008).

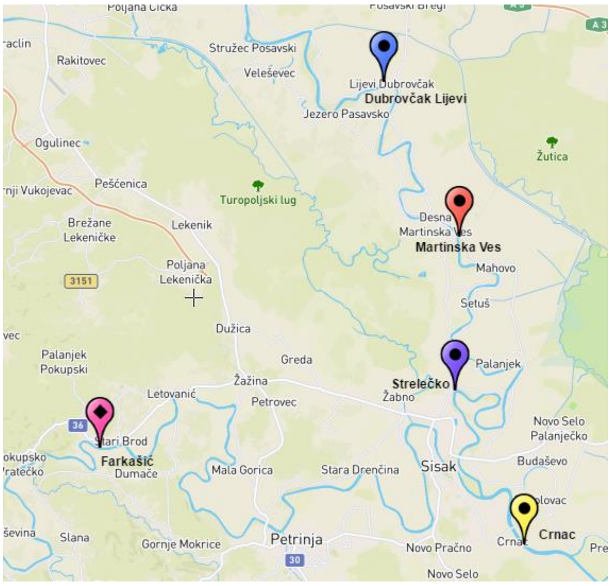

Figure 1. Overview of analysed river reach (Source: Scribble Maps)

METHODOLOGY

Methodology used for flood hazard assessment on Sava River reach combined application of flow routing, flood frequency analysis and numerical model computations as supplement to the traditional univariate flood frequency analysis. Water levels are available for GS Dubrovčak Lijevi and GS Strelečko, and discharges for GS Crnac on Sava River and GS Farkašić on Kupa River. In order to calculate daily discharges for analysed river reach, tributary inflow from GS Farkašić was subtracted from overall Sava River discharge recorded downstream of the confluence on GS Crnac. Pairwise data for calculated discharges was determined using regression with water levels recorded on Sava River upstream from the confluence (GS Strelečko and GS Dubrovčak Lijevi). Paired and routed flow data was used in flood frequency analysis to identify data distribution and calculate discharge for defined return period. According to data availability, flood frequency analysis was conducted on water level data for GS Dubrovčak Lijevi and GS Strelečko, and discharge data for GS Farkašić and GS Crnac in order to determine corresponding 100-year return period water levels and discharges. Water level and discharge data is available for the period since 1955 for GS Crnac and since 1965 for GS Farkašić. Water level from GS Dubrovčak Lijevi is taken since 1909 and since 1987 for GS Strelečko. Since period of operation differs for all gauging stations, it is difficult to gather relevant data for analysed rive reach. This emphasises need for implementation of numerical model into flood frequency analysis and using combined data from both, main river and its tributary. In following figure (Figure 2) are given maximum annual water levels and discharges for all analysed gauging stations.

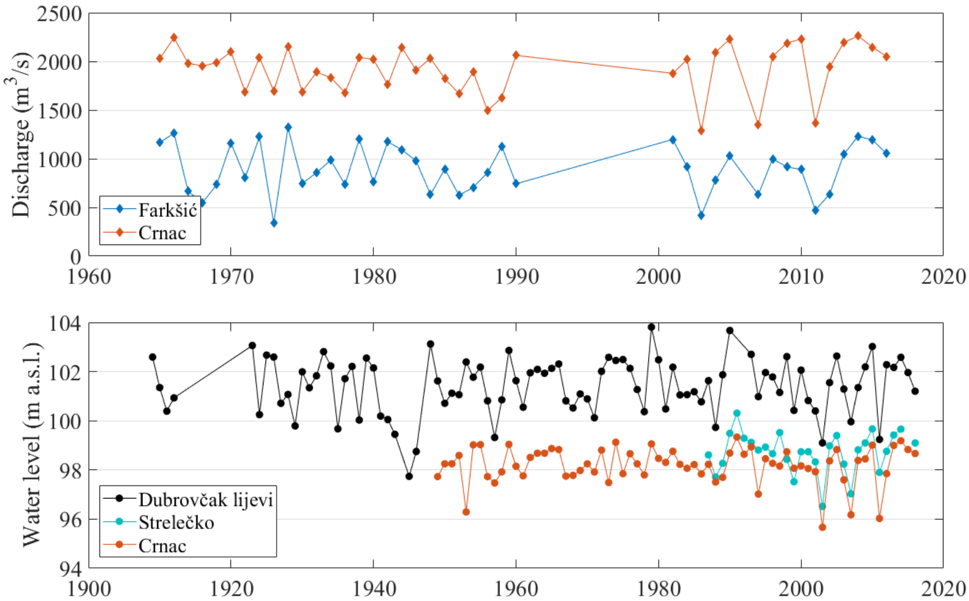

Figure 2. Flow and stage hydrographs for maximum annual water levels and discharges for all analysed gauging stations

Hydrological events during which high flow of Sava and Kupa River coincide were identified and used for selection of appropriate hydrological events that result in significant backwater effect and thus pose most threat on levees. Based on these events stage-discharge curve segment corresponding to high water flows was constructed for use in levee design analysis. Design flood event water levels for the entire reach are calculated using 1D numerical model HEC-RAS, calibrated using gauging station recordings in order to obtain reliable water profiles for selected high flow hydrological events. Final verification of the proposed methodology for levee design places emphasis on the observation of flood situations that occurred in the past which are used to verify assumptions introduced in the analysis through flow measurement techniques, statistical distribution of annual flow extremes and numerical model calculations. Conducted research supplements current practices used in flood risk management.

RESULTS

The average discharge of the Sava River immediately downstream of the Kupa River confluence is 532 m^3/s and of the Kupa River is 199 m^3/s. Similar relationships can be observed for average minimum and maximum annual discharged (Table 1). This indicates that upstream of the confluence, i.e. the analysed reach, flow regime of both rivers is similar. When high water events coincide where discharges are similar, significant backwater effect can be expected on tributary, as well as the main river. The overview of analysed gauging stations is shown in the table below.

Table 1. Characteristic flow and water level data for the gauging stations

Gauging station	Minimum		Average		Maximum	
	Q [m³/s]	*H* [m a.s.l.]	*Q* [m³/s]	*H* [m a.s.l.]	*Q* [m³/s]	*H* [m a.s.l.]
Dubrovčak Lijevi	-	91.56	-	93.63	-	103.81
Strelečko	-	89.61	-	93.06	-	99.67
Crnac	71.1	88.73	532.4	92.60	2331.0	99.32
Farkašić	13.6	94.78	199.2	96.82	1631.0	103.70

Definition of relevant discharge subset

Hydrological data from gauging stations located on Sava River are used to calibrate HEC-RAS model in order to obtain 100-year return period water level at the Martinska Ves located between GS Strelečko and GS Dubrovčak Lijevi. For the calibration of the numerical model Manning coefficient of roughness for the main channel and for the floodplains is determined using measured pairs of discharge – water level data for high flow events. Discharge data analysis for both stations was conducted for the period from 1965 which represents their common operating period. For the calibration of the HEC RAS model for the main channel as upstream boundary condition flow rates of ± 10% of the mean flow was selected. As the result of the calibration, a *Q-n* relationship was defined (Figure 3). Some values of the Manning coefficient of roughness are quite scattered and hence were excluded from the considerations as they do not represent desired flow events. As the selected value of the Manning coefficient of roughness for the main channel, the average value of the selected data was taken and amounts to n = 0.027 $s^{1/}m^{-1/3}$. Since the Manning coefficient of roughness for the main channel was determined, it is also necessary to define Manning coefficient of roughness for the floodplains. The calibration was conducted using peak discharge of selected flood waves and the value of n = 0.05 $s^{1/}m^{-1/3}$ was adopted.

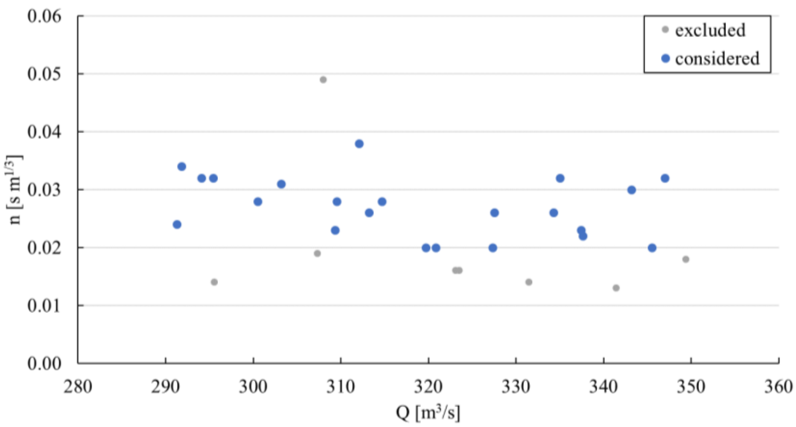

Figure 3. *Q-n* relationship scatter plot

For the calibration of the numerical model, annual flow extremes for the period since year 1987 were selected. The downstream boundary condition for the calibration was water level at GS Strelečko, and upstream boundary condition was the discharge obtained by subtracting the discharges from GS Farkašić from discharges from GS Crnac. The calibration of the model was conducted by varying the upstream condition until the calculated water level at GS Dubrovčak Lijevi was equal to the observed one. Graphical representation of the results obtained is shown in the figure below. What may be noticed in this graph is that there is a shift in the time between the flood wave obtained by subtraction and flood wave obtained from the calibration. Time shift can be explained by time travel of the flood wave through the river reach and thus, the discharge obtained by subtraction on GS Crnac was recorded on GS Dubrovčak Lijevi two days earlier to take into account this time lag.

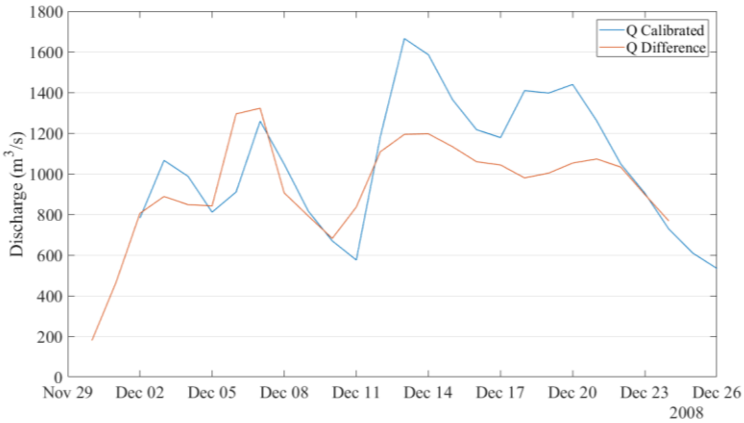

Figure 4. Q calibrated and Q difference without a shift in time

Annual maximum flow distribution

Considering that Manning coefficients of roughness for the main channel and for the floodplains were determined, the numerical model computations of water levels can be conducted. The result from the numerical computations for 100-year return period discharge for the analysed reach upstream from the Kupa River confluence is corresponding water level at the location of the Martinska Ves which amounts to 103.02 m a.s.l. To confirm the calculated data, rating curve for the GS Strelečko is constructed for the data for the period since 1987, i.e. start of operation for GS Strelečko. From the rating curve (Figure 5), it can be seen that the data are scattered hence it is necessary to define relevant data subset that covers the high flow events. Hydrological events during which coincide high water flows both on the Sava and Kupa River were identified and used for selection of appropriate hydrological events for that result in extreme backwater effect and thus pose the most threat on levees.

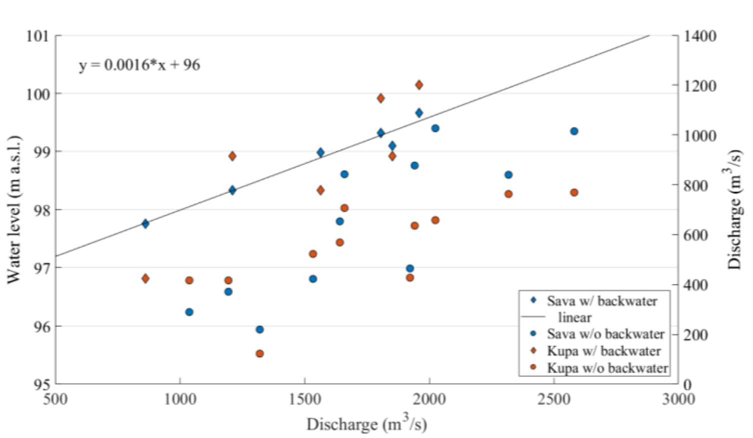

Figure 5. Rating curve with backwater effect

The difference between stream flow of Sava River and Kupa River is expressed as the percentage of river Sava flow. If the flow difference is less than 50%, then we can say that the river Kupa affects the water level in the river Sava. Selected dataset for GS Strelečko is described with the equation:

$$H = 0.0016 * Q + 96.395, \tag{1}$$

where H is water level [m a.s.l.], and Q is discharge [m^3/s].

Verification with the field data

Paired and routed flow data was used in flood frequency analysis to identify data distribution and calculate flow for selected return period range. From fitted Gamma distribution discharge for 100-year return period is calculated to be Q = 2591 m^3/s. For the 100-year return period water level H_{100} = 100.652 m a.s.l, from the rating curve for GS Strelečko. The results from the calibrated numerical model for which boundary conditions were 100-year water levels calculated for GS Strelečko and GS Dubrovčak Lijevi based on measured data, suggest that these boundary conditions correspond to 100-year return period discharge of Q_{100} = 2630 m^3/s for the upstream reach from the confluence. Comparing the value of 100-year return period discharge obtained from the HEC RAS numerical model and from the rating curve, the difference of 39 m^3/s can be noticed. Hence, it can be concluded that the setup and calibration of the numerical model is reliable.

Based on calibrated numerical model, the 100-year return period water level at the location Martinska Ves is calculated as H_{100} = 103.02 m a.s.l. During the flood event of September 2010, levees along the analysed river reach were required to be temporarily and urgently additionally heightened up to 1 m in height in order to prevent flooding. Current levee crest height is 103.18 m a.s.l., based on previous analyses that determined 100-year flood will result with water level 101.90 m a.s.l., which is 1.12 m lower than water level resulting from numerical model results for 100-year flood in this research. When this difference is compared to the levee temporary heightening data, it can be seen that results correspond well, leading towards the conclusion that 100-year flood is significantly higher than preciously determined and that there is a threat of levee overflowing in the future.

In addition to the risk categorization in Eurocode, there is another method of risk categorization according to the International Levee Handbook (CIRIA, 2013). Risk categories ranging from I to IV are determined based on the duration of the flood event, the height of the levee, the number of endangered people and the possible damaging effects on buildings and infrastructure. In this paper, to determine the risk category for the design levee, flood event of duration from one day to one week was selected. The maximum height of the levee was determined based on calculated design water level and safety addition of 1.2 m. the number of endangered people was selected based on the last census of the population from 2011. The potential damage downstream of the Martinska Ves can be estimated as low.

CONCLUSION

Major challenge in reliable water level calculation for flood hazard is lack of long-term recordings from gauging stations covering relevant river reach. In analysed Sava River reach there is no discharge measurement which makes it very difficult to determine corresponding design water level. In this research Kupa River discharge measurement is used to calculate Sava River discharge upstream of the confluence by subtracting its discharge from Sava River taking into account flow wave lag between the gauging stations. It is shown from numerical model results that, when designing the flood defence system, it is necessary to consider all the joint influences of the flow regime in order to correctly define the design water level according to which the whole flood defence system is dimensioned.

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