Chapter 5

Historical, Hydrological and Hydraulics Studies for Sustainable Flood Management

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Additional information is available at the end of the chapter

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Abstract

Extreme events such as floods can endanger human lives and cause large economic damage. The Savinja River catchment is one of the most frequently flooded areas in Slovenia, Europe. In order to evaluate the impact of the proposed flood mitigation measures on the flood safety in this catchment, the combined hydrological and hydraulic modelling approach was carried out. The hydrological model Hydrologiska Byråns Vattenbalansavdelning (HBV-light) was used to perform hydrological modelling. The hydraulic calculations were carried out using the HEC-RAS 5.0.3 model in order to simulate the combined one- and two-dimensional unsteady flow. Using the calibrated and validated hydrological and hydraulic models, the impact of the proposed measures was assessed in the light of the sustainable flood management. Additionally, with analyses of the historical data and past flood events, we were able to investigate the characteristics of the extreme floods in this area and also downstream at the confluence with the Sava River. Moreover, it was found that the backwater effect has an important role on the water level and flood safety along the river reach, which is often neglected in the aspect of flood management.

Keywords: flood management, hydrological modelling, hydraulic modelling, Savinja catchment, historical events

1. Introduction

Water regime and questions related to floods are usually consequences of the development in the past. Today's look of the rivers and streams in some parts of the Europe is still a result of the construction works from Roman times (**Figure 1**). Construction works began to intensify two centuries ago when large inundation areas were taken away from rivers for agricultural purposes. Due to the reduction of inundation areas, the river flows increased, and narrow river channels could not carry it anymore. Nowadays, we can see the consequences of the development in the past, and we are looking for sustainable solutions for the next centuries and next generations. Fortunately, we have a lot of observations, measurements, experiences and sophisticated tools [1] to support decision-making processes in order to achieve the sustainable flood management. This study focuses on the flood safety in the Slovenia that is part of the Danube River basin [2].

The inundated areas endangered due to the extreme floods (floods with 100-year return period: Q100) in Slovenia cover about 700 km^2, which is about 4% of the total area of the country and urban areas such as Celje and Ljubljana cities [3]. The Savinja River catchment is one of the areas with the highest flood risk potential in Slovenia, especially highly populated and urbanised areas, as, for example, cities Celje and Laško were often severely damaged during the floods in the past [3]. City Celje can be even regarded as the town with the highest flood risk in Slovenia with the first flood benchmark dating back to 1672 [3]. Large floods occurred in this area in 1954 (**Figure 2**), 1989, 1990, 1998 and 2007 [3, 4]. Due to the potential further climate changes (e.g. climate change or variability) or land-use changes, the flood risk could increase in the future [5–7]. Therefore, the effective flood protection measures have to be taken in order to reduce the potential flood damage also considering the hydrological variability and at the same time, not to worsen the situation downstream at the confluence with the Sava River and consequently, at the location of the Krško Nuclear Power Plant and several hydropower plants that are located in this area (lower Sava River in Slovenia). With this regard, the characteristics of the past extreme events have to be taken into account when planning floods' protection measures or implementing sustainable flood management.

Therefore, the main aim of this study was to investigate the flood safety in the Savinja River catchment and to analyse the influence of the proposed flood protection measures on flood

Figure 1. Austrian military map of the Celje city (on map Zilli) from the period 1763 to 1787 [8, 9].

Figure 2. Floods in Celje city in 1954 [10].

safety in this catchment. The combined hydrological-hydraulic analyses were performed in order to achieve this aim. Moreover, influence of the backwater effect on the flood safety was also investigated.

2. Data and methods

Savinja River catchment is part of the Sava River catchment that drains into the Danube River. The Savinja River catchment covers about 1851 km^2 (**Figure 3**). Due to its topography, the Savinja River catchment has significant torrential characteristics [11].

In the processes of the model development and hydrological analysis, officially measured data were used (Slovenian Environment Agency). Discharge data from stations located on the following rivers in the Savinja catchment was applied: Lučnica, Dreta, Bolska, Rečica, Paka, Ložnica, Hudinja, Voglajna and Savinja. These are the main tributaries of the Savinja catchment that have relatively significant influence on the flood safety in the Savinja catchment (**Figure 4**). Peak discharge information (different data periods ranging from 1907 to 2013) was used to perform the flood frequency analysis, and hourly data were applied in the process of hydrological and hydraulic models' development. Moreover, precipitation, potential evapotranspiration and air temperature data from several stations in the area were also included in the hydrological model.

2.1. Hydrological model

The Hydrologiska Byråns Vattenbalansavdelning (HBV-light) model [12] and PEST model calibration software [13] were used in the process of model development. This hydrological

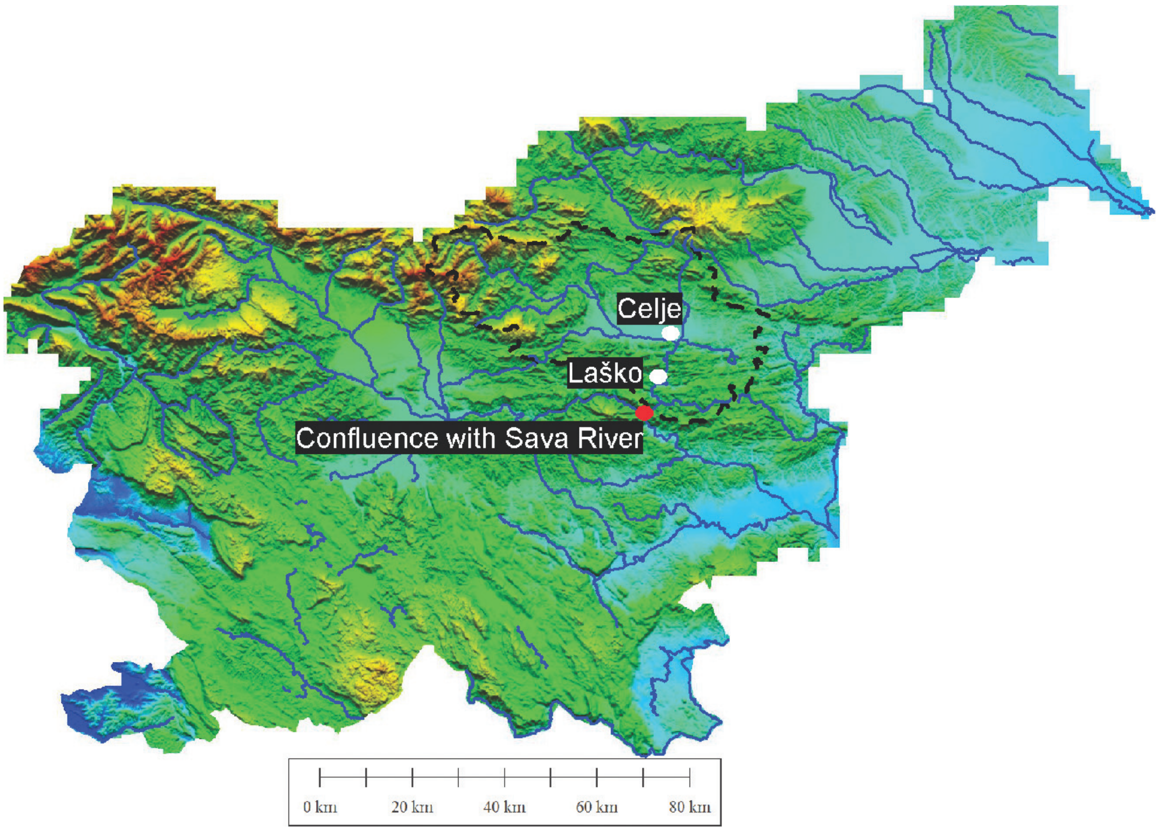

Figure 3. The Savinja River catchment on a map of Slovenia with indicated cities Celje and Laško and confluence of the Savinja River and Sava River. Important infrastructure such Krško Nuclear Power Plant is located downstream of the confluence of the Savinja and Sava Rivers.

model was already used for the flash flood forecasting in the Savinja River catchment [11] and was also recently used for the hydrological analysis and modelling of the large flood in the Bosna River catchment that occurred in May 2014 [14]. As an alternative in some other hydrological applications, some other hydrological model with different characteristics such as HEC-HMS or SWAT model [2, 15] could be used.

Figure 5 shows the model scheme of the Savinja catchment as it was defined in the HBV-light model. The Savinja catchment was initially divided into 21 sub-catchments (each of these sub-catchments was described with 34 parameters) that were selected based on the discharge data availability, and these 21 sub-catchments were eventually further divided into 77 sub-catchments (**Figure 6**). Thiessen polygons were applied to determine the spatial rainfall distribution (**Figure 7**). Moreover, in the process of model calibration and validation, daily rainfall data were also used in order to increase the density of rainfall stations in the Savinja catchment (hourly rainfall distribution from the nearest station was combined with daily rainfall amounts). Mean monthly evapotranspiration values for stations Celje, Maribor, Starše and Šmartno pri Slovenj Gradcu were also used as part of the hydrological modelling.

Calibration of the hydrological model HBV-light was carried out using the PEST software [13] that was already used for this purpose in case of the Bosna River catchment [15]. Due to the large number of parameters (34 for each sub-catchment) and consequently, high computational

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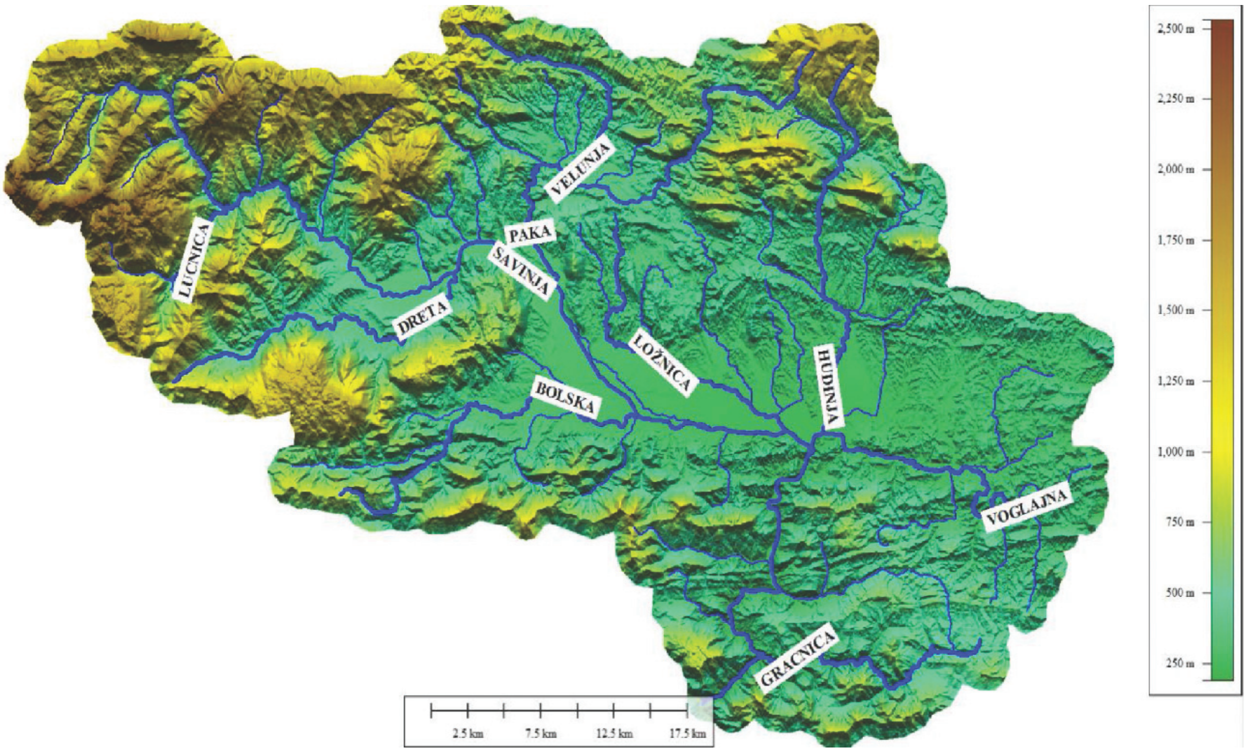

Figure 4. The Savinja River catchment with the most important rivers from the flood safety perspective. Note that Celje city is located at the confluence of the Savinja, Hudinja and Voglajna Rivers and that about 90% of the total Savinja catchment drains into this confluence; only 10% of the area contributes to runoff downstream of this location.

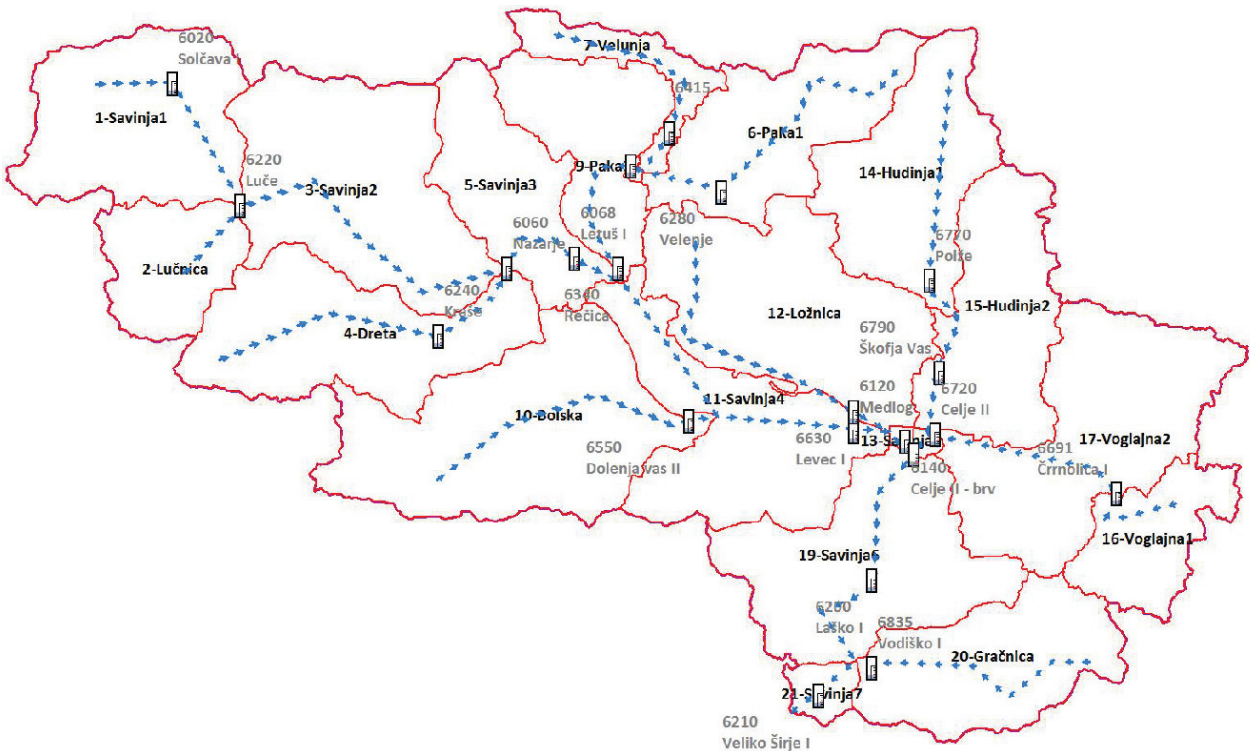

Figure 5. Modelling scheme of the Savinja River catchment with discharge gauging stations that were applied in this study.

Figure 6. Hydrological model scheme of the Savinja River catchment with 77 sub-catchments.

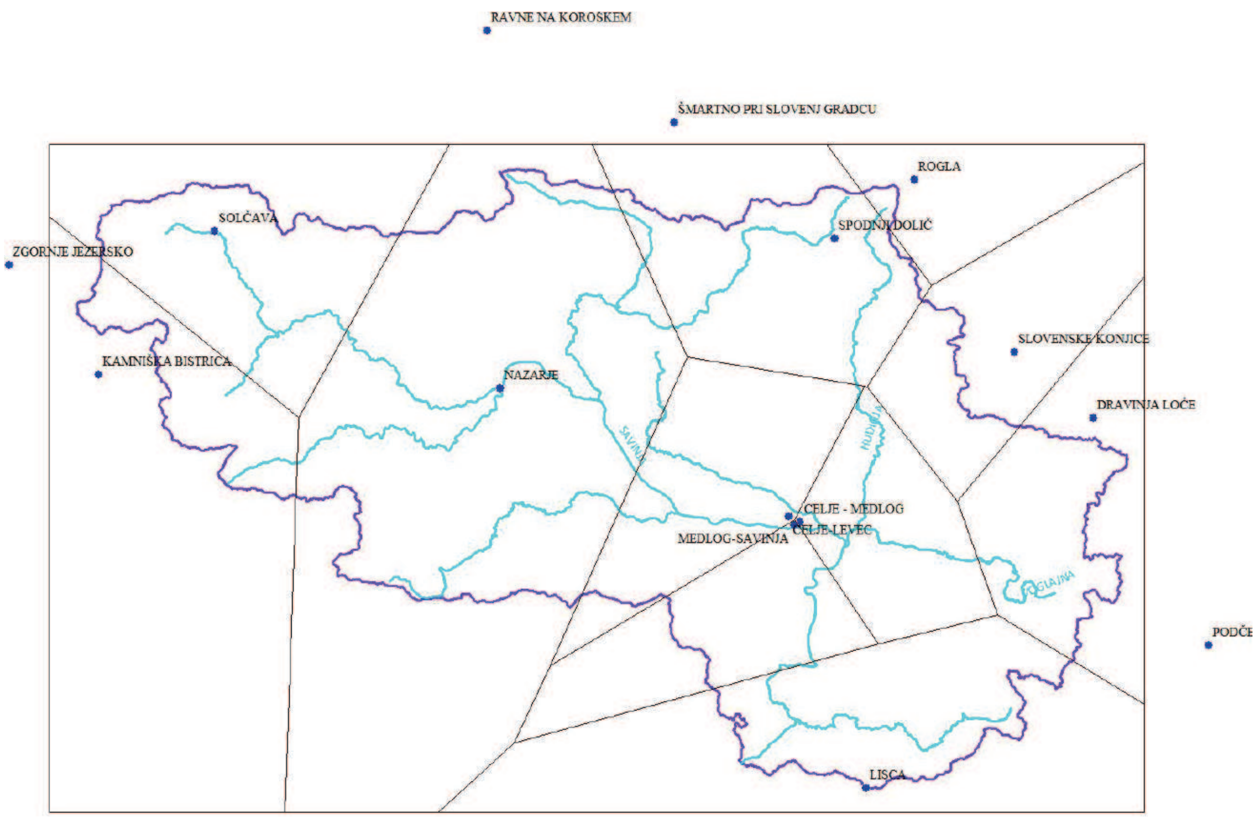

Figure 7. Thiessen polygons for rainfall stations with hourly rainfall data availability that were used in the process of the hydrological model development.

demands, the beoPEST module was used for parallel calibration of the hydrological model. Hourly discharge data and information about peak discharge values were used in the process of model calibration, whereas the initial parameter values and limits were defined based on the experiences obtained from the Bosna River modelling [15].

2.2. Hydraulic model

The Savinja River catchment was also modelled with the hydraulic model HEC-RAS 5.0.3 that enables one- or two-dimensional unsteady flow simulations [16]. One-dimensional calculations were performed in the river channel, and two-dimensional calculations were conducted on the floodplain areas. Detailed model description is available in the HEC-RAS user's manual [16]. The most important rivers in the Savinja catchment from the flood safety perspective were included in the model (Dreta, Ložnica, Voglajna, Hudinja and Savinja Rivers); other rivers were considered in the model as lateral inflows into the Savinja River. Average slope of these modelled rivers varies from 0.2 to 0.6%. In total, more than 135 km of river network with more than 2400 cross sections were incorporated in the model. Geodetically measured river cross sections were combined with 1 m digital terrain model of the Savinja catchment. The selected Manning roughness coefficients were between 0.03 and 0.04 for the river channel, between 0.035 and 0.05 for the flood area within the cross section and between 0.06 and 0.1 for the 2D flood area. The size of cells covering 2D flood areas was between 20 × 20 m and 30 × 30 m (computational mesh). However, it should be noted that each cell is described with hydraulic

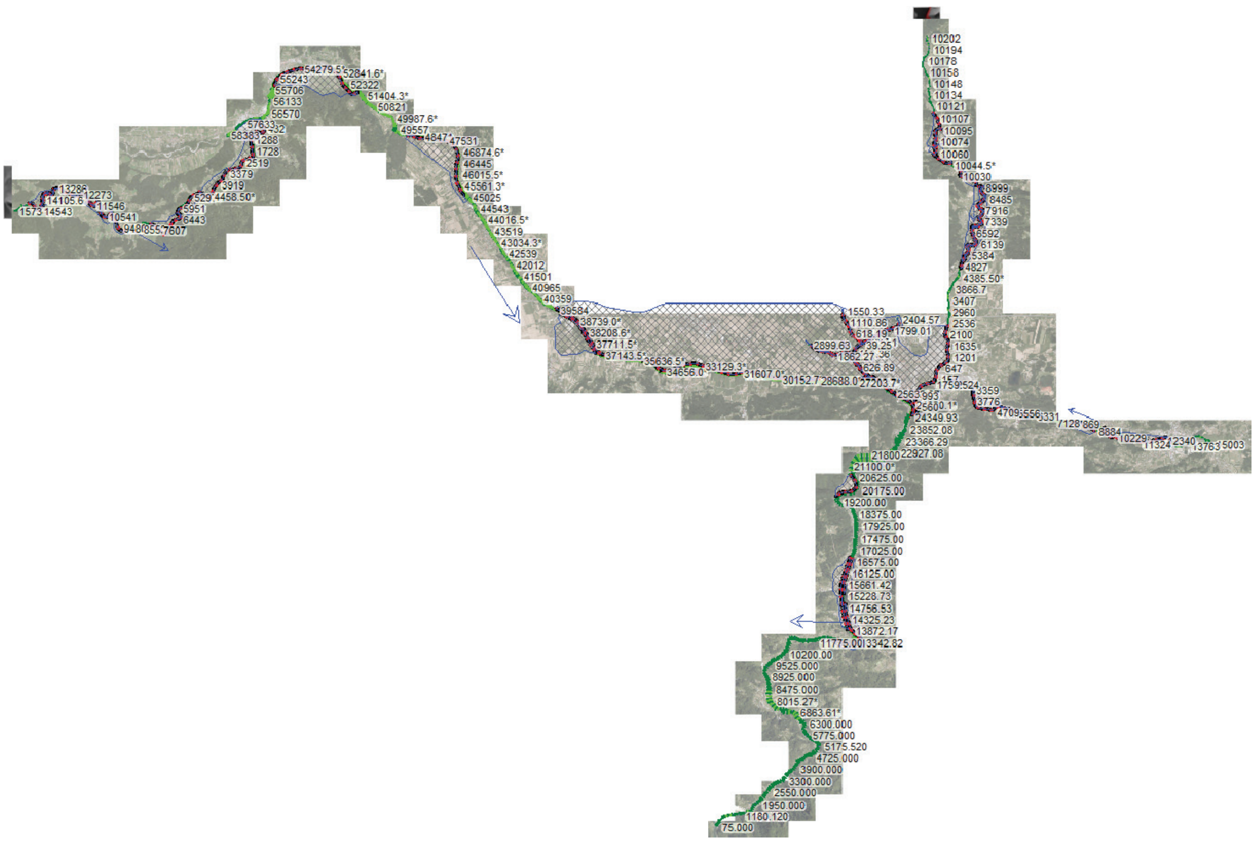

Figure 8. The extent of the hydraulic model from the confluence of Dreta and Savinja Rivers to the confluence of Savinja and Sava Rivers (including Dreta, Ložnica, Voglajna, Hudinja Rivers).

properties table based on the underlying digital terrain model used (1 m resolution). The HEC-RAS pre-processor computes the elevation-volume relationship and other geometric characteristics crucial for hydraulic calculations for each cell face [16]. **Figure 8** shows the main rivers that were included in the hydraulic model from the confluence of the Savinja and Dreta Rivers to the confluence of the Savinja and Sava Rivers. It should be noted that due to the improved 2D modelling algorithm that is implemented in the HEC-RAS version 5 [16], the entire 135 km of the river network with multiple flood areas was modelled as one model. Moreover, the total computational time did not exceed 2.5 h.

3. Results and discussion

This section presents the results of hydrological and hydraulic model calibration and validation and some results of the investigation of the influence of the proposed flood safety protection measures in the Savinja River catchment.

3.1. Hydrological model and analysis

The hydrological model was calibrated based on the flood event that occurred in September 2007 and caused large damage in different parts of Slovenia [2]. The average value of the Nash-Sutcliffe coefficients for the calibration of the model for the 21 sub-catchments (with available discharge data) was 0.85. **Figure 9** shows an example of the calibration results for the location of the Laško gauging station on the Savinja River with the Nash-Sutcliffe coefficient as 0.93.

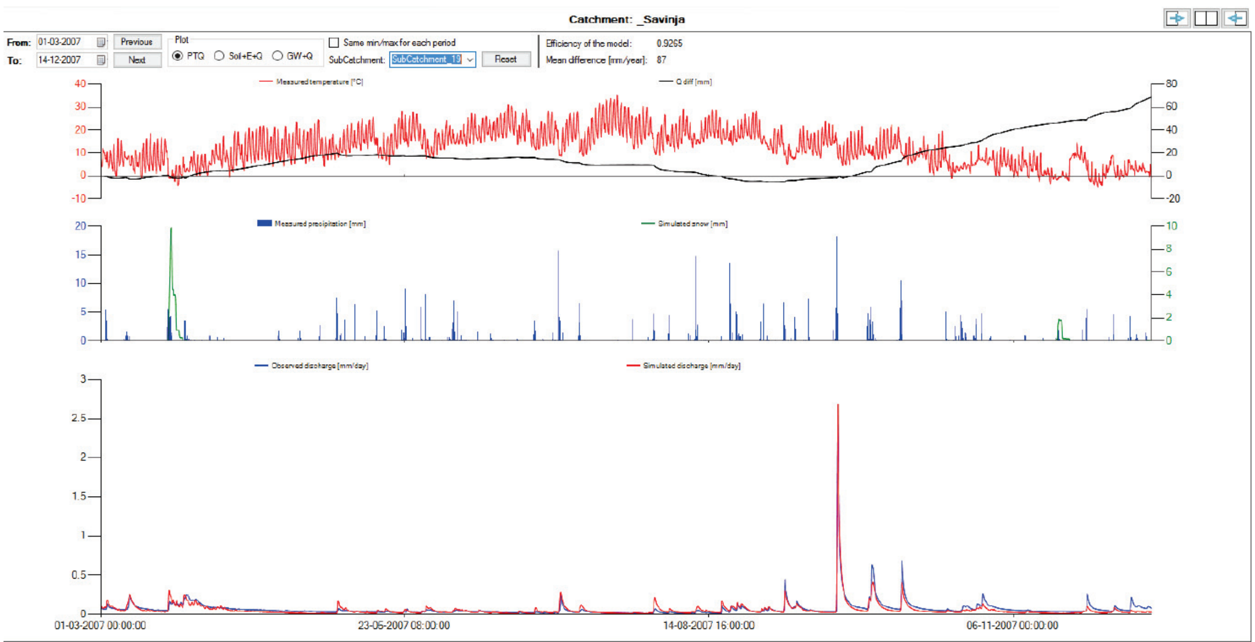

Figure 9. Hydrological model calibration results using the data from year 2007 for the station Laško on the Savinja River (in the lower figure with red and blue is simulated and observed discharge, respectively).

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The validation of the model was performed using the data from floods that occurred in years 1990 and 1998 and also caused large damage in the Savinja River catchment [3, 4]. For the 1990 event, the average value of the Nash-Sutcliffe coefficients for nine stations with available data was 0.85. Using the calibrated and validated hydrological model, we were able to reconstruct the hydrological situation in the Savinja catchment also for the locations where discharge data were not available (either no gauging station or station was damaged during the flood) for floods that occurred in years 1990, 1998 and 2007. **Table 1** shows calibration results for the 2007 flood event for 19 sub-catchments where measured discharge data were available in order to perform evaluation of the hydrological model. Moreover, **Table 2** shows hydrological model validation results for the 1990 flood event for gauging stations with available measured discharge data. The number of gauging stations in the 1990 was smaller than in the case of 2007 because gauging network was extended in the recent decades and several gauging stations were damaged during the 1990 flood event.

Sub-catchment	Model discharge sum [mm/period]	Measured discharge sum [mm/period]	Nash-Sutcliffe	R^2
1-Savinja1-Luče	566	573	0.91	0.91
2-Lučnica-Luče	818	895	0.93	0.93
3-Savinja2-Nazarje	750	801	0.84	0.85
4-Dreta-Kraše	741	764	0.98	0.98
5-Savinja3-Letuš	727	718	0.98	0.98
6-Paka1-Velenje	475	451	0.80	0.80
7-Velunja-Gaberke	454	455	0.73	0.73
8-Paka2-Šoštanj	419	350	0.78	0.86
9-Paka3-Rečica	400	428	0.85	0.85
10-Bolska-Dolenja_vas	489	521	0.90	0.91
11-Savinja4-Medlog	551	506	0.94	0.95
12-Ložnica-Levec	332	394	0.91	0.91
13-Savinja5-Celje_brv	525	509	0.94	0.95
14-Hudinja1-Polže	347	379	0.89	0.89
15-Hudinja2-Škofja_vas	298	344	0.94	0.95
17-Voglajna2-Celje	201	288	0.26	0.45
19-Savinja6-Laško	445	459	0.92	0.93
20-Gračnica-Vodiško	296	337	0.68	0.70
21-Savinja7-Veliko Širje	425	448	0.67	0.78

Note that computational period to calculate discharge sum was from 1.3.2007 to 14.12.2007.

Table 1. Hydrological model calibration results for the 2007 flood event for the 19 sub-catchments where measured discharge data were available.

Sub-catchment	Model discharge sum [mm/period]	Measured discharge sum [mm/period]	Nash-Sutcliffe	R^2
1-Savinja1-Luče	2562	3010	0.85	0.89
4-Dreta-Kraše	4442	4901	0.90	0.92
5-Savinja3-Letuš	4285	3692	0.59	0.89
12-Ložnica-Levec	1453	1845	0.94	0.96
13-Savinja5-Celje_brv	2970	3111	0.97	0.98
15-Hudinja2-Škofja_vas	1278	1382	0.79	0.83
17-Voglajna2-Celje	1011	1478	0.79	0.87
19-Savinja6-Laško	2444	2582	0.97	0.97
21-Savinja7-Veliko Širje	2320	1301	0.84	0.91

Table 2. Hydrological model validation results for the 1990 flood event for the sub-catchments where measured discharge data were available.

In order to define the design hydrographs, the flood frequency analysis was also performed. The annual maximum method was used for sample definition and log-Pearson type III distribution was applied to define the relationship between design discharge and return period.

3.2. Hydraulic model and analysis

The calibration and validation of the hydraulic model were also performed using the data from 1990, 1998 and 2007 floods. Besides discharge data, information about water level was also used (rating curves were used to transform water level data to discharge). Comparison between the measured maximum flood extent on the floodplain areas and computed inundation extent was also carried out. **Figure 10** shows an example of the calibration results for the gauging station Celje on the Savinja River in the year 1990. Similar results were also obtained for some other gauging stations in the Savinja catchment for the 1990, 1998 and 2007 events. Model evaluation was performed on rivers Dreta, Ložnica, Voglajna, Hudinja and Savinja. **Figure 11** shows calibration results for the large natural floodplain area before the Celje city for the 1990 event. Similar graphical comparison was also carried out for other flooding areas.

3.3. Flood safety

The calibrated and validated hydrological and hydraulic models of the Savinja River catchment were used to investigate the impact of the proposed flood protection measures on the flood safety. The main suggested flood protection measures are dry retention (flood-control) reservoirs that are planned to be built at several locations in the Savinja catchment. Eight flood-control reservoirs are to be constructed in the location of the large natural flood area before the Celje city (**Figure 11**). Relatively sophisticated and complex hydro-technical equipment is selected to operate these reservoirs with the total volume of approximately 8×10^6 m^3. **Figure 12** shows comparison between three different situations, namely natural-actual conditions during the 1990 event, full operation of the proposed flood-control reservoirs with increased volume

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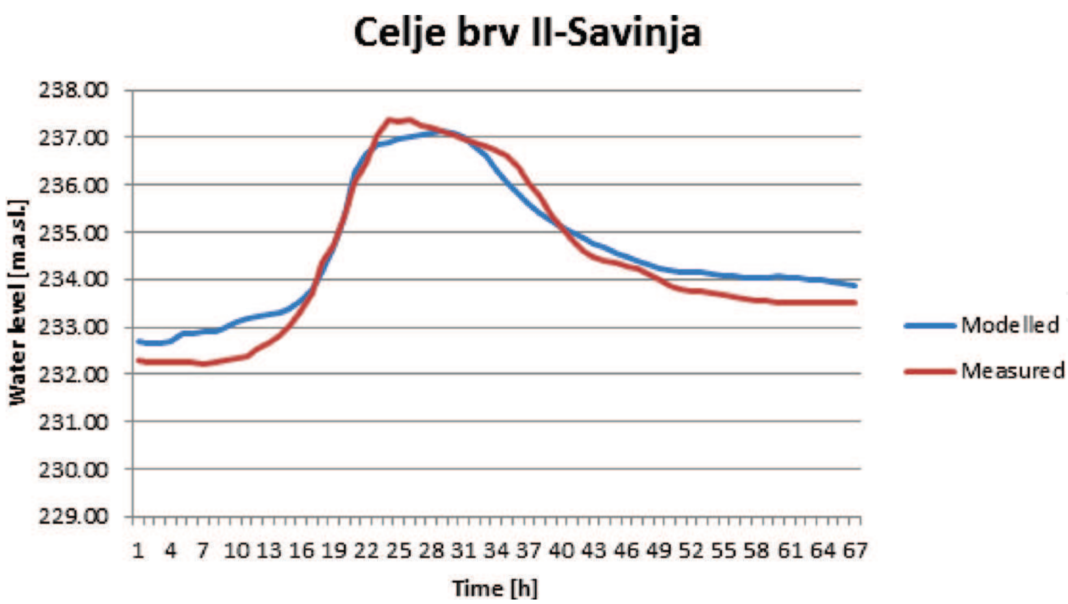

Figure 10. Calibration results for the gauging station Celje on the Savinja River for the 1990 event (blue is modelled water level and red is measured water level by the Slovenian Environment Agency).

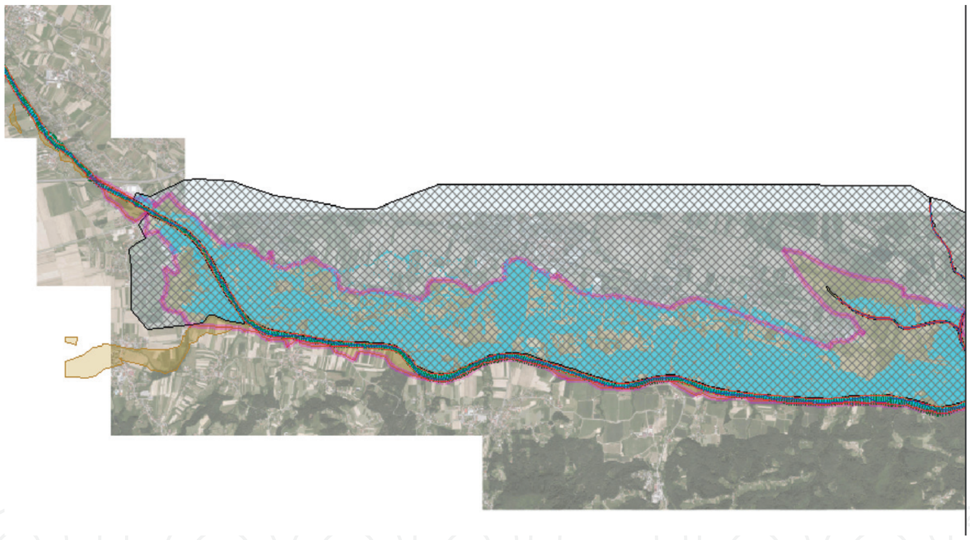

Figure 11. Calibration results for the largest natural floodplain area before the Celje city for the 1990 event (light blue is modelled extent of floodplain inundation by combined 1D/2D model and grey with pink outline is measured extent of floodplain inundation).

(retention of 10×10^6 m^3) and proposed flood-control reservoirs that failed to operate. We can conclude that proposed flood-control reservoirs reduce the peak discharge for about 150 m^3/s; however, potential technical problems with hydro-technical equipment would lead to an increase in peak discharge for approximately 100 m^3/s due to the exclusion of large natural floodplain area (**Figure 12**). It can be seen that the construction of the reservoirs would lead to about 15% decrease in the peak discharge compared to the natural conditions during the 1990 event. This means that the flood risk downstream of the Celje city would decrease in case of operation of reservoirs without any problems and according to the procedure.

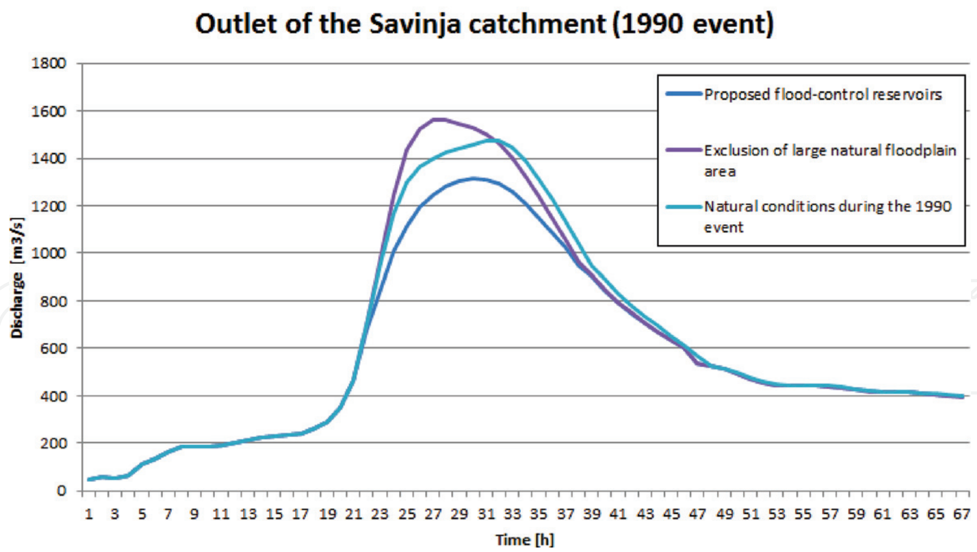

Figure 12. Impact of the proposed flood-control reservoirs with increased total volume (10×10^6 m^3) on the situation at the Savinja outlet during the 1990 flood (dark blue), exclusion of large natural flood area before the Celje city (situation when proposed flood-control reservoirs fail to operate, purple) and actual situation during the 1990 flood (light blue).

Moreover, several smaller flood protection measures (e.g. channel widening at critical cross sections, river banks' reconstruction, local level construction) are also proposed in the Savinja catchment (mostly on rivers Ložnica, Hudinja and Voglajna). The analyses of these measures showed that they mostly positively influence the flood situation at the confluence of Savinja and Sava Rivers. Flood protection measures mostly fasten the hydrograph propagation but often do not significantly influence the peak discharge values (the decrease in the peak discharge is, in most cases, smaller than 1 or 2%). The analysis of catastrophic past flood events demonstrated that the peak discharge on the Savinja River mostly occurs before the peak discharge on the Sava River (**Figure 13**). Thus, faster hydrograph propagation has a positive

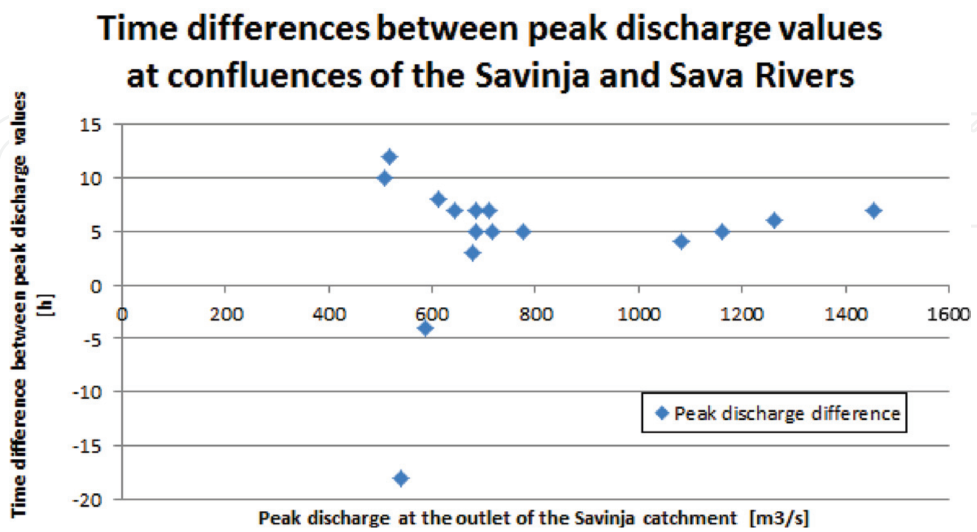

Figure 13. Analysis of time differences between peak discharge values at the confluence of the Savinja and Sava Rivers. Positive values indicate that peak discharge of the Savinja River occurs before the peak discharge of the Sava River.

influence on the situation in the lower Sava River. This kind of local measures mostly have minor impact on the global situation in the larger catchment such as the Savinja River catchment but can lead to improved situation locally. Similar conclusions were also made for the case study of the alpine Inn River in Austria [17].

Furthermore, several other aspects of the flood safety such as the impact of high waters at the river confluences on the downstream flood safety were also investigated but are not discussed in this chapter.

3.4. Backwater effect

Using the calibrated and validated combined hydrological (HBV-light) and hydraulic (HEC-RAS 5) models, we investigated the influence of the proposed flood protection measures (e.g. several flood-control reservoirs are to be built in the large natural flood area before the Celje city) on the flood safety. Moreover, using the hydraulic model HEC-RAS that is presented in Section 3.2, we also investigated the backwater effect on different tributaries in the Savinja catchment. **Figure 14** shows an example of the backwater effect on the Ložnica River. It can be seen that due to the increased peak discharge on the Savinja River, the maximum water on the Ložnica River also increases. This increase is the largest for the cross section located near the rivers' confluence (about 0.6 m for peak discharge increase at 400 m^3/s) and generally, decreases for upstream river station. Moreover, the backwater effect is detected for the cross section that is located 1.5 km upstream of the confluence of the Savinja and Ložnica Rivers. Similar analysis was performed for other rivers (e.g. Hudinja and Voglajna; Voglajna and Savinja). The backwater effect can be up to 0.25 m for a peak discharge of 1000 m^3/s. This kind of analysis can be very useful also for the policy makers because it is essential to understand

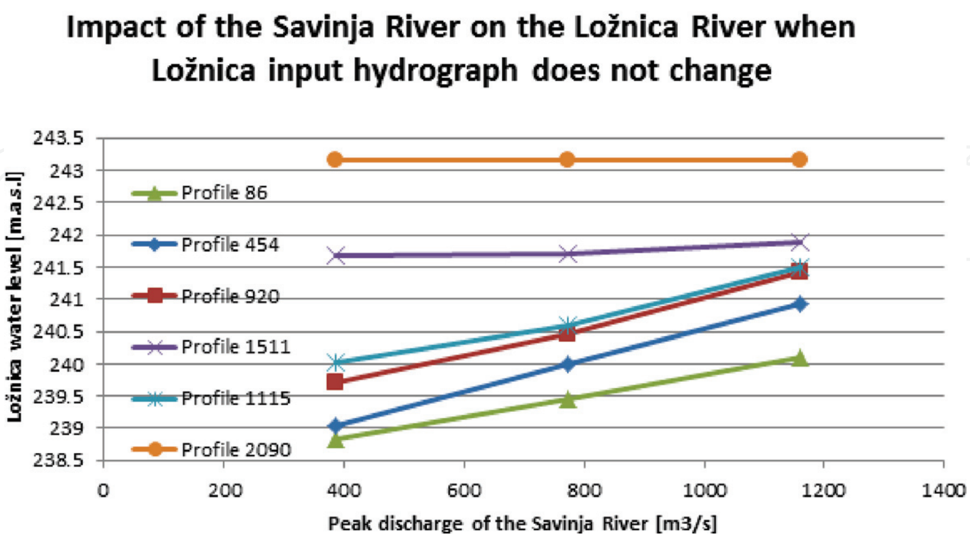

Figure 14. The influence of the Savinja River on the Ložnica River (backwater effect) when the Ložnica input hydrograph is constant during different hydraulic model runs. Different coloured lines represent different cross sections on the Ložnica River where the number indicates river station from the confluence with the Savinja River upstream [m].

that some local measure can also have significant impact on the upstream flood conditions and also on the flood situation at the upstream tributary.

4. Conclusions

In this chapter, combined hydrological and hydraulic modelling was performed in order to investigate the influence of the proposed flood protection measures on the flood safety in the Savinja catchment and in the lower Sava River catchment in Slovenia. The main conclusions are: (1) some of the proposed flood protection measures have positive influence on the flood situation in the Savinja catchment and also at the confluence with the Sava River (either faster hydrograph propagation or peak discharge maximum water level reduction); (2) the main flood protection measures (several flood-control reservoirs) are to be built in the natural large floodplain area before the Celje city and potential problems with operation (or some other problems such as increased sediment transport at the reservoirs inflow) of these reservoirs would lead to the flood safety decrease; and (3) backwater effect in the Savinja River catchment can have a large impact on the flood safety, for example, the backwater effect at the confluence of Savinja and Ložnica Rivers can be up to 0.25 m at the 1000 m^3/s peak discharge of the Savinja River. These conclusions indicate that (small) local measures do not really play an important role in the global flood situation at the catchment and that some local measure can even worsen the flood situation upstream of the measure location. Therefore, complex models (hydrological and hydraulic) of the entire catchment are needed in order to really understand the flood behaviour and to select the most suitable measure that will have positive impacts on the flood safety. Moreover, the selection of the flood measure should also be in-line with the sustainable flood risk management, which means that environmental, social and economic conditions that are mutually connected should be investigated.

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