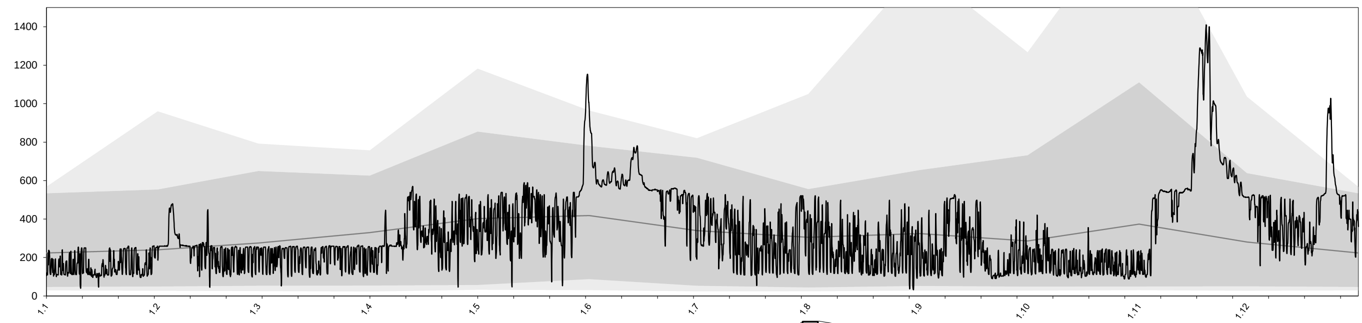
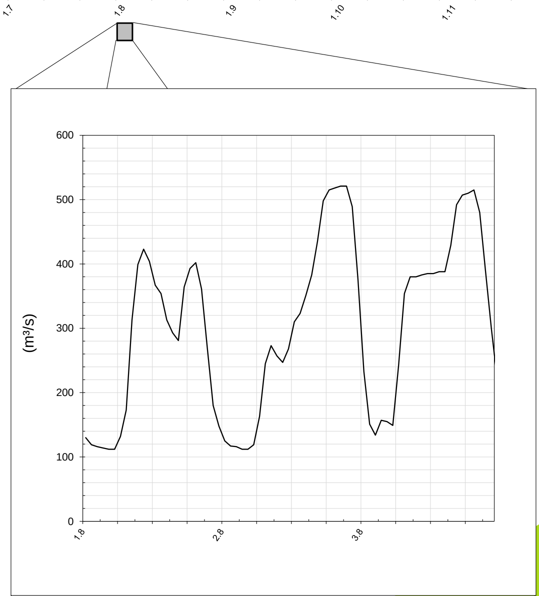
Project co-funded by European Union funds (ERDF, IPA)
Project number: DTP3-308-2.3- lifeline MDD

Interreg Danube Transnational Programme
lifelineMDD

Sub-daily flow regimes of the Drava River with a focus on the hydropower plant Dubrava

Hydrological impacts, potential ecological effects and mitigation measures





DTP3-308-2.3- lifeline MDD
Hydropeaking study

DI Dr. Franz Greimel
engineering consultant for water management and environment
December, 2022

IMPRESSUM:

Author:

DI Dr. Franz Greimel
engineering consultant for water management and environment
Bäuerlegasse 29/30
1200 Vienna, Austria
franzgreimel@netscape.net

Project staff:
Günther Unfer, Bernhard Zeiringer

Many thanks to:
The hydrographic services of Austria, Slovenia and Croatia,
Ivana Korn Varga (WWF Adria) and Kerstin Böck (WWF Austria)

Recommended citation:

Greimel, F., Zeiringer, B. & G. Unfer (2022): Sub-daily flow regimes of the Drava River with a focus on the hydropower plant Dubrava, Hydrological impacts, potential ecological effects and mitigation measures, Hydropeaking study, Deliverable report for EU-Interreg DTP project "lifelineMDD", 74 Pages, Vienna.

Contents

I. Introduction

The present report is the result of a study conducted within the DTP3-308-2.3 lifeline MDD, financed by the European Union´s Interreg Danube Transnational Programme. The area analysed and targeted by the present study (hereinafter called "target area") comprises river sections in the 5-country Biosphere Reserve Mura-Drava-Danube (TBR MDD, Figure 1), shared between Austria, Slovenia, Hungary, Croatia and Serbia. Spanning Austria, Slovenia, Hungary, Croatia and Serbia, the lower courses of the Drava and Mura Rivers and related sections of the Danube are among Europe's most ecologically important riverine areas. The three rivers form a "green belt" 700 kilometres long, connecting almost 1.000,000 hectares of highly valuable natural and cultural landscapes, including a chain of 13 individual protected areas and 3.000 km2 of Natura 2000 sites. This is the reason why, in 2009, the Prime Ministers of Croatia and Hungary signed a joint agreement to establish the Mura-Drava-Danube Transboundary Biosphere Reserve across both countries. Two years later, in 2011, Austria, Serbia and Slovenia joined this initiative. Together with Croatia and Hungary, the five respective ministers of environment agreed to establish the world´s first five-country Biosphere reserve and Europe´s largest river protected area. Step by step the TBR MDD was realized: Hungary and Croatia (in 2012), Serbia (in 2017), Slovenia (in 2018) and Austria (2019) achieved UNESCO designation. The pentalateral designation was submitted in 2020 and designation finally achieved in September 2021.

The project´s work package for *Establishing the scientific knowledge base* (Work Package T1) has proposed as its aim to establish, as a first, a scientific knowledge base regarding vertical, lateral and longitudinal connectivity within the Mura-Drava-Danube bio-corridor. All studies' results and the overlaid GIS data collected therefore build the basis for a synthesis report on biotic indicators and abiotic framework conditions. This builds the basis for long-term conservation and restoration goals within the 5-country Biosphere Reserve Mura-Drava-Danube (TBR MDD) as well as for formulation of a TBR MDD River Restoration Strategy, elaborated in the framework of the same project (Output OT2.4). The facts and results presented in this project therefore come from a first ever such scientific assessment, which was done between July 2020 and March 2021 (year), harmonized on 5-country scale, setting the ground for future decision-making on 5-country level on river management and restoration. Whereas such activities and knowledge in each of the countries involved in the TBR MDD partly exist, this was the first time methods and area were harmonized for monitoring and studies of the biotic elements and the abiotic framework conditions for the Mura-Drava-Danube river corridor.

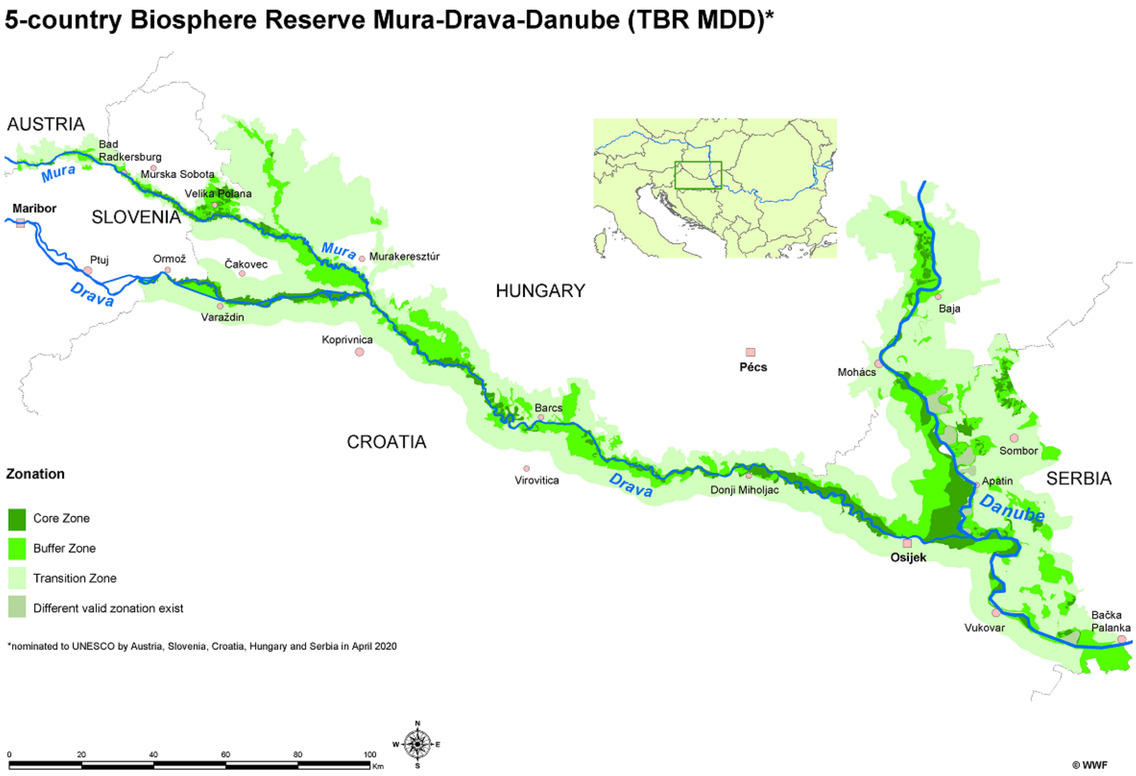


Figure 1. Map of the 5-country Biosphere Reserve Mura-Drava-Danube according to UNESCO designation in September 2021 (WWF Austria)

Hydropower dams are impacting the rivers and the floodplain landscape of the 5-country Mura-Drava-Danube Biosphere Reserve. On the Drava River there are 22 hydropower plants all the way from Austria and Slovenia to Croatia. They have been impacting the Drava River ecosystem for many decades, however they are also impacting the Drava reaches downstream from the last dam in the line, the Dubrava hydropower dam. This study takes a closer look at the hydrological and potential ecological consequences of hydropower plant operation, based on available data and on the state of scientific knowledge.

The objectives of the present study are

- to describe the sub-daily flow regimes in the Drava catchment using all available time series (chapter II-A),
- to investigate in detail the hydrological effects of the Dubrava hydropower plant (chapter II-B), and
- to estimate the fish ecological impacts considering the morphological condition of the lower Drava river, the available fish ecological data and based on recent scientific literature (chapter III).
- Finally, possible mitigation measures are outlined based on the conclusions (chapter III).

II. Hydrology

A detailed description of sub-daily flow regimes requires a standardized approach to detect the hydrological situation documented in multiple hydrographs, as well as a standardized definition of flow fluctuation events. Here, increase and decrease events can be distinguished. Both event types, i.e. increase event (IC) and decrease event (DC), are highly relevant when the hydrological situation is to be interpreted ecologically (e.g. drift and stranding risk due to hydropeaking). To detect both event types, an event-based algorithm for automated analysis of time series was developed and implemented into the open source R-package HydroPeak (Grün et al., 2021). The algorithm calculates flow (Q) differences of consecutive time steps (ts) of the discrete hydrograph curves (Q_{ts1}, Q_{ts2},..., Q_{tsn}) and discriminates between time steps with increasing (IC: $Q_{ts1} < Q_{ts2}$) and decreasing flow (DC: $Q_{ts1} > Q_{ts2}$). Continuous time steps with equal trends are defined as a single fluctuation event (Figure 2). For each event a set of parameters related to the intensity is calculated by the algorithm: the highest flow change within a time step represents parameter (1) - Maximum Flow Rate (MAFR). Parameter (2) - Mean Flow Rate (MEFR) is calculated by the event amplitude divided by the number of time steps. (3) The Amplitude (AMP) of an event is defined as the difference between the flow maximum (Q_{max}) and the flow minimum (Q_{min}). Parameter (4) – Flow Ratio (FR) is defined as $(Q_{max})/(Q_{min})$. The Duration (DUR) of an event (5) is simply the number of continuous time steps with equal flow trend. (Table I, Figure 2) (Greimel et al., 2016). The R-package HydroPeak (Grün et al., 2021) is applied to all hydrographs analyzed in chapter II.

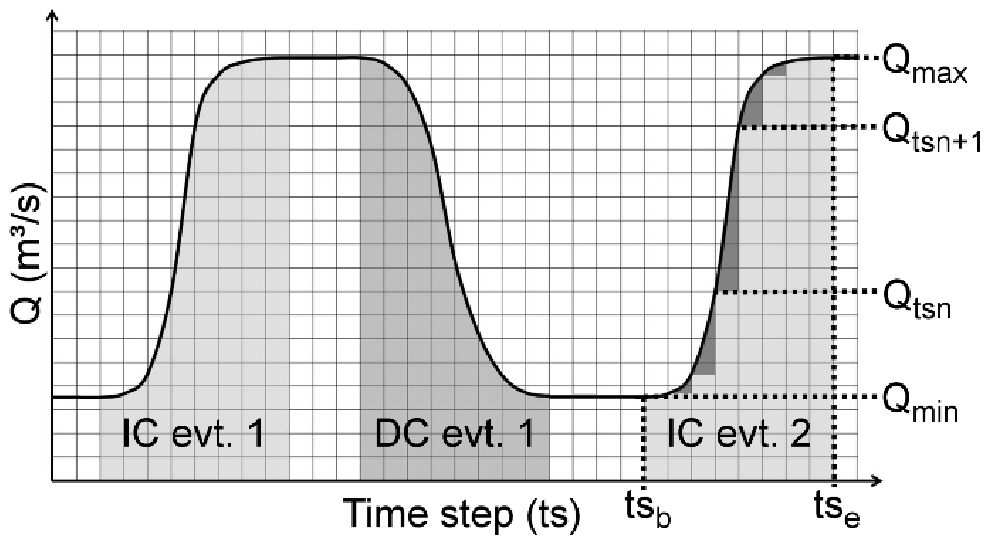


Figure 2. Events definition and relevant values to calculate flow fluctuation parameters illustrated at increase event 2 (IC evt. 2): time step event beginning (ts_b), time step event ending (ts_e), maximum event flow (Q_{max}), minimum event flow (Q_{min}), flow of a specific time step (Q_{tsn}), flow of subsequent time step (Q_{tsn+1}) (Greimel et al., 2016)

Table I: Event based parameters: definitions and units (Greimel et al., 2016, modified).

Nr.	Parameter	Acronym	Definition	Unit
1	Maximum flow fluctuation rate	MAFR	max(abs((Q_{tsn+1}) - (Q_{tsn})))	m^3/s^2
2	Mean flow fluctuation rate	MEFR	Amplitude/Duration	m^3/s^2
3	Amplitude	AMP	Q_{max} - Q_{min}	m^3/s
4	Flow ratio	FR	Q_{max}/Q_{min}	
5	Duration	DUR	ts_e - ts_b	s

t_{sb} - time step event beginning, t_{se} - time step event ending, Q_{max} - maximum event flow, Q_{min} - minimum event flow, Q_{tsn} - flow of a specific time step, Q_{tsn+1} - flow of subsequent time step, max – maximum, abs – absolute, s – second

In hydrology, two main approaches can describe hydropeaking waves (Greimel et al., 2022a). The Eulerian approach is a local or static approach where the hydrograph is analysed from a point fixed in a river (Figure 3 – left). This approach is equivalent to measuring the bedload passing through a given location per time unit in river sediment studies. Many ecohydrological studies have built upon this Eulerian perspective to characterize and describe hydropeaking waves and sub-daily flow regimes (e.g., Sauterleute and Charmasson, 2014; Bevelhimer et al., 2015; Greimel et al., 2016; Courret et al., 2021; Li and Pasternack, 2021). Hydrological data drawn from Eulerian assessments are commonly used to predict alterations to biological effects, both at the local scale (Saltveit et al., 2001; Auer et al., 2017) and linked to the population scale (Schmutz et al., 2015; Hayes et al., 2021). The Eulerian analysis is described in chapter II-A.

The alternative assessment approach is the Lagrange perspective. Here, the river flow motion is analysed for separate flow events, such as a hydropeaking wave, which can be followed downstream (Figure 3 – right). In sedimentological terms, this perspective is equivalent to tracking gravel the river transports. Understanding the translation and possible retention of source-specific hydropeaking waves in a Lagrangian perspective is crucial to adhere to the ‘polluter-pays’ principle of the EU Water Framework Directive. The Lagrangian analysis is described in chapter II-B.

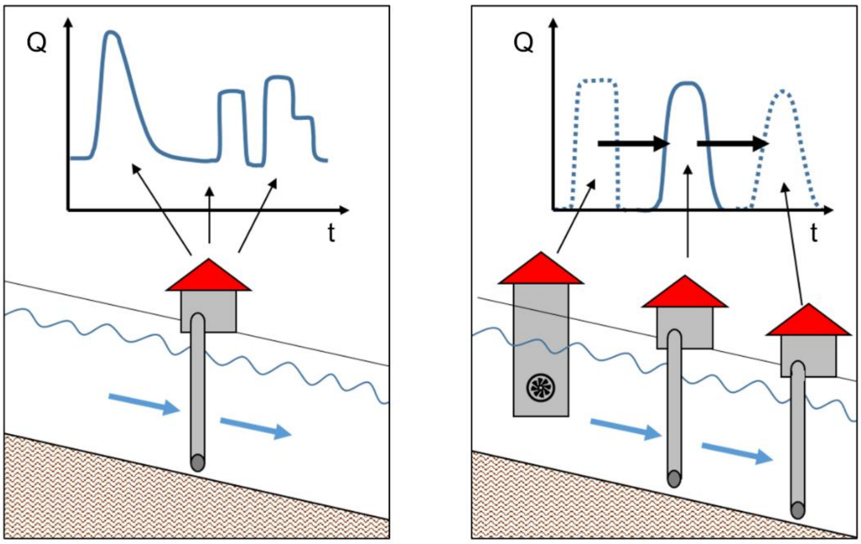


Figure 3: Contrasting the Eulerian view (left) with the perspective of Lagrangian view (right) (Greimel et al., 2022a)

A. Eulerian view

The Eulerian approach can be applied on a catchment or a national scale in order to examine hydrographs available and to obtain an overview of anthropogenic influences (Greimel et al., 2022b). To describe and compare hydrographs from the whole Drava River (strongly varying catchment size at the hydrographs) and to select specific (e.g, rapid) increase and decrease events without subjective judgements and in a standardized way, the method described in Greimel et al., 2022b is used, where the estimated intensity of natural flow fluctuations related to mean flow conditions is used as a nationwide benchmark (GW_{100}).

Since the upper part of the Drava catchment area is in Austria and also the hydrology of the middle and lower Drava is basically comparable to Austrian rivers in the Alpine foothills and Austrian lowland rivers, the Austrian benchmark definition according to Greimel et al. 2022b is applied, where the standardized selection of sub-daily flow fluctuations with reference to GW_{100} can be adjusted with respect to different intensity parameters (e.g., amplitude, flow rate). In this study, all sub-daily flow fluctuations whose maximum flow rate exceeds GW_{10} (i.e., 10% of GW_{100}) are analyzed. Based on these boundary conditions, all available time series are evaluated, the annual frequencies of the documented flow fluctuations are presented (Figure 4) and exemplified using the year 2019 (available for all hydrographs except Donji Miholjac, chapter V-C). In addition, the intensity of the flow fluctuations is presented referring to the data basis of

60 (chapter V-A) and 15 minutes (available for Austrian hydrographs, chapter V-B). For the Donja Dubrava hydrograph, the frequency and intensity of the sub-daily fluctuations are presented additionally on a monthly data basis (Figure 28 – Figure 30), since this river section is analyzed in more detail in chapter II-B.

1. Data basis

Data were collected from hydropower plant operators and hydrographic services with the support of WWF Adria (Table 2). In Slovenia and Croatia, the maximum resolution is 60 minutes (1 time step (ts) = 60 minutes). The maximum data resolution of all Austrian hydrographs (all hydrographs upstream of Dravograd) is one value per 15 minutes (1 ts = 15 minutes), which allows comparison of results based on 15- and 60-minutes data for these hydrographs. All values with minute reference (e.g., cm/min) are based on an averaging of the underlying time series with lower resolution.

Table 2: Hydrographs used for Eulerian analysis

Hydrograph ID	River	Name	Catchment (km^2)	MQ (m^3/s)	Time series
212043	Isel	Hinterbichl	107	5	1976 - 2021
212183	Isel	Waier	285	11	1976 - 2021
212092	Isel	Brühl	518	21	1976 - 2021
212167	Isel	Lienz	1.199	40	1976 - 2021
212316	Drau	Lienz-Peggetz	1.876	56	1977 - 2021
212324	Drau	Oberdrauburg-OWF	2.112	61	1977 - 2020
213660	Drau	Dellach-OWF	2.199	67	2013 - 2021
212357	Drau	Sachsenburg (Brücke)	2.561	69	1976 - 2020
213199	Drau	Drauhofen	3.674	109	1976 - 2021
213215	Drau	Amlach	4.790	131	1976 - 2020
213173	Drau	Lavamünd Ort	11.052	255	2005 - 2019
213595	Drau	Lavamünd Grenze	12.007	258	2011 - 2019
600420	Drau	Dravograd (Q-KW)	12.609	280	2010 - 2021
600421	Drau	Maribor - Otok (Q-KW)	13.417	297	2010 - 2021
600422	Drau	Ptuj	13.575	325	2019 - 2021
600423	Drau	Borl	14.624	53	2010 - 2021
600412	Drau	Donja Dubrava	16.682	317	2003 - 2019
600413	Drau	Botovo	31.038	475	2001 - 2019
600414	Drau	Novo Virje Skela	31.803	484	2001 - 2019
600415	Drau	Terezino Polje	33.916	492	2001 - 2019
600416	Drau	Donji Miholjac	37.142	509	2001 - 2016
600417	Drau	Belisce	38.500	524	2003 - 2019

(Hydrograph ID – internal database ID, MQ – mean flow, Catchment size calculated by GIS analysis)

2. Results and Interpretation

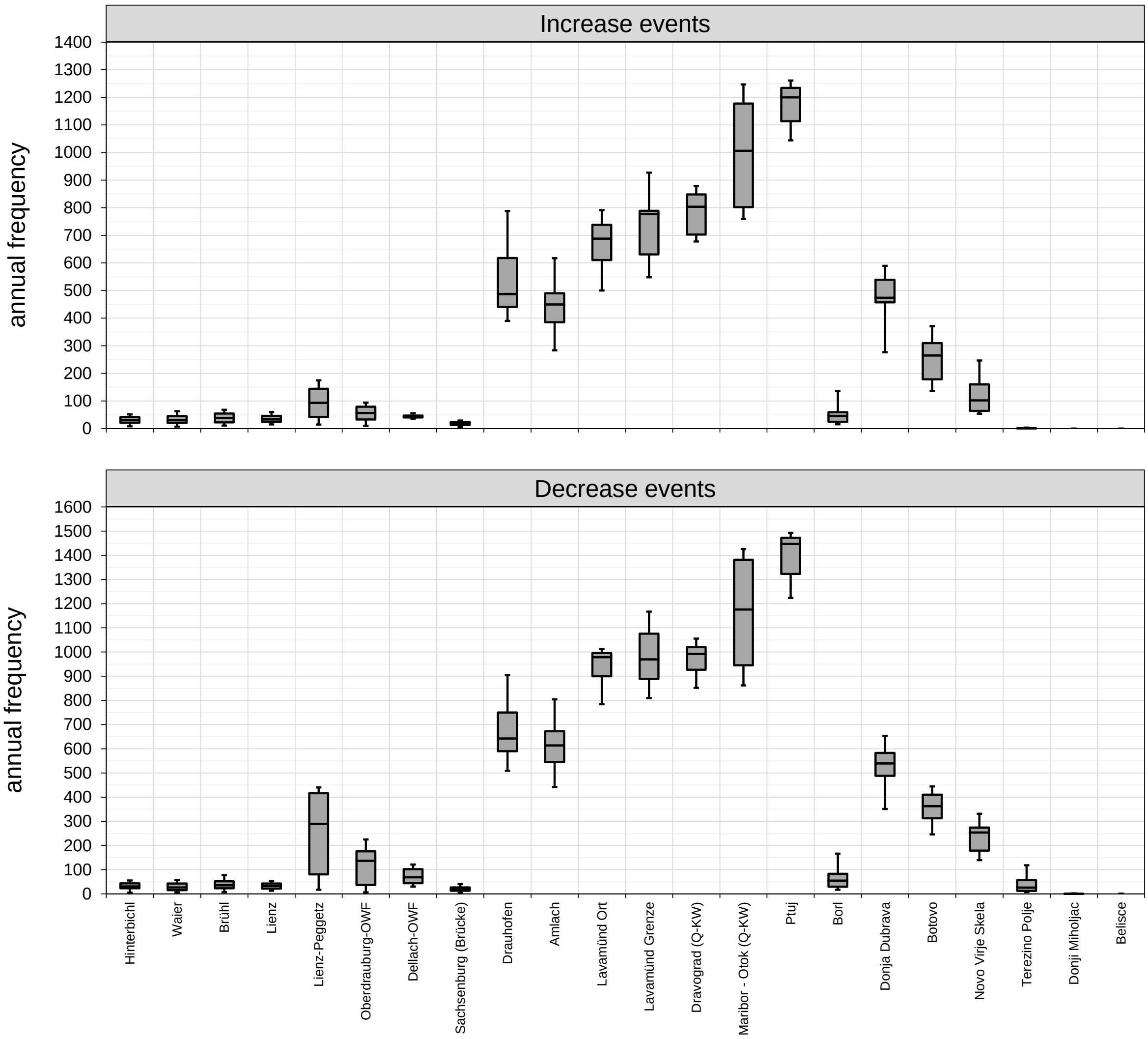


Figure 4: Annual frequency of sub-daily flow fluctuations with a maximum flow rate >GW10 (Data basis: 60 minutes resolution, whiskers correspond to 5% and 95% percentiles)

Based on Euler's analysis, the following flow regimes (according to Mader et al, 1996) and sub-daily flow regimes (according to Greimel et al, 2016) can be delineated in the Drava River basin:

1. **Isel** – hydrographs Hinterbichl, Waier, Brühl, Lienz
   Flow regime: Nivoglacial, glacial influence decreasing downstream
   Sub-daily flow regime: Anthropogenically influenced to a comparatively minor extent (hydrograph Lienz); characterized by an average of about 30-40 increase and decrease events (Figure 4) (at 15-minute resolution 50-60, Figure 31) per year due to melting events in spring (snow) and summer (glacier) and precipitation events exclusively during the summer half-year (Figure 34 - Figure 37);

2. **Drava, Lienz to Sachsenburg** – hydrographs Lienz-Peggetz, Oberdrauburg, Dellach, Sachsenburg
   Flow regime: Nivoglacial, glacial influence decreasing downstream
   Sub-daily flow regime: Anthropogenically influenced, anthropogenic influence decreasing downstream; characterized by an average of about 100-20 increase events and 300-20 decrease events (Figure 4) (at 15-minute resolution 700-50 increase and 1000-100 decrease events, Figure 31) per year due to year-round hydropeaking waves from the hydropower plant Strassen-Amlach, partially overlapping with natural flow fluctuations from spring to late fall (Figure 38 - Figure 41);

3. **Drava, Drauhofen to Amlach** – hydrographs Drauhofen, Amlach
   Flow regime: Nival
   Sub-daily flow regime: Anthropogenically influenced, anthropogenic influence decreasing downstream; characterized by an average of about 500-450 increase events and 650-600 decrease events (Figure 4) (at 15-minute resolution 3300-3200 increase and 4100-4000 decrease events, Figure 31) per year due to year-round hydropeaking waves from the hydropower plant Malta Unterstufe, partially overlapping with natural flow fluctuations from spring to late fall (Figure 42, Figure 43);

4. **Drava, Paternion to Ptuj** – hydrograph: Lavamünd Ort, Lavamünd Grenze, Dravograd, Maribor, Ptuj

   Flow regime: Nivopluvial regime

   Sub-daily flow regime: Anthropogenically influenced, anthropogenic influence increasing downstream; characterized by an average of about 700-1200 increase events and 1000-1450 decrease events (Figure 4) (at 15-minute resolution in Lavamünd about 3200 increase and 4000 decrease events, Figure 31) per year due to year-round hydropeaking waves from several Austrian and Slovenian hydropower plants (Schwellbetrieb), which partly overlap with natural flow fluctuations throughout the year, clustered in spring and autumn (Figure 44 - Figure 48);

5. **Drava, Maribor to Donja Dubrava (residual flow sections)** – hydrograph Borl

   Flow regime: residual flow, nival and pluvial influences discernible to a limited extend

   Sub-daily flow regime: Partially anthropogenically influenced; characterized by an average of about 50 increase and decrease events (Figure 4) per year mainly due to precipitation events in spring and autumn, but also due to temporary periods with hydropeaking waves from upstream hydropower plants (e.g., December 2019 - Figure 49);

6. **Drava, Donja Dubrava to Terezino Polje** – hydrographs Donja Dubrava, Botovo, Novo Virje Skela, Terezino Polje

   Flow regime: Nivopluvial

   Sub-daily flow regime: Anthropogenically influenced, anthropogenic influence decreasing downstream; characterized by an average of about 450-0 increase events and 550-25 decrease events (Figure 4) per year due to year-round hydropeaking waves from the Dubrava hydropower plant (Schwellbetrieb); at high flow periods, hardly any hydropeaking waves are detectable (Figure 50 - Figure 54);

7. **Drava, downstream of Terezino Polje** – hydrographs Donji Miholjac, Belišće

   Flow regime: Moderately nivopluvial

   Sub-daily flow regime: moderately anthropogenically influenced, anthropogenic influence decreasing downstream; at a data resolution of 60 minutes no event exceeds the maximum flow rate of GW_{10}; the sub-daily flow regime is influenced by natural and artificial flow fluctuations; at high flow periods, hardly any hydropeaking waves are detectable (Figure 55);

B. Lagrangian view

Hydraulic state-of-the-art modelling techniques can be applied to characterize the downstream development of hydropeaking waves including ecological relevant parameters such as the flow rate (Hauer et al., 2013, 2017; Juárez et al., 2019; Moreira et al., 2020; Burman et al., 2021). However, the basic data required for the creation of hydrodynamic models (e.g., detailed digital terrain data) for extended river sections are hardly available. In contrast, hydrograph data can usually be easily analysed and are available. Therefore, the empirical hydrological method PeakTrace, implemented in the R-package HydroRoute (Grün et al., 2022), is applied to enable the routing of hydropeaking waves in order to assess the changes in unsteady flows along the Drava River downstream of Donja Dubrava (Greimel et al. 2022).

The application of PeakTrace (chapter II-B-2-a) is based on flow series (Table 3), offering the opportunity to interpolate between neighbouring hydrographs. The goal is to link PeakTrace results (hydrological scenarios, Table 6) to ecological responses, e.g., by incorporating critical thresholds of specific river organisms and life stages (chapter III). Such thresholds usually refer to stage measurements (e.g., cm/min or cm/h) and not to flow-related metrics (e.g., (m^3/s)/min). This means that the flow-related PeakTrace results have to be transformed into stage-related metrics, which can be done approximately by regression models (Greimel et al., 2022a).

The regression models, originally established for Austrian rivers (Greimel, 2022b) to estimate the specific vertical stage shift resulting from a flow fluctuation of 1 m^3/s (dW_{spec} in m/(m^3/s)) are also applied for the lower Drava. In addition to the variables mean flow, catchment size and altitude, a factor related to river width (determined from aerial photos edited in QGIS) is considered in the approximate determination of dW_{spec} (Greimel et al., 2017). First, individual regression models are fitted for dW_{spec} at low, medium, and high flow ranges. The results of these regression models are then calibrated for the Drava using the available flow/stage relation curves downstream of Donja Dubrava such that the mean error is zero (Greimel et al, 2021a).

Based on dW_{spec} for the low, mean and high flow range further regression models are fitted in order to model specific “dW_{spec}-functions” over the entire flow spectrum for all transects where the river width is determined. That allows the estimation of the resulting stage fluctuations for each flow fluctuation starting from any base- (increase events) or peak flow (decrease events). This enables the PeakTrace results to be expressed in terms of flow (chapter II-B-2-a) and stage (chapter II-B-2-c), with the goal of using the stage-related curves to estimate the magnitude of expected stage fluctuations as a basis for ecological interpretation.

Based on the calibration, it can be assumed that the curve shapes are correct on average. The deviations from the mean curve, which are mainly due to the different river widths, are only intended to give an impression of a possible range of variation and do not claim to exactly reproduce the resulting stage fluctuations in a given profile. This would require a much greater effort (i.e., the creation and extensive calibration of a comprehensive HD model). This has to be considered in the ecological assessment by mainly referring to the mean curve and not to extreme values (chapter III).

1. Data basis

Data were collected from hydropower plant operators and hydrographic services with the support of WWF Adria (Table 3). The data resolution of all hydrographs is one value per 60 minutes (1 time step (ts) = 60 minutes), since higher resolution data were not available outside of Austria. All values with minute reference (e.g. cm/min) are based on an averaging of the underlying time series with lower resolution.

Table 3: Hydrographs used for Lagrangian analysis

Hydrograph ID	River	Name	Catchment (km^2)	MQ (m^3/s)	Time series	Station	Distance to HPP (rkm)	LAG (h)
600412	Drava	Donja Dubrava	16.682	317	2003 - 2019	S1	5,4	0
600413	Drava	Botovo	31.091	475	2001 - 2019	S2	20,4	03:00
600414	Drava	Novo Virje Skela	31.852	484	2001 - 2019	S3	47,1	08:00
600415	Drava	Terezino Polje	34.209	492	2001 - 2019	S4	94,3	18:00
600416	Drava	Donji Miholjac	38.031	509	2001 - 2016	S5	165,3	36:00
600417	Drava	Belisce	38.445	524	2003 - 2019	S6	192,8	43:00

(Hydrograph ID – internal database ID, MQ – mean flow, Station – hydrograph number downstream of the hydropower plant Donja Dubrava, HPP – hydropower plant, rkm – river kilometer, LAG – flow time between S1 and S_x,)

2. Results and Interpretation

a) PeakTrace – application

Identification of associated events

The sub-daily flow fluctuations recorded at the Donja Dubrava hydrograph (Station 1) can be excellently traced to Terezino Polje (S4) by automatic settings related to increase (IC) and decrease (DC) events. Downstream, amplitudes of both event types decrease sharply (Figure 5, Figure 6, see also Figure 55) and few associated events can be identified using the automatic settings (Figure 7, Figure 8), requiring manual processing to track flow fluctuations further downstream. Since it can be assumed that the hydropeaking effect is greatest next to the hydropower plant and the available resources are limited within the scope of this study, the Lagrangian analysis focuses on the first 100 km downstream of the Dubrava hydropower plant (Station 1 – Station 4).

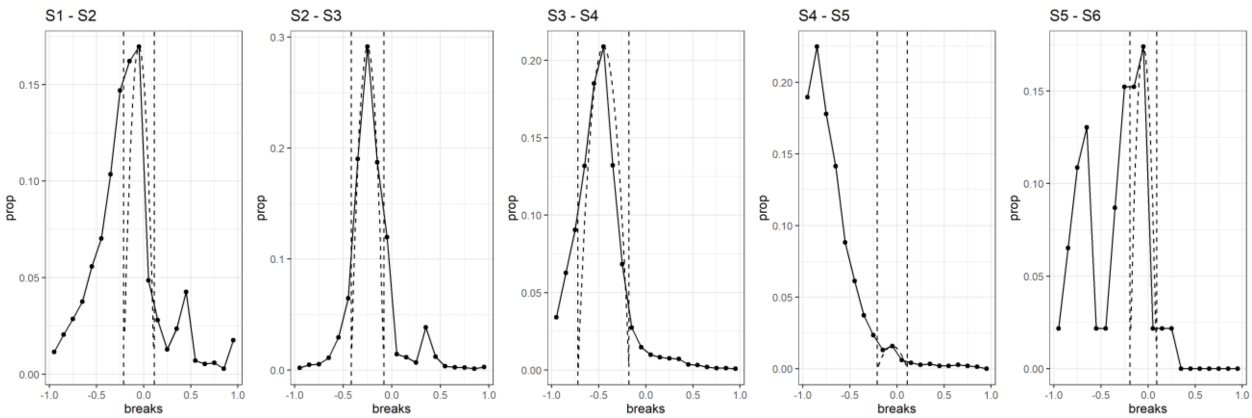


Figure 5: Automatic threshold determination for the identification of associated increase events between neighbouring stations (Grün et al., 2022)

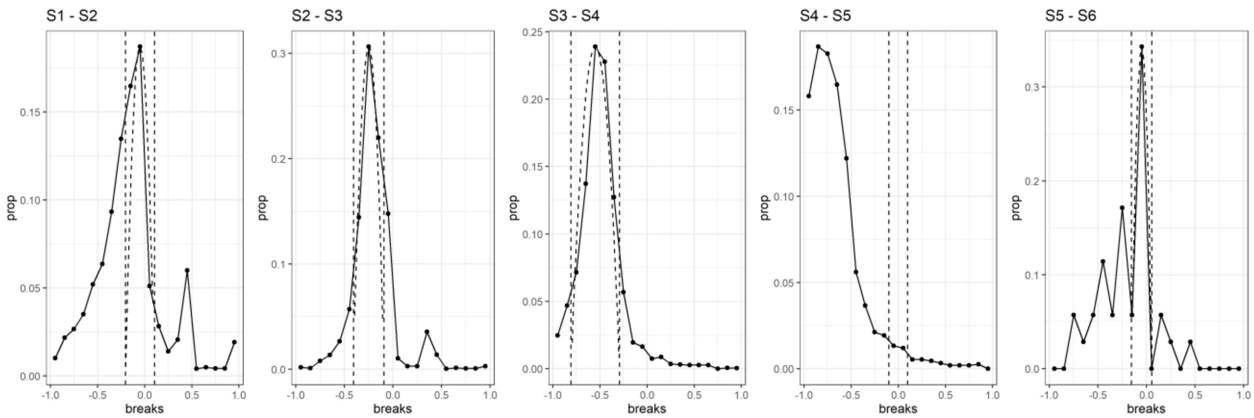


Figure 6: Automatic threshold determination for the identification of associated decrease events between neighbouring stations (Grün et al., 2022)

Scatter plots of event-based metrics and linear models between neighbouring hydrographs

The Scatter plots referring to the identified associated events between neighbouring hydrographs are shown in Figure 7and Figure 8. The fitted linear models to assess changes in unsteady flows along the analysed river reach are summarized in Table 4 and Table 5.

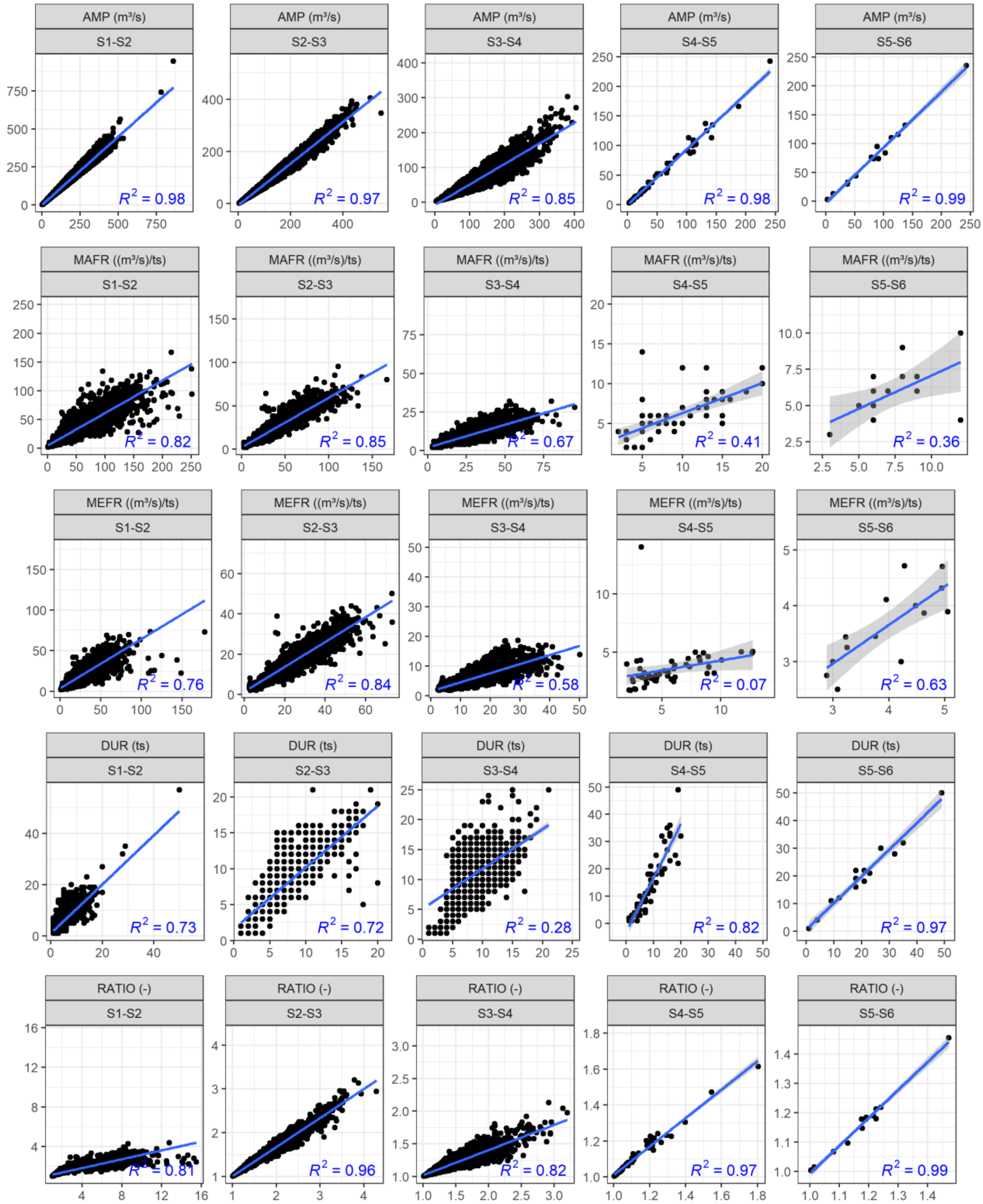


Figure 7: Scatter plots referring to identified associated increase events between neighbouring stations

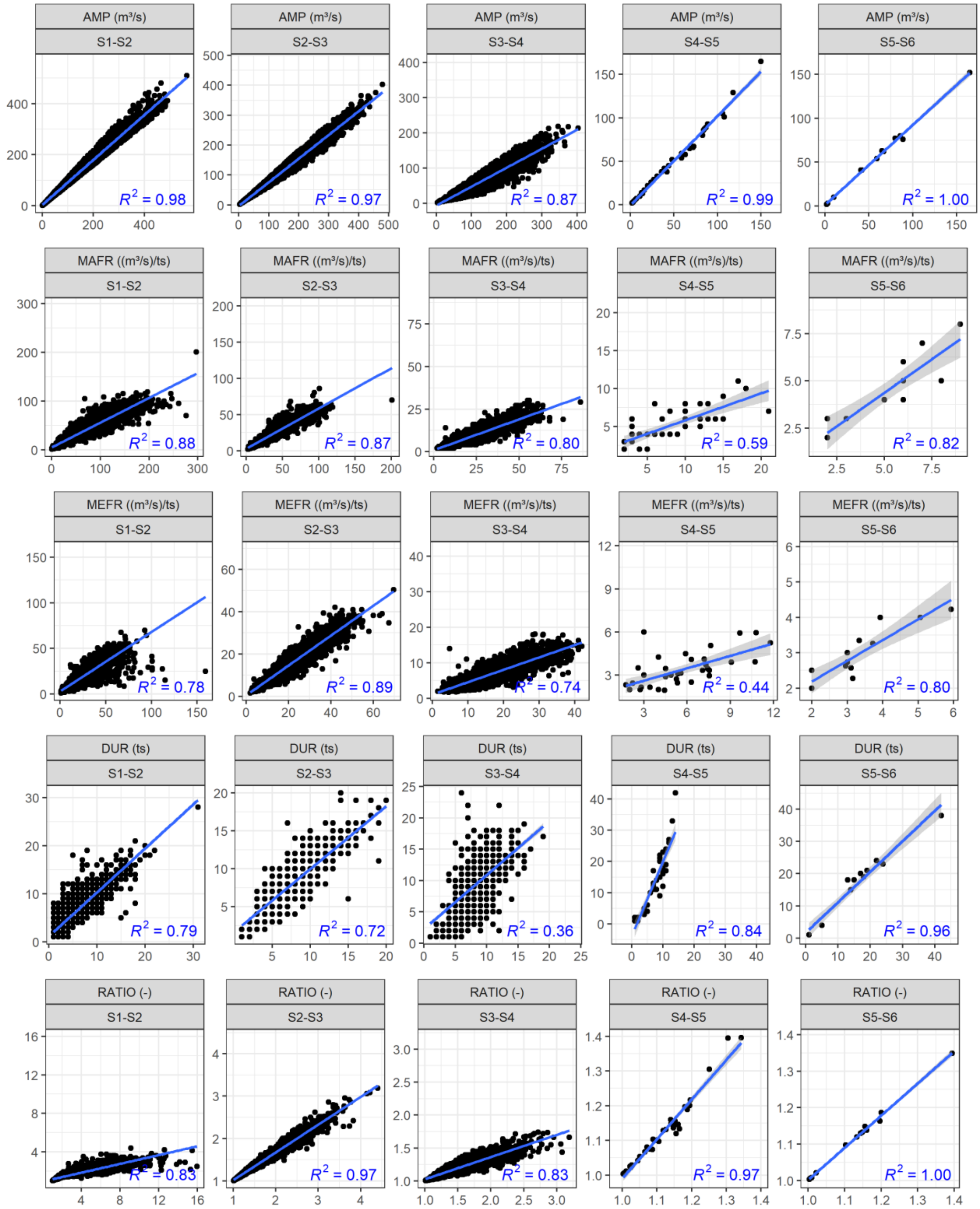


Figure 8: Scatter plots referring to identified associated decrease events between neighbouring stations

Table 4: Fitted linear models to describe the changes in unsteady flows between the neighboring hydrographs for increase events

Station.x	Station.y	Metric	Intercept	Slope	N	R^2
S1	S2	amp	0,96	0,90	4134	0,98
S1	S2	dur	1,02	0,95	4134	0,73
S1	S2	mafr	4,54	0,57	4134	0,82
S1	S2	mefr	3,63	0,61	4134	0,76
S1	S2	ratio	0,95	0,22	4134	0,81
S2	S3	amp	-5,17	0,80	2677	0,97
S2	S3	dur	1,64	0,85	2677	0,72
S2	S3	mafr	2,27	0,57	2677	0,85
S2	S3	mefr	1,48	0,62	2677	0,84
S2	S3	ratio	0,34	0,66	2677	0,96
S3	S4	amp	-7,43	0,59	1896	0,85
S3	S4	dur	5,12	0,67	1896	0,28
S3	S4	mafr	2,07	0,30	1896	0,67
S3	S4	mefr	1,50	0,31	1896	0,58
S3	S4	ratio	0,64	0,38	1896	0,82

(Station.x – upstream hydrograph, Station.y – downstream hydrograph, event-based parameters: amp – amplitude, dur – duration, mafr – maximum flow rate, mefr – mean flow rate, ratio – base/peak flow ratio)

Table 5: Fitted linear models to describe the changes in unsteady flows between the neighboring hydrographs for decrease events

Station.x	Station.y	Metric	Intercept	Slope	N	R^2
S1	S2	amp	3,20	0,88	4153	0,98
S1	S2	dur	1,11	0,91	4153	0,79
S1	S2	mafr	4,83	0,51	4153	0,88
S1	S2	mefr	3,06	0,65	4153	0,78
S1	S2	ratio	0,94	0,23	4153	0,83
S2	S3	amp	-3,31	0,79	2604	0,97
S2	S3	dur	1,69	0,83	2604	0,72
S2	S3	mafr	3,11	0,55	2604	0,87
S2	S3	mefr	0,47	0,71	2604	0,89
S2	S3	ratio	0,36	0,65	2604	0,97
S3	S4	amp	-6,66	0,54	2031	0,87
S3	S4	dur	2,26	0,86	2031	0,36
S3	S4	mafr	0,89	0,36	2031	0,80
S3	S4	mefr	1,10	0,35	2031	0,74
S3	S4	ratio	0,69	0,34	2031	0,83

(Station.x – upstream hydrograph, Station.y – downstream hydrograph, event-based parameters: amp – amplitude, dur – duration, mafr – maximum flow rate, mefr – mean flow rate, ratio – base/peak flow ratio)

Scenario definition

The goal of the scenario definition is to analyze the entire range of possible hydropeaking waves and their downstream development (routing). The Scatter plots for the hydropeaking amplitude indicate that the maximum power plant flow is about 500 m^3/s (Figure 7, Figure 8: AMP S1-S2 – x axis). With respect to the expected maximum power plant flow of 500 m^3/s, the scenarios presented in Table 6 are defined with reference to the hydrograph of Donja Dubrava as station 1.

Table 6: Routing scenarios referring to the hydrograph of Donja Dubrava (station 1) (Q_max refers to the expected maximum power plant flow of 500 m³/s)

Station	Metric	Value	Name
S1	AMP	500	Q_max
S1	AMP	375	Q_0.75
S1	AMP	250	Q_0.5
S1	AMP	125	Q_0.25
S1	AMP	62,5	Q_0.125
S1	MAFR	500	Q_max
S1	MAFR	375	Q_0.75
S1	MAFR	250	Q_0.5
S1	MAFR	125	Q_0.25
S1	MAFR	62,5	Q_0.125
S1	MEFR	500	Q_max
S1	MEFR	375	Q_0.75
S1	MEFR	250	Q_0.5
S1	MEFR	125	Q_0.25
S1	MEFR	62,5	Q_0.125
S1	DUR	1	
S1	RATIO	Max	

(VALUE – intensity at station 1 (AMP – amplitude (m^3/s), MAFR – maximum flow rate ((m^3/s)/60 min), MEFR – mean flow rate ((m^3/s)/60 min), DUR – duration (1 timestep = 60 min), RATIO – base/peak flow ratio – maximum measured value at station 1)

Exceedance frequency of scenarios and definition of the ecological assessment basis

Since even a few high-intensity hydropeaking waves can lead to significant negative ecological impacts (Schmutz et al., 2013), it makes sense to define a high-intensity scenario as an ecological assessment basis. To determine which scenarios to evaluate from an ecological perspective, annual exceedance frequencies are presented in Figure 9 and Figure 10.

Concerning the hydropeaking amplitude, the maximum scenario 1 is reached on average once per year, scenario 0.75 about five times, and scenario 0.5 more than 50 times (Figure 9 and Figure 10– right). This means that the range between scenarios 0.5 and 0.75 is crucial for the ecological assessment as this intensity range is reached comparatively often by intense hydropeaking waves. The amplitudes of the increase and decrease events are highly redundant, so it seems to be sufficient to represent the amplitude of either one event type. In the following, the amplitude is therefore exclusively related to increase events.

The maximum flow rate, which is repeatedly reached by increase and decrease events, is about 200 m^3/s per 60 minutes. (Figure 7, Figure 8: MAFR S1-S2 – x axis). This is also reflected in the annual exceedances of the scenarios, with the annual maximum being scenario 0.5, which corresponds to a flow rate of 250 m^3/s per hour. Scenario 0.25 is regularly exceeded, on average about 20 times per year (Figure 9 and Figure 10 – left). However, since it can be assumed that the hydropower plant flow may be operated between standstill and maximum flow within 60 minutes or shorter time, the actual flow rates probably cannot be recorded in the vicinity downstream of the hydropower plant due to a too low temporal data resolution and the data discretization method (i.e., averaging). Based on the available data on maximum flow rates, the range between the 0.25 and 0.5 scenarios must serve as the basis for the ecological assessment, although it can be assumed that the actual flow rates of intense hydropeaking waves are higher. However, to investigate this in detail, time series with higher resolution are needed (e.g., 5- or 15-minute data).

In chapter II-B-2-b) and II-B-2-c), the above scenarios are represented by solid black lines when displaying the routing results, in contrast to the other scenarios (dashed).

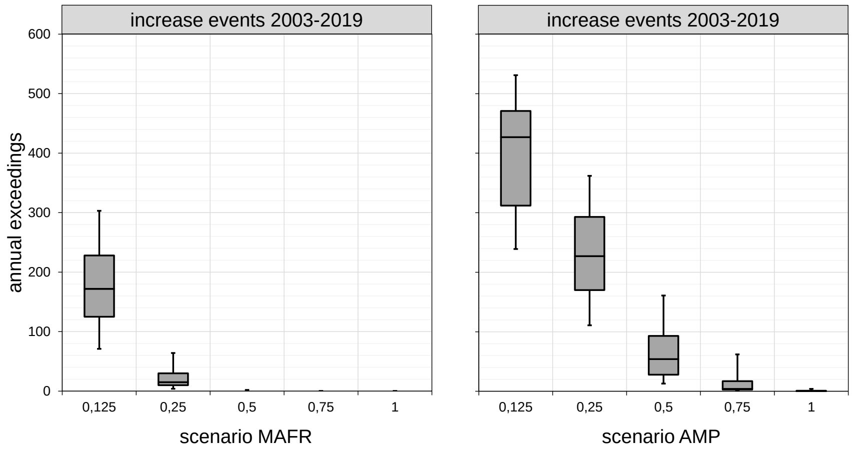


Figure 9: Donja Dubrava - annual scenario exceedings of increase events related to maximum flow rate (MAFR - left) and amplitude (AMP - right)

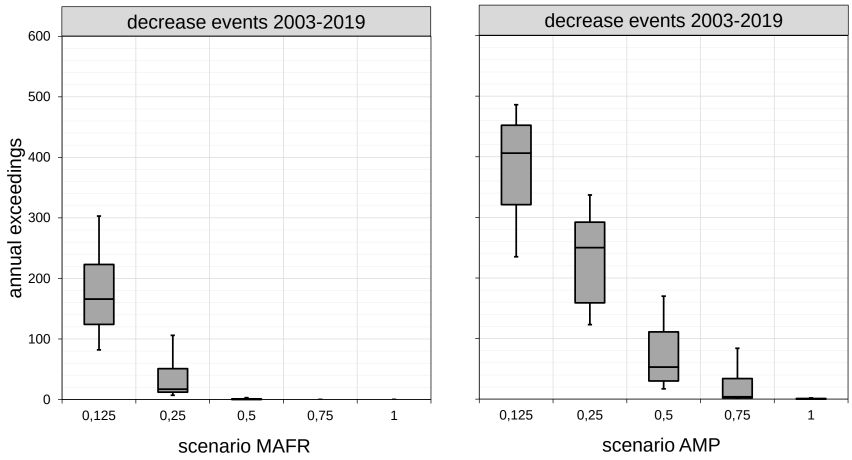


Figure 10: Donja Dubrava - annual scenario exceedings of decrease events related to maximum flow rate (MAFR - left) and amplitude (AMP - right)

Scenario routing

Finally, the scenarios (Table 6) are routed by a combination of the linear models (Table 4, Table 5) in terms of increase (Figure 11) and decrease (Figure 12) events. The modelled DUR-scenario refers to an initial value of one timestep (60 minutes), the Ratio-scenario to the maximum measured associated event at Donja Dubrava (approx. 1:15). The most important parameters for ecological interpretation (AMP, MAFR) are further processed in the following chapters.

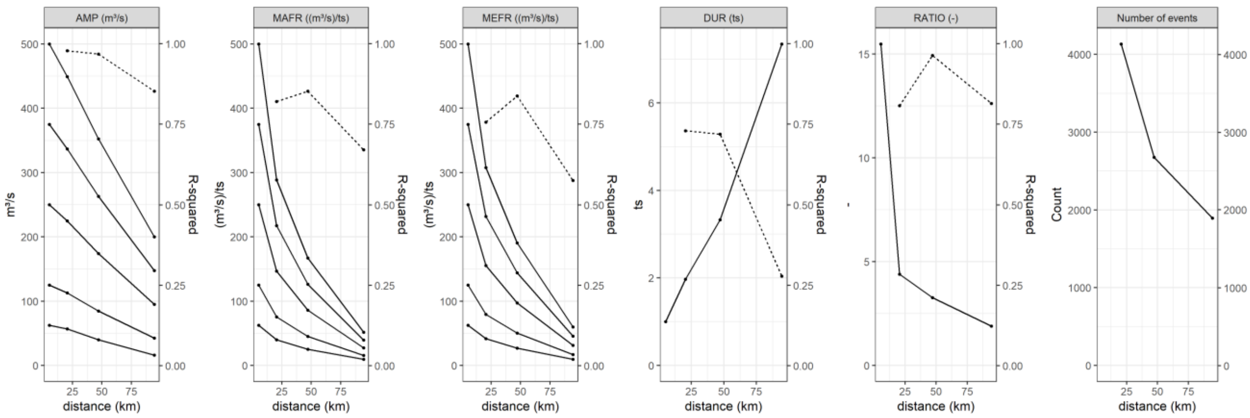


Figure 11: PeakTrace results regarding increase events

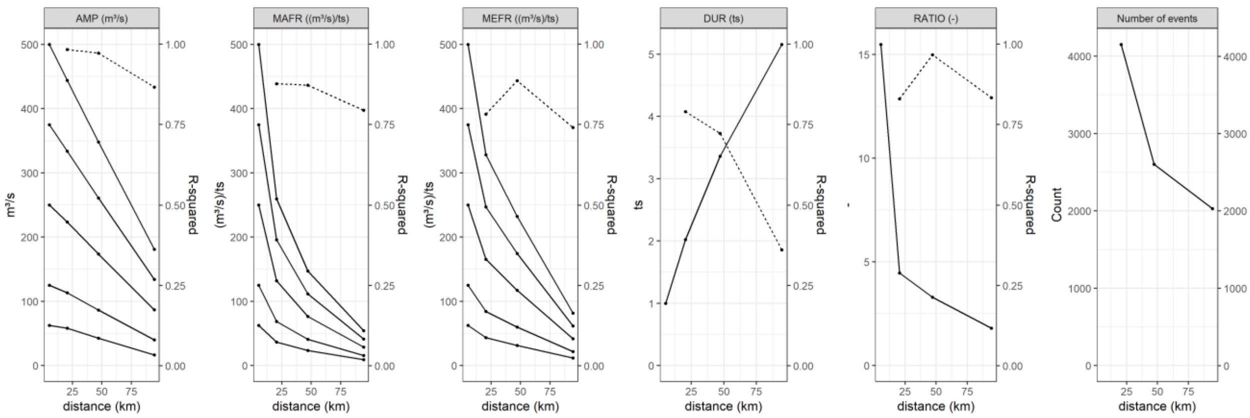


Figure 12: PeakTrace results regarding decrease events

b) Flow-related routing results

The flow-related routing results referring to the hydropeaking amplitudes and the maximum flow rates of increase and decrease events are shown in Figure 13 to Figure 15.

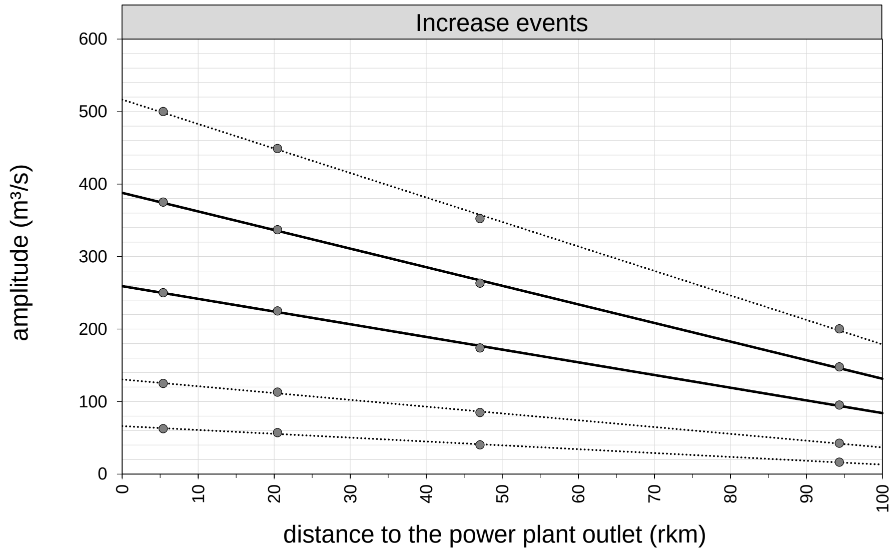


Figure 13: Flow-related routing results in terms of hydropeaking amplitudes (referring to increase events; area between the non-dotted scenarios: intensity of intense hydropeaks repeatedly documented in the available time series)

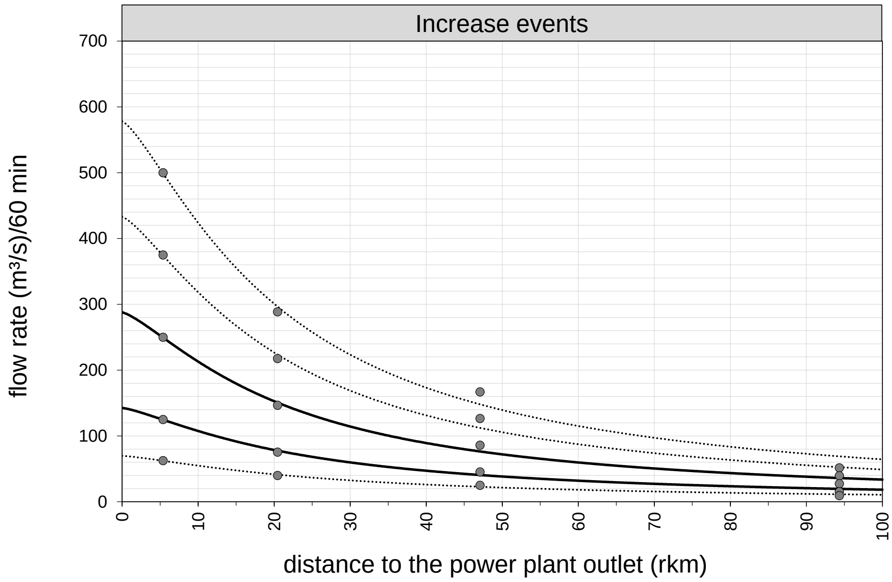


Figure 14: Flow-related routing results in terms of maximum flow rates of increase events (area between the non-dotted scenarios: intensity of intense hydropeaks repeatedly documented in the available time series)

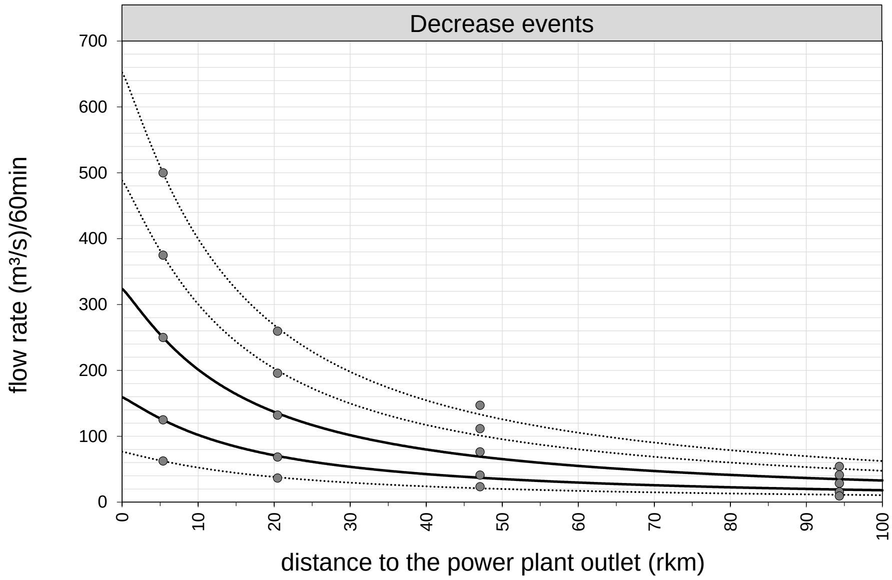


Figure 15: Flow-related routing results in terms of maximum flow rates of decrease events (area between the non-dotted scenarios: intensity of intense hydropeaks repeatedly documented in the available time series)

c) Stage-related routing results

Since resulting stage fluctuations depend on the baseflow (i.e., the flow situation if the power plant does not turbinate water) situation in the river (lower baseflow – higher stage fluctuations/higher baseflow – lower stage fluctuations), it is necessary to consider the baseflow in order to obtain a realistic picture of the hydropeaking effects. By specifying that increase events begin with baseflow and decrease events end with baseflow, hydropeaking scenarios can be analyzed using a standardized approach with respect to characteristic baseflows. To get an idea of the characteristic baseflows during the year, the Donja Dubrava hydrograph for the last three available years (2017-2019) is presented below (Figure 16). In addition, Table 7 provides an overview of routed flow parameters downstream of the Dubrava hydropower plant.

First, it is noticeable that from a flow of about 500 m^3/s (or 2 times MQ, Table 7), hardly any hydropeaking waves are visible (Figure 16). This is probably due to the fact that the power plant is constantly operating at maximum load when the inflow is above the maximum power plant capacity and the reservoir is full. Hydropeaking at flow conditions above 500 m^3/s is therefore not characteristic downstream of the Dubrava hydropower plant. In contrast, hydropeaking waves occur very frequently at baseflows between Q95 and MQ, which means that these baseflow conditions are characteristic and therefore relevant for the ecological assessment (Figure 17 to Figure 22). Both baseflow situations can occur throughout the year, although baseflows around MQ are likely concentrated during periods of snowmelt in the spring and high precipitation in the fall. (Figure 16). This result is also supported by plotting the monthly flow distribution with respect to the entire time series (Figure 51). The stage-related routing results for the characteristic baseflow situations are shown in Figure 17 – Figure 19 (Q95 – low flow) and Figure *20* – Figure 22 (MQ – mean flow).

Table 7: Characteristic flow parameters downstream of the Dubrava hydropower plant

distance to HPP (rkm)	Catchment Area (km^2)	Q95 (m^3/s)	MQ (m^3/s)	2 MQ (m^3/s)
10,9	16687	82	246	492
31,6	31121	189	567	1134
43,7	31408	197	590	1179
69,9	32389	204	612	1224
80,2	32927	216	648	1296
100	34312	228	684	1368

(rkm – river kilometer, Q95 – flow value exceeded 95% of time, MQ – mean flow, HPP – hydropower plant)

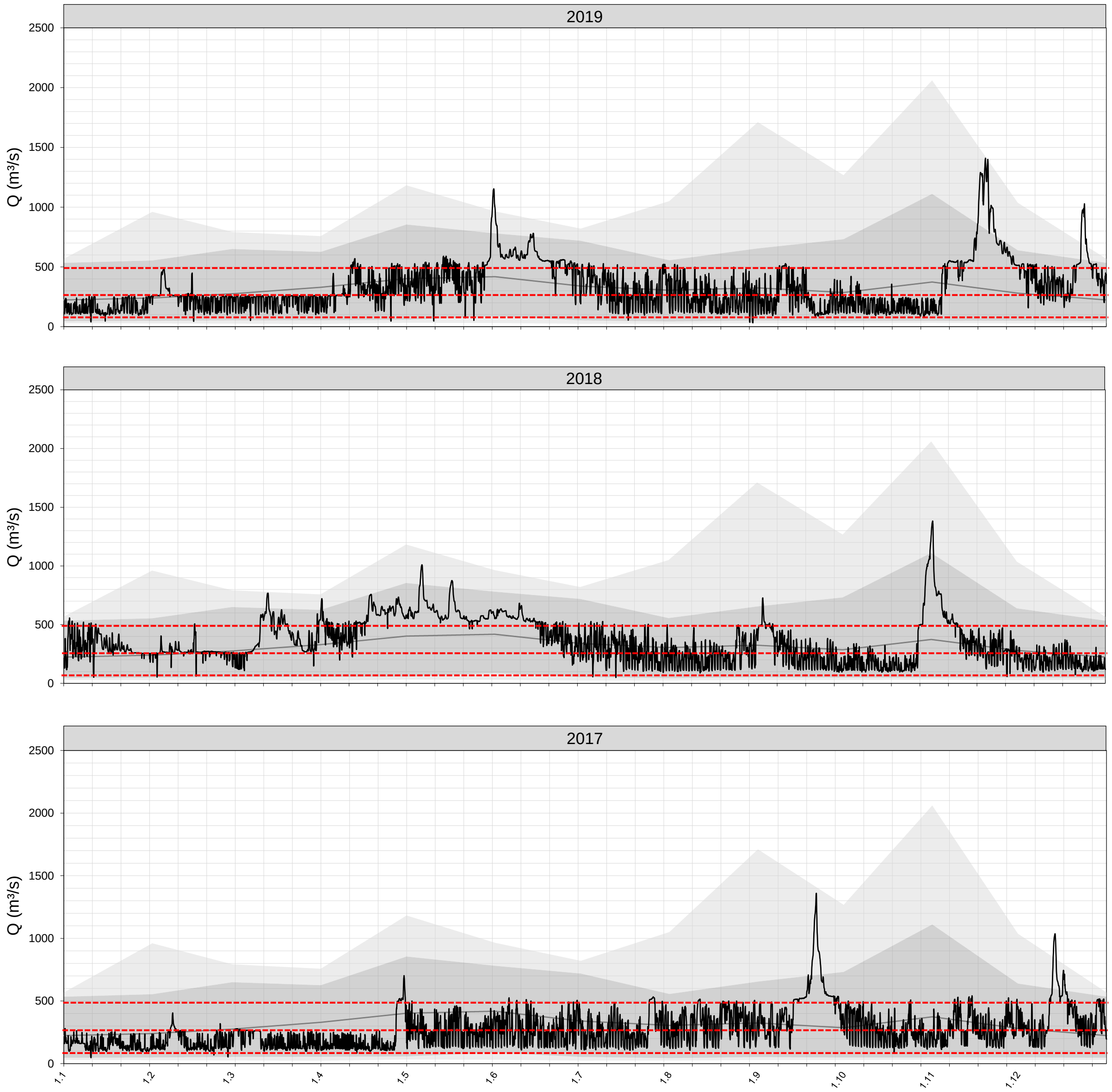


Figure 16: Donja Dubrava hydrograph 2019 (top), 2018 (middle) and 2017 (bottom) (black line: flow, dark grey: long-term 25% percentile of the monthly minimum flow to 75% percentile of the monthly maximum flow, light grey: long-term 5% of the monthly minimum flow to 95% percentile of the monthly maximum flow, red: characteristic flow parameters at Donja Dubrava (Table 7))

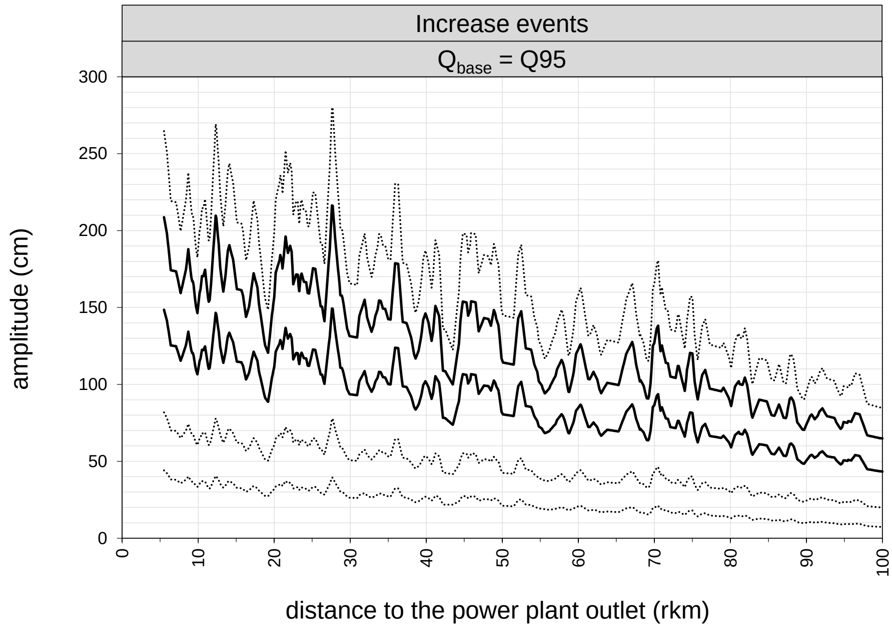


Figure 17: Stage-related routing results in terms of hydropeaking amplitudes at baseflow Q95 (referring to increase events; area between the non-dotted scenarios: intensity of intense hydropeaks repeatedly documented in the available time series)

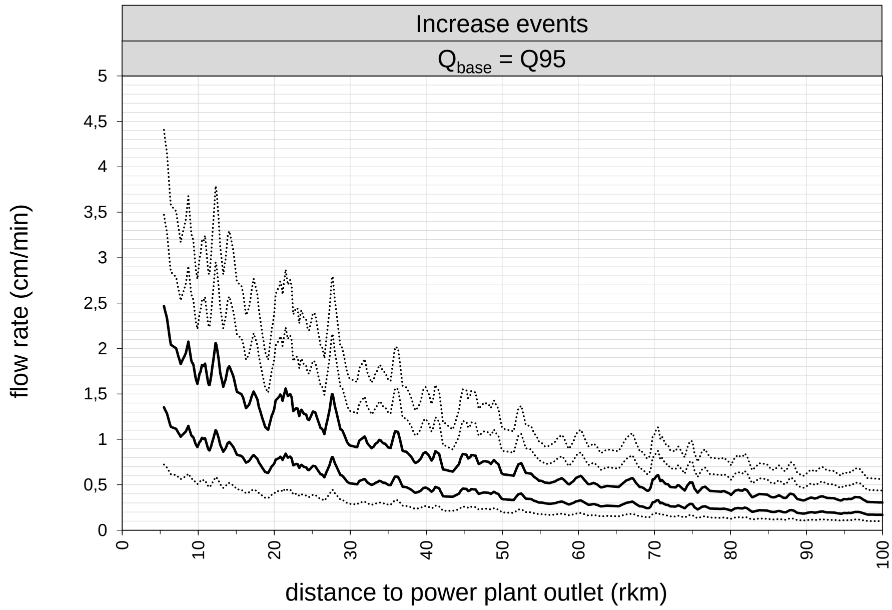


Figure 18: Stage-related routing results in terms of maximum flow rates of increase events at baseflow Q95 (area between the non-dotted scenarios: intensity of intense hydropeaks repeatedly documented in the available time series)

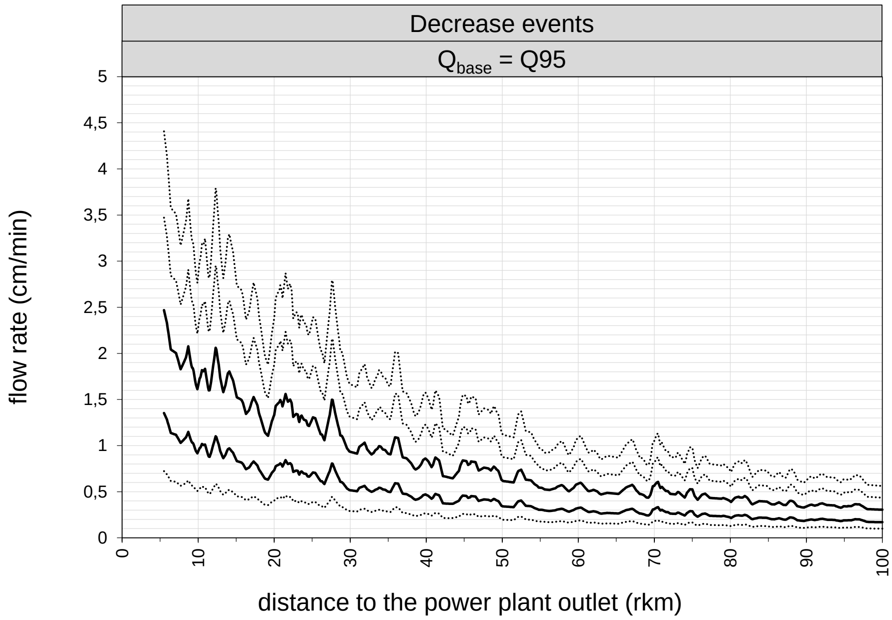


Figure 19: Stage- routing results in terms of maximum flow rates of decrease events at baseflow Q95 (area between the non-dotted scenarios: intensity of intense hydropeaks repeatedly documented in the available time series)

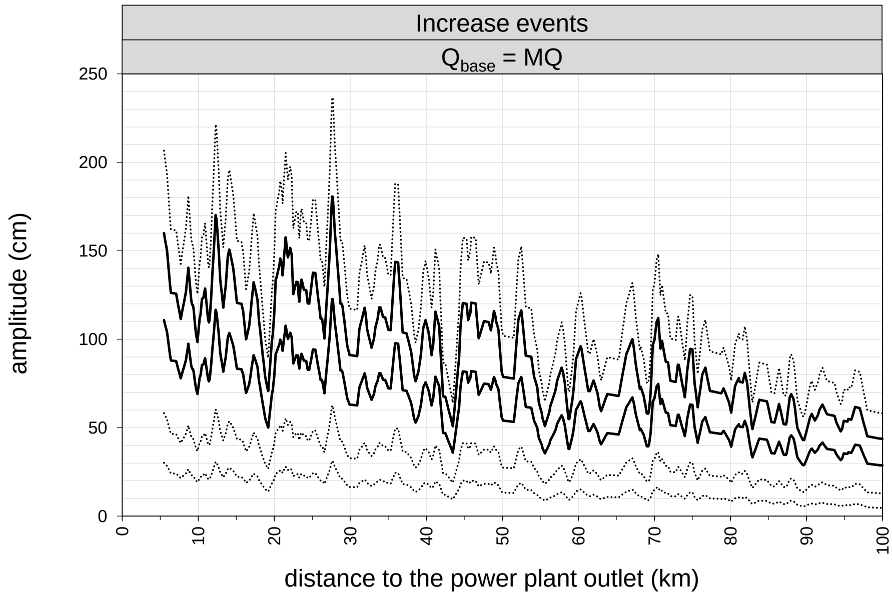


Figure 20: Stage-related routing results in terms of hydropeaking amplitudes at baseflow MQ (referring to increase events; area between the non-dotted scenarios: intensity of intense hydropeaks repeatedly documented in the available time series)

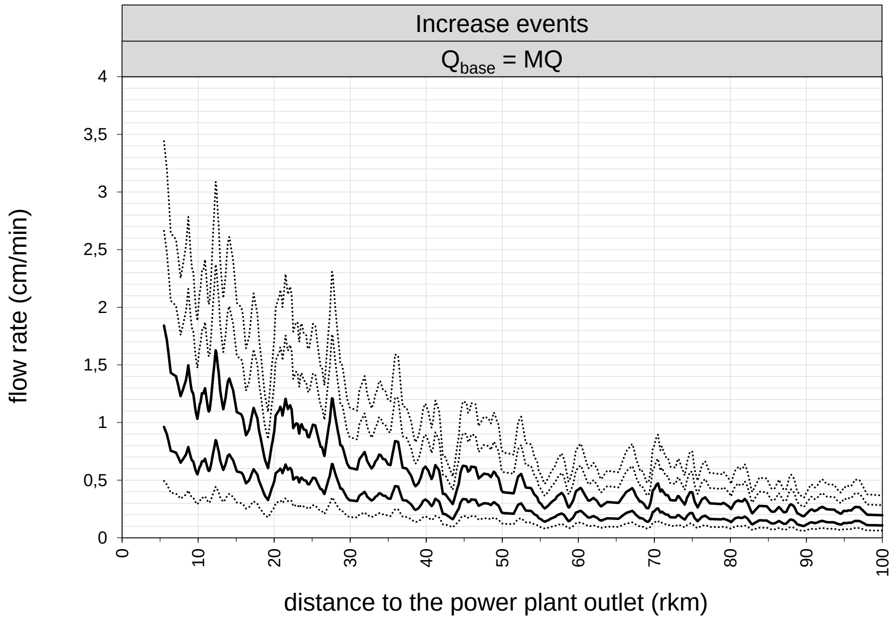


Figure 21: Stage-related routing results in terms of maximum flow rates of increase events at baseflow MQ (area between the non-dotted scenarios: intensity of intense hydropeaks repeatedly documented in the available time series)

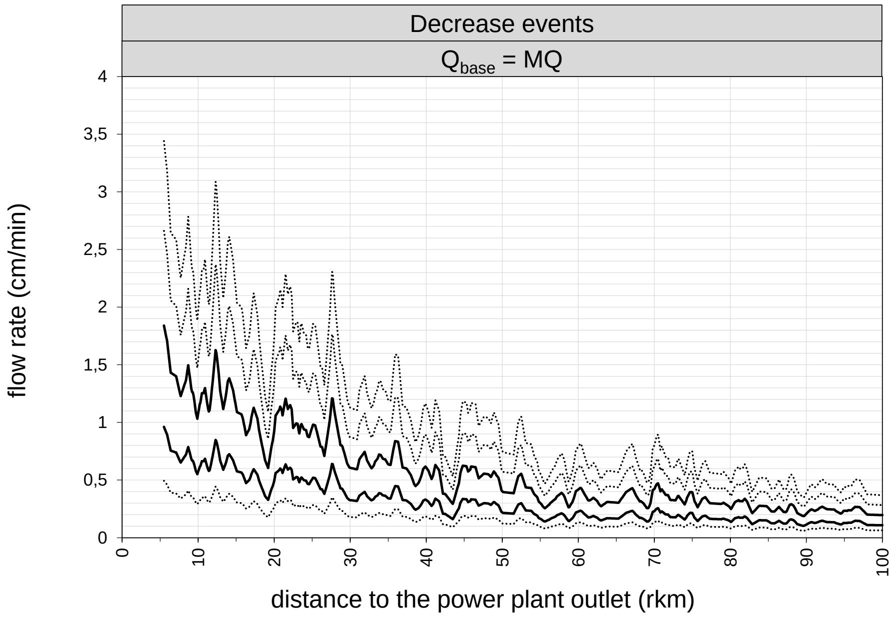


Figure 22: Stage- routing results in terms of maximum flow rates of decrease events at baseflow MQ (area between the non-dotted scenarios: intensity of intense hydropeaks repeatedly documented in the available time series)

III. Expert opinion / Conclusions

The following findings, important for ecological interpretation, can be derived from the hydromorphological analyses performed.

Eulerian view – a hydrological overview of the Drava River

Based on Euler's analysis, which investigates flow fluctuations independently of their source, several sub-daily flow regimes were delineated in the Drava River. In the uppermost part of the catchment, hydrological conditions are largely unaffected. The Isel River (the hydrologically larger river at the confluence with the Drava River) shows an anthropogenically minor influenced sub-daily flow regime with a comparatively high number of natural flow fluctuations compared to non-glacier influenced unregulated rivers. However, compared to river sections with hydropeaking, the number of flow fluctuations in the Isel River is low.

Downstream of the Strassen-Amlach hydropower plant next to Lienz, the number of flow fluctuations increases significantly. In the following approximately 60 river kilometers, the hydropeaking waves are then damped due to the flowing retention effect, so that only a few rapid flow fluctuations are detected at Sachsenburg. At the Malta Unterstufe (Malta Lower Dam) hydropower plant next to Drauhofen, additional hydropeaking waves are released into the Drava River, increasing the number of anthropogenic flow fluctuations to several hundred (60-minute data) to thousands of events per year (15-minute data). Downstream, the hydropeaking waves are again attenuated by the flowing retention until the beginning of the extended run-of-river chain between Paternion/Austria and Dubrava/Croatia.

Here, the anthropogenic influence increases with each run-of-river power plant due to hydropeaking ("Schwellbetrieb"), in which the storage capacity (backwater) of several run-of-river power plants is managed collectively (Greimel et al., 2016). The energy-economically optimized use of the storage volume leads to artificial flow fluctuations, to such an extent that even with the data resolution of 60 minutes, more than 1000 events per year are detected. The hydrologically most impacted section of the Drava River is therefore located in Slovenia downstream of Maribor.

However, this strongly impacted section is interrupted several times up to Donja Dubrava by residual flow stretches, where the hydropeaks are diverted from the Drava River for most of the year, resulting in a large decrease in the number of flow fluctuations. Unfortunately, a time series is only available for the residual flow section in Borl, which allows a hydrological description of this very important habitat in view of the severely impacted hydrological situation.

Downstream of the Dubrava hydropower plant, the number of flow fluctuations is of a similar magnitude as downstream of the Malta Unterstufe (Malta Lower Dam) hydropower plant and a characteristic section begins again in which the hydropeaking waves are damped by the flowing retention. Here, however, the anthropogenic flow fluctuations are damped due to the extended free-flowing River section up to the mouth into the Danube River to such an extent that no more rapid flow fluctuations are detected in Belišće. The remaining anthropogenic influence is only recognizable by the comparatively regularly occurring flow fluctuations in low and mean flow periods with rather low amplitudes compared to the natural events.

Lagrangian View – hydropeaking impacts of the Dubrava hydropower plant

In addition to the overview of the sub-daily flow regimes of the Drava River, the river section downstream of Donja Dubrava was investigated in more detail using the Lagrangian approach, where the flow fluctuations of a specific source (the Dubrava hydropower plant) were followed downstream over several hydrographs.

The scenarios that serve as the ecological assessment basis were defined, with scenarios chosen whose intensity is reached by intense hydropeaking waves. The results summarized in Table 8 refer to these scenarios; for more detailed results, see the charts in chapters II-B-2-a) and chapter II-B-2-c). It is worth noting that, based on the available data on maximum flow rates, comparatively low scenarios must be used as the basis for the ecological assessment, although it can be assumed that the actual flow rates of intense hydropeaking waves are higher. Referring to the hydrographs in Lavamünd where a similar hydrological situation exists as in Donja Dubrava and a comparison of results based on 15- and 60-minutes data resolution is possible, the maximum flow rate of strong hydropeaks (95 % percentile) is underestimated by about 50% at a 60 minutes resolution, while the median is in a similar order of magnitude. However, to investigate this in detail, time series with higher resolution would be needed in Donja Dubrava.

Table 8: Dubrava hydropower plant - summarized routing results for the scenarios relevant to the ecological assessment

Station/hydrographs		1	2	3	4
Distance to PP (rkm)		5,4	20,4	47,1	94,3
Amplitude - increase events	(m^3/s)	250 - 375	225 - 340	175 - 260	225 - 340
	baseflow Q95 (cm)	150 - 210	120 - 180	90 - 130	50 - 70
	baseflow MQ (cm)	110 - 160	80 - 130	70 - 110	30 - 60
Max. flow rate - increase events	(m^3/s)/h	125 - 250	80 - 150	40 - 80	15 - 40
	baseflow Q95 (cm/min)	1.3 - 2.5	0.8 - 1.5	0.4 - 0.7	0.2 - 0.3
	baseflow MQ (cm/min)	1 - 1.8	0.5 - 1	0.2 - 0.5	0.1 - 0.2
Max. flow rate - decrease events	(m^3/s)/h	125 - 250	70 - 120	40 - 70	15 - 35
	baseflow Q95 (cm/min)	1.3 - 2.5	0.7 - 1.3	0.3 - 0.7	0.2 - 0.3
	baseflow MQ (cm/min)	1 - 1.8	0.5 - 1	0.2 - 0.5	0.1 - 0.2

(rkm – river kilometer, Q95 – flow value exceeded 95% of time, MQ – mean flow; due to high redundancy, amplitudes only refer to increase events)

Fish Ecological interpretation

Hydropeaking has been identified as a serious pressure on fish populations in alpine rivers (Parasiewicz et al. 1998; Person et al. 2013). Within an extensive study on hydropeaking, it was demonstrated that fish communities are strongly affected by hydropeaking in Alpine rivers of Austria (Schmutz et al. 2013 and 2015). Hydropeaking has several negative effects especially on juvenile fish stages. According to Young et al. (2011) adverse effects include (1) stranding or lateral displacement of fish along the banks; (2) drift and downstream displacement; and (3) reduced spawning and rearing success which may occur due to spawning pit (nest) dewatering and mistimed or obstructed migration. Gravel bars and shallow habitats along the shoreline are preferred habitats of juvenile life stages. However, these habitats are primarily affected by water level fluctuations. Stranded fish can be divided into the following categories: (1) Stranded fish that remain on the substrate and suffocate; and (2) entrapment, when fish are isolated in potholes with no access to the free-flowing surface water (Higgins and Bradford 1996; Hunter 1992). Stranding depends on the flow rate of decrease events (downramping rate), the lateral gradient of gravel bars, substrate size, morphological sub-structures within or near the gravel bars and its connectivity to refuge and main channel habitats (Hauer et al. 2014). Higher beach stranding occurs more frequently on lower gradient bars than on steeper banks (Adams et al. 1999; Hunter 1992). Higher fish stranding rates occur in larger cobbles where water drains through rather than flowing off (Hunter 1992, Hauer et al. 2014). Fish stranding risk increases with increasing downramping rate (Führer et al. 2022, Hayes et al. 2019, Zeiringer et al. 2014, Schmutz et al. 2013, Halleraker et al. 2003; Hunter 1992). Downstream displacement of small fishes as a consequence of hydropeaking also has been documented by several authors (Auer et al. 2017, Schmutz et al. 2013, Bell et al. 2001; Shirvell 1994). Although stranding and drift has been studied and described in the literature mainly for salmonids, recent work with a focus on cyprinids (Führer et al. 2022, Hayes et al. 2022) also indicates considerable negative consequences for these species, especially at early life stages.

The fish ecological study within "lifeline MDD" (Rauch 2022) was designed to get an overview of the fish species communities in the longitudinal course of the Mura and Drava rivers. The focus of the surveys was on species occurrence and distribution. However, the report also includes analyses and calculations on quantitative stock characteristics (biomass, individual density), which, due to the limited sampling effort (fishing of selected sections, limited to one season/one water level), are suitable for comparison between the fished sections (CPUE), but must generally be interpreted with caution. In order to describe and assess the hydropeaking related consequences downstream of Donja Dubrava in detail on the basis of fish ecological surveys, a targeted study design would have had to be applied. However, the data obtained in Rauch (2022) give clear indications of a serious impact of the hydropower plant operation on the fish population in at least three of the studied sections (SR, SD and S4; Rauch 2022). The fish study showed that the Mura and Drava rivers are clearly dominated by the guild of rheophilic gravel spawners, with the (*Chondrostoma nasus*) and barbel (*Barbus barbus*) as the quantitatively most important fish species at the center of the species community (Rauch 2022).

Directly downstream of the Dubrava hydropower plant, the sections "SD" and "S4" were electro-fished as part of the above-mentioned study (Rauch 2022), which primarily can be used to interpret the fish ecological effects of the hydropower plant operation. In addition, the results of the residual flow section (SR) caused by the hydropower plant and the sections further downstream (S5, S6, and S7) can be included in the interpretation. Section S5 is located about 25 km downstream of the confluence with the Mura River, S6 another about 50 km downstream, and S7 again about 80 km downstream of S6 (Rauch 2022). In the area of sampling reach S6, the river type of the Drava changes (Schwarz 2022). There, the transition of the Drava from an alpine, gravel-dominated river to a water body dominated by sandy sediments takes place. This change in river type not only results in different morphological and sedimentological conditions, but also leads to a natural change in the fish species community from a community strongly characterized by rheophilic species to species that are less dependent on gravel habitats, especially with regard to reproduction. Therefore, the Drava's fish community in the lowermost sections of the Drava are also less sensitive to hydropeaking operations.

In the hydropeaking section of the river relevant to this study, mainly the juveniles of the predominant rheophilic, gravel-spawning cyprinids such as nase (*Chondrostoma nasus*), barbel (*Barbus barbus*), asp (*Aspius aspius*) or cactus roach (*Rutilus virgo*) and some others inhabit shallow gravel habitats along the banks. The juveniles of all these rheophilic species are particularly sensitive to power plant-induced water level fluctuations and get potentially affected by stranding and drift displacement.

Führer et al. (2022) investigated the stranding risk of early developmental stages of the nase (*Chondrostoma nasus*) under the influence of hydropeaking in mesocosm experiments under near-natural conditions in a flow channel. Different hydropeaking scenarios (downramping rate 0.7 – 1,5 cm/min.) were investigated on gravel banks with different slopes and depending on the time of day. They found a clear dependence of the stranding risk on the downramping rate as well as a clear influence of the gravel bank slope. They also found that stranding rates were significantly higher at night. These results are in line with previous studies with salmonids (Auer et al. 2017, Schmutz et al. 2015). In the above-mentioned study (Führer et al. 2022) stranding rates of generally up to 33% and during the night even up to 60% were documented. While the study by Führer et al. (2022) focused on early larval stages with fish lengths of 14-16 mm, Hayes et al. (2022) show that the risk of stranding already decreases significantly (5-40%) with increasing fish length (18 mm). This indicates that stranding and related mortality of juvenile cyprinid-larvae (dominating species: nase (*Chondrostoma nasus*), barbel (*Barbus barbus*) is of major relevance during a limited time period of a few weeks in April and May.

The hydropeaking intensity concerning the downramping rate downstream of Donja Dubrava is exactly in the order of magnitude identified as critical by Führer et al. (2022) (Table 8). The affected section extends up to approx. 50 km downstream of the hydropower plant, whereby the hydropeaking intensity decreases continuously downstream (Table 8). Depending on the baseflow, the number of hydropeaking events and daytime during the sensitive phase of larval development of the nase (*Chondrostoma nasus*) (April-May) stranding is certain to occur downstream of Donja Dubrava. Due to the fact that the section of the Drava downstream of Donja Dubrava provides suitable juvenile habitats at all simulated baseflows because of its largely natural morphology, the risk of stranding is also always given during the year. In addition, the amplitudes of the hydropower plant operation in Donja Dubrava reach heights of up to 2 m and even about 100 km downstream amplitudes of about half a meter can still be detected (Table 8). According to the morphological conditions (wide flow profile with shallow gravel banks) there is a considerable risk of so-called pool trapping (Cushman, 1985; Bretschko & Moog, 1990; Kjaerstad et al., 2018, Schmutz et al., 2013) and consequently high predation mortality by e. g. bank related birds may occur.

Further, some results presented in Rauch (2022) also point at a significant influence of the operation mode of the Dubrava hydropower plant on the fish community in the downstream Drava section. The length frequency distribution of the nase (*Chondrostoma nasus*) near the power plant shows that, apart from a few juveniles caught in the residual flow stretch, juvenile nase (*Chondrostoma nasus*) are completely absent (Figure 23). Downstream of Donja Dubrava, nase (*Chondrostoma nasus*) were only found from lengths of approx. 30 cm on (Figure 23). This is in sharp contrast to all other sections sampled during the study (Rauch 2022), where juvenile fish dominate in numbers throughout (Figure 24). This result is underlined by the comparison of the mean lengths of individuals along the study area (MDD), where the deviations in the vicinity of Donja Dubrava become obvious (Figure 24, circled in red).

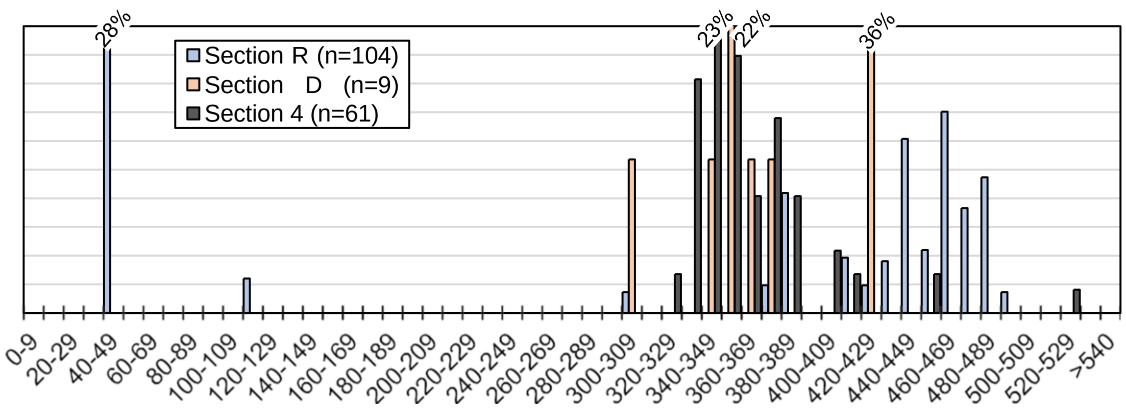


Figure 23: Length frequency diagram of the nase (Chondrostoma nasus) in the vicinity of Donja Dubrava (Rauch 2022)

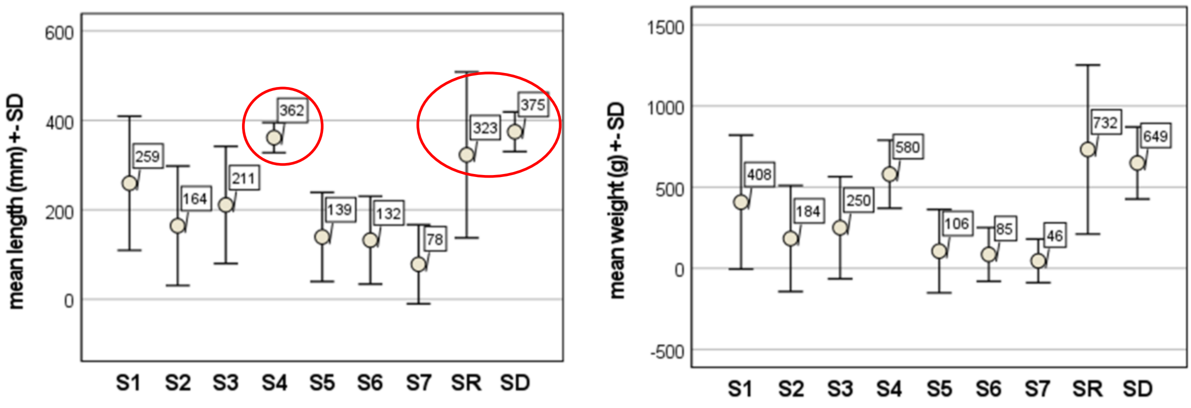


Figure 24: Error bar plot of mean length and mean weight (+- std. deviation) of nase in sampled sections in the Mura and Drava (Rauch 2022)

The density of juvenile nase (*Chondrostoma nasus*) is also significantly reduced in the residual flow stretch created by the Dubrava hydropower plant and only a few juveniles of the nase (*Chondrostoma nasus*) were caught during the fish survey (Figure 23). Although the residual flow stretch has excellent structural features and both suitable reproductive and spawning habitats are present, densities of juveniles of rheophilic fish species are clearly reduced (Rauch 2022). The analysis of the upstream residual flow section with the gauge in Borl (Hydrograph ID 600423) shows that the residual flow section there is also repeatedly influenced by hydropeaking (Figure 4). Without having corresponding data from the Donja Dubrava residual flow stretch, we assume that similar hydropeaking phenomena also occur there, and that hydropeaking also causes damage to spawning, displacement and stranding of early developmental stages of rheophilic fish fauna.

<u>Possible hydropeaking mitigation measures</u>

From the fish ecological interpretation, it is clear that hydropeaking from the Dubrava hydropower plant can have a significant impact on the fish fauna of the Drava River. Even though detailed investigations are missing so far, an influence can be assumed as certain based on the hydrological analyses and the indications that can be derived from the fish study (Rauch 2022). Therefore, it is also appropriate to consider which measures could be considered to best dampen or prevent the potential impact of hydropeaking in Donja Dubrava.

Different measures are described, to reduce adverse ecological impacts of hydropeaking (Bruder et al., 2016; Halleraker et al., 2016; Moreira et al., 2019; European Commission, 2020; Smokorowski, 2021). Measures aiming at mitigating the hydrological situation to reduce negative ecological impacts are referred to as "direct measures" (Greimel et al., 2018), i.e., the reduction of the intensity and/or the frequency of hydropeaking waves by:

- the operational restriction of a storage hydropower plant (e.g., ecologically adapted operation mode)
- the attenuation of hydropeaking waves through retention volume (e.g., through the construction of retention basins, though possibly not feasible for Drava) or optimized management of existing retention volume (e.g., volume in run-of-river impoundments, flood retention basins) or by-pass valves (by-pass the flow around the turbine in order to uncouple turbine and hydropower plant flow in the short term)
- the diversion of hydropeaking waves (e.g., by a diversion hydropower plant) and relocating tailrace into a larger water body (e.g., lake, impoundments)

Depending on the type and extent of mitigation scenario, different hydrological improvements can be achieved by the implementation of direct mitigation measures (Figure 25). Furthermore, these improvements can be assigned to the major expected ecological impact, although it can be assumed that the ecological effects are partially interlinked to each other:

- Attenuation of the flow rate of downramping events / reduction of the stranding risk (Figure 25-a)
- Attenuation of the flow rate of upramping events / reduction of the drift risk (Figure 25-b)
- Reduction in amplitude / reduction in hydropeaking-related impacts on habitat alteration (Figure 25-c)
- Attenuation of the flow rate of up- and downramping events / reduction of drift and stranding risk (Figure 25-d)
- Attenuation of the flow rate of up- and downramping events and reduction in amplitude / reduction in drift and stranding risk and hydropeaking impacts on habitat alteration (Figure 25-e)

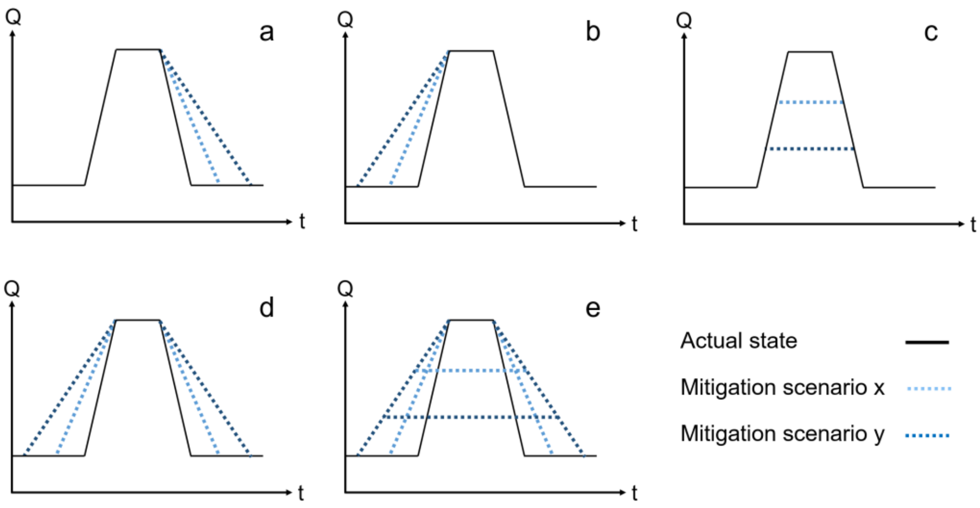


Figure 25: Schematic sketch depicting hydrological effects of direct mitigation measures (flow - Q; time - t) at different mitigation scenarios (light blue line vs. dark blue line) (Greimel et al. 2021b)

Below listed are the exemplified direct measures that can be potentially implemented for a hydrological effect/improvement (Greimel et al, 2021b).

- Operational restrictions can achieve any hydrologic effect in principle (Figure 25-a, b, c, d, e).
- By-pass-valves are typically designed to dampen the flow rate of decrease events (Figure 25-a), but might also be programmed to dampen increase events (Figure 25-b) that will enable highly flexible hydropeaking operation (Halleraker et al., in prep.).
- The flow rate of increase and decrease events (Figure 25-d) can be mainly reduced by attenuation through retention volume, while limiting the amplitude in general requires very high retention volume.
- Hydropeaking diversion trough bypass channels can divert hydropeaking waves partially or completely, or prevent that hydropeaking waves enter the river. Thus, the limitation of the hydropeaking amplitude may also result in a limitation of the flow rate of increase and decrease events (Figure 25-e).

Beside direct measures, indirect measures can be implemented to reduce the ecological impacts of hydropeaking. Indirect measures can be described as morphological/sedimentological (e.g., habitat improvement, reduction of the hydraulic intensity) or technical (e.g., artificial spawning channels) measures that do not influence the hydrological situation itself but lead to an increased habitat quality as an indirect positive effect (Schmutz et al., 2013; Hauer et al., 2014, 2017; Greimel et al., 2018). A combination of several direct and indirect measures may be required to achieve the greatest ecological effect.

Several EU policies address concrete measures to mitigate hydropeaking, to ensure sustainable ecosystems (European Commission, 2021). Some technically available options may not be feasible due to nature protection regulation (e.g, Birds & Habitats Directives). Overall restoration must comply with EU Water Framework Directive requirements.

The EU Water Framework Directive sets concrete environmental targets for water bodies ("good ecological status" or "good ecological potential") that are affected by anthropogenic pressures such as hydropeaking (Halleraker et al., 2016; European Commission, 2020). The legal basis on the path to achieving the two target states differ significantly. Good ecological status is an absolute target defined on a river type-specific basis using ecological parameters and thresholds. From a legal point of view, technically feasible measures can be demanded according to the polluter pays principle until the target state is reached, provided that the costs incurred are reasonable. When determining the good ecological potential, on the one hand the ecological effectiveness of measures to reduce the impact of hydropeaking has to be considered. On the other hand, the extent to which these measures are expected to restrict the use of the hydropower plants (in particular system-relevant impacts) or have adverse effect on the wider environment has to be assessed (European Commission, 2020).

With regard to the section of the Drava River influenced by the Dubrava hydropower plant, it will be necessary

- to determine the target condition to be achieved,
- to determine the measures that are technically feasible in principle within the framework of a feasibility study,
- to describe the expected ecological and energy-economic effects of the realizable measures and
- to provide comprehensible and transparent justification as to why certain measures are not feasible,

before the targeted restoration is in line with the EU Water Framework Directive.

From the present study, it can be concluded that the maximum flow rate of decrease events must be limited to 50-60 m^3/s per hour with reference to the Donja Dubrava hydrograph in order to significantly reduce the risk of fish stranding (Führer et al., 2022) in the first 50 kilometers downstream of the Dubrava hydropower plant, which could also reduce the stranding risk for benthic invertebrates (Perry & Perry, 1986; Kastenhofer, 2018).

In addition, reduced hydropeaking amplitudes would be very positive from an ecological perspective, as the artificially induced water exchange zone would be reduced and thus the associated negative ecological impacts (e.g., pool trapping of fish, hydraulic stress to benthic invertebrates) would likely decrease (Cushman, 1985; Bretschko & Moog, 1990; Kjaerstad et al., 2018, Schmutz et al., 2013). Reducing the flow rate of increase events would also be targeted to reduce the drift risk to aquatic organisms (Gibbins et al., 2007; Timusk et al., 2016).

With regard to the overall hydrologically stressed Drava, the residual flow stretches in Slovenia and Croatia are of particular importance, as they can form "indispensable ecological stepping stones" if the habitat is maintained and improved by ecologically optimized eFlows and hydropeaking is kept away.

IV. References

Adams SR, Keevin TM, Killgore KJ, Hoover JJ (1999): Stranding potential of young fishes subjected tosimulated vessel-induced drawdown. Trans Am Fish Soc 128: 1230–1234.

Auer, S., Zeiringer, B., Führer, S., Tonolla, D., and Schmutz, S. (2017): Effects of river bank heterogeneity and time of day on drift and stranding of juvenile European grayling (Thymallus thymallus L.) caused by hydropeaking. Sci. Total Environ. 575, 1515–1521. doi:10.1016/j.scitotenv.2016.10.029.

Bell E, Duffy WG, Roelofs TD (2001): Fidelity and survival of juvenile coho salmon in response to a flood. Trans Am Fish Soc 130(3):450–458.

Bevelhimer, M. S., McManamay, R. A., and O'Connor, B. (2015): Characterizing Sub-Daily Flow Regimes: Implications of Hydrologic Resolution on Ecohydrology Studies. River Res. Appl. 31, 867–879. doi:10.1002/rra.2781.

Bretschko, G., & Moog O., (1990): Downstream Effects of Intermittent Power Generation. Water Science and Technology 22: 127-135.

Bruder, A., Tonolla, D., Schweizer, S., Vollenweider, S., Langhans, S.D., & Wüest, A. (2016): A conceptual framework for hydropeaking mitigation. Science of The Total Environment, 568, 1204-1212. DOI: 10.1016/j.scitotenv.2016.05.032.

Burman, A. J., Hedger, R. D., Hellström, J. G. I., Andersson, A. G., and Sundt-Hansen, L. E. (2021): Modelling the downstream longitudinal effects of frequent hydropeaking on the spawning potential and stranding susceptibility of salmonids. Sci. Total Environ. 796, 148999. doi:10.1016/j.scitotenv.2021.148999.

Courret, D., Baran, P., and Larinier, M. (2021): An indicator to characterize hydrological alteration due to hydropeaking. J. Ecohydraulics 6, 139–156. doi:10.1080/24705357.2020.1871307.

Cushman, R. M., (1985): Review of ecological effects of rapidly varying flows downstream from hydroelectric facilities. North American Journal of Fisheries Management 5: 330-339.

European Commission, (2020): Guidance Document No. 37 Steps for defining and assessing ecological potential for improving comparability of Heavily Modified Water Bodies, CIRCABC.

European Commission, (2021): Sustainable Finance and EU Taxonomy: Regulation (EU) 2020/852.

Führer S, Hayes DS, Hasler T, Graf DRM, Fauchery E, Mameri D, Schmutz S and Auer S (2022): Stranding of larval nase (Chondrostoma nasus L.) depending on bank slope, down-ramping rate and daytime. Front. Environ. Sci. 10:966418. doi: 10.3389/fenvs.2022.966418

Gibbins, C., Vericat D., & Batalla R. J., (2007): When is stream invertebrate drift catastrophic? The role of hydraulics and sediment transport in initiating drift during flood events. Freshwater Biology 52: 2369-2384.

Greimel, F., Zeiringer, B., Höller, N., Grün, B., Godina, R., and Schmutz, S. (2016): A method to detect and characterize sub-daily flow fluctuations. Hydrol. Process. 30, 2063–2078. doi:10.1002/hyp.10773.

Greimel, F., Zeiringer, B., Hauer, C., Holzapfel, P., Fuhrmann, M., Haslauer, M., Führer, S., Höller, N., Grün, B., Habersack, H. & S. Schmutz (2017): Technischer Bericht B - Ökologische Bewertung schwalldämpfender Maßnahmen sowie weiterführende Analysen und Modelle. Ergänzung zu Endbericht: Suremma, Sustainable River Management - Energiewirtschaftliche und umweltrelevante Bewertung möglicher schwalldämpfender Maßnahmen. Forschungsbericht, Wien, Innsbruck, 69 Seiten.

Greimel, F., Schülting L., Graf W., Bondar-Kunze E., Auer S., Zeiringer B., & Hauer C., (2018): Hydropeaking Impacts and Mitigation, In Schmutz, S., & J. Sendzimir (eds), Riverine Ecosystem Management. Springer International Publishing, Cham: 91-110, http://link.springer.com/10.1007/978-3-319-73250-3_5.

Greimel, F., Zeiringer, B., Höller, N. & S. Schmutz (2021a): Technischer Bericht I – Modelle und Analyseschritte zur Erfassung von anthropogenen Einflüssen auf das Abflussregime und hydrologisches Monitoringkonzept. Ergänzung zu Endbericht: SuREmMa+ Entwicklung einer Methode zur ökologischen und energiewirtschaftlichen Bewertung von Maßnahmen zur Minderung von negativen schwall- und sunkbedingten ökologischen Auswirkungen, Forschungsbericht, Wien, 48 Seiten.

Greimel, F., Neubarth J., Fuhrmann M., Zoltan L., Zeiringer B., Schülting L., Führer S., Auer S., Leitner P., Dossi F., Holzapfel P., Pfleger M., Leobner I., Sumper R., Pazmandy J., Graf W., Hauer C. & Schmutz S., (2021b): SuREmMa+: Entwicklung einer Methode zur ökologischen und energiewirtschaftlichen Bewertung von Maßnahmen zur Minderung von negativen schwall- und sunkbedingten ökologischen Auswirkungen. Forschungsbericht, BMLRT, Wien, 158 Seiten.

Greimel F, Grün B, Hayes D, Höller N, Haider J, Zeiringer B, Holzapfel P, Hauer C, Schmutz S (2022a): "PeakTrace: Routing of Hydropeaking Waves Using Multiple Hydrographs – A Novel Approach." River Research and Applications. DOI: 10.1002/rra.3978.

Greimel, F. (2022b): Characterization of dub-daily flow fluctuations as a basis for sustainable hydropeaking management, Dissertation, University of Natural Resources and Life Sciences, Vienna.

Grün, B., Haider, J., & Greimel, F., (2021): HydroPeak - Detect and Characterize Sub-Daily Flow Fluctuations. Available at: https://cran.r-project.org/package=hydropeak.

Grün, B., Haider, J., & Greimel, F., (2022): HydroRoute - Trace Longitudinal Hydropeaking Waves. Available at: https://cran.r-project.org/package=hydroroute.

Hauer, C., Schober, B., and Habersack, H. (2013): Impact analysis of river morphology and roughness variability on hydropeaking based on numerical modelling. Hydrol. Process. 27, 2209–2224. doi:10.1002/hyp.9519.

Hauer, C., Holzapfel, P., Leitner, P., and Graf, W. (2017): Longitudinal assessment of hydropeaking impacts on various scales for an improved process understanding and the design of mitigation measures. Sci. Total Environ. 575, 1503–1514. doi:10.1016/j.scitotenv.2016.10.031.

Hauer, C., Unfer, G., Holzapfel, P., Haimann, M. and Habersack, H. (2014): Impact of channel bar form and grain size variability on estimated stranding risk of juvenile brown trout during hydropeaking, Earth Surface Processes and Landforms, 39, pages 1622– 1641, doi: 10.1002/esp.3552

Halleraker J. H., Bund W. v. d., Bussettini M., Gosling R., Döbbelt-Grüne S., Hensman J., Kling J., Koller-Kreimel V., Pollard P., Kampa E., & Döbbelt-Grüne S., (2016): Working Group ECOSTAT report on common understanding of using mitigation measures for reaching Good Ecological Potential for heavily modified water bodies - Part 1: Impacted by water storage. JRC Report EUR 28413.

Hayes, D.S., Auer S., Fauchery E. et al. (2022): The interactive effect of river bank morphology and daytime on downstream displacement and stranding of cyprinid larvae in hydropeaking conditions, Ecohydrology & Hydrobiology, https://doi.org/10.1016/j.ecohyd.2022.12.001

Hayes, D. S., Lautsch, E., Unfer, G., Greimel, F., Zeiringer, B., Höller, N., et al. (2021): Response of European grayling, Thymallus thymallus, to multiple stressors in hydropeaking rivers. J. Environ. Manage. 292, 112737. doi:10.1016/j.jenvman.2021.112737.

Hayes, D. S., Moreira, M., Boavida, I., Haslauer, M., Unfer, G., Zeiringer, B., et al. (2019): Life stage-specific hydropeaking flow rules. Sustainability 11 (6), 1547. doi:10.3390/su11061547

Higgins PS, Bradford MJ (1996): Evaluation of a large-scale fish salvage to reduce the impacts of controlled flow reduction in a regulated river. N Am J Fish Manag 16:666–673.

Hunter MA (1992): Hydropower flow fluctuations and salmonids: a review of the biological effects, mechanical causes, and options for mitigation. Washington Department of Fisheries Technical Report 119, Olympia.

Juárez, A., Adeva-Bustos, A., Alfredsen, K., and Dønnum, B.O. (2019): Performance of a twodimensional hydraulic model for the evaluation of stranding areas and characterization of rapid fluctuations in hydropeaking rivers. Water (Switzerland), 11 (2), art. no. 201. doi:10.3390/w11020201.

Kastenhofer, O., (2018): Stranden von Makrozoobenthos infolge von Schwall und Sunk. Bachelorarbeit, ZHAW, Zürich.

Kjaerstad, G., Arnekleiv J. V., Speed J. D. M., & Herland A. K., (2018): Effects of hydropeaking on benthic invertebrate community composition in two central Norwegian rivers. River Research and Applications 34: 218-231.

Li, T., and Pasternack, G. B. (2021): Revealing the diversity of hydropeaking flow regimes. J. Hydrol. 598, 126392. doi:10.1016/J.JHYDROL.2021.126392.

Mader, H., T. Steidl, & R. Wimmer (1996): Abflussregime Österreichischer Fliessgewässer – Beitrag zu einer bundesweiten Fließgewässertypologie. Umweltbundesamt, Wien.

Moreira M., Hayes D. S., Boavida I., Schletterer M., Schmutz S., & Pinheiro A., (2019): Ecologically-based criteria for hydropeaking mitigation: a review. Sci. Total Environ. 657, 1508–1522. doi:10.1016/j.scitotenv.2018.12.107.

Moreira, M., Schletterer, M., Quaresma, A., Boavida, I., and Pinheiro, A. (2020): New insights into hydropeaking mitigation assessment from a diversion hydropower plant: The GKI project (Tyrol, Austria). Ecol. Eng. 158, 106035. doi:10.1016/j.ecoleng.2020.106035.

Parasiewicz P, Schmutz S, Moog O. (1998): The effect of managed hydropower peaking on the physical habitat, benthos and fish fauna in the River Bregenzerach in Austria. Fish Manag Ecol 5:403–417.

Perry S. A., & Perry W. B., (1986): Effects of experimental flow regulation on invertebrate drift and stranding in the Flathead and Kootenai Rivers, Montana, USA. Hydrobiologia 134: 171-182.

Person E, Bieri M, Peter A, Schleiss AJ. (2013): Mitigation measures for fish habitat improvement in Alpine rivers affected by hydropower operations. Ecohydrology.

Rauch, P. (2022): Fish Community Characterization in the Mura-Drava-Danube Region; Deliverable report for EU-Interreg DTP project "lifelineMDD"

Saltveit, S. J., Halleraker, J. H., Arnekleiv, J. V., and Harby, A. (2001): Field experiments on stranding in juvenile atlantic salmon (Salmo salar) and brown trout (Salmo trutta) during rapid flow decreases caused by hydropeaking. Regul. Rivers Res. Manag. 17, 609–622. doi:10.1002/rrr.652.

Sauterleute, J. F., and Charmasson, J. (2014): A computational tool for the characterisation of rapid fluctuations in flow and stage in rivers caused by hydropeaking. Environ. Model. Softw. 55, 266–278. doi:10.1016/j.envsoft.2014.02.004.

Schmutz S., Fohler N., Friedrich T., Fuhrmann M., Graf W., Greimel F., Höller N., Jungwirth M., Leitner P., Moog O., Melcher A., Müllner K., Ochsenhofer G., Salcher G., Steidl C., Unfer G., Zeiringer B. (2013): Schwallproblematik an Österreichs Fließgewässern – Ökologische Folgen und Sanierungsmöglichkeiten, Wien.

Schmutz, S., Bakken, T. H., Friedrich, T., Greimel, F., Harby, A., Jungwirth, M., et al. (2015): Response of Fish Communities to Hydrological and Morphological Alterations in Hydropeaking Rivers of Austria. River Res. Appl. 31, 919–930. doi:10.1002/rra.2795.

Schwarz, U. (2022): River Training Structures and Historical Mapping within the Mura-Drava-Danube TBR. Deliverable report for EU-Interreg DTP project "lifelineMDD", pp. 79, Vienna.

Shirvell CS (1994): Effects of changes in streamflow on the microhabitat use and movements of sympatric juvenile coho salmon (Oncorhynchus kisutch) and Chinook salmon (O. tshawytscha) in a natural stream. Can J Fish Aquat Sci 51:1644–1652.

Smokorowski, K. E., (2021): The ups and downs of hydropeaking: a Canadian perspective on the need for, and ecological costs of, peaking hydropower production. Hydrobiol. 2021. doi:10.1007/S10750-020-04480-Y.

Timusk, E. R., Smokorowski K. E., & Jones N. E., (2016): An experimental test of sub-hourly changes in macroinvertebrate drift density associated with hydropeaking in a regulated river. Journal of Freshwater Ecology 31: 555-570.

Young PS, Cech JJ, Thompson LC. (2011): Hydropower-related pulsed-flow impacts on stream fishes: a brief review, conceptual model, knowledge gaps, and research needs. Rev Fish Biol Fish.

Zeiringer, B., Fohler, N., Auer, S., Greimel, F., Schmutz, S., (2014): Experiments on drifting and stranding of juvenile grayling during fluctuating flow in nature-like channels with different morphological structures. In: 10th International Symposium on Ecohydraulics (Trondheim), p. 4.

V. Annex

A. Intensity of flow fluctuations – data basis 60 minutes

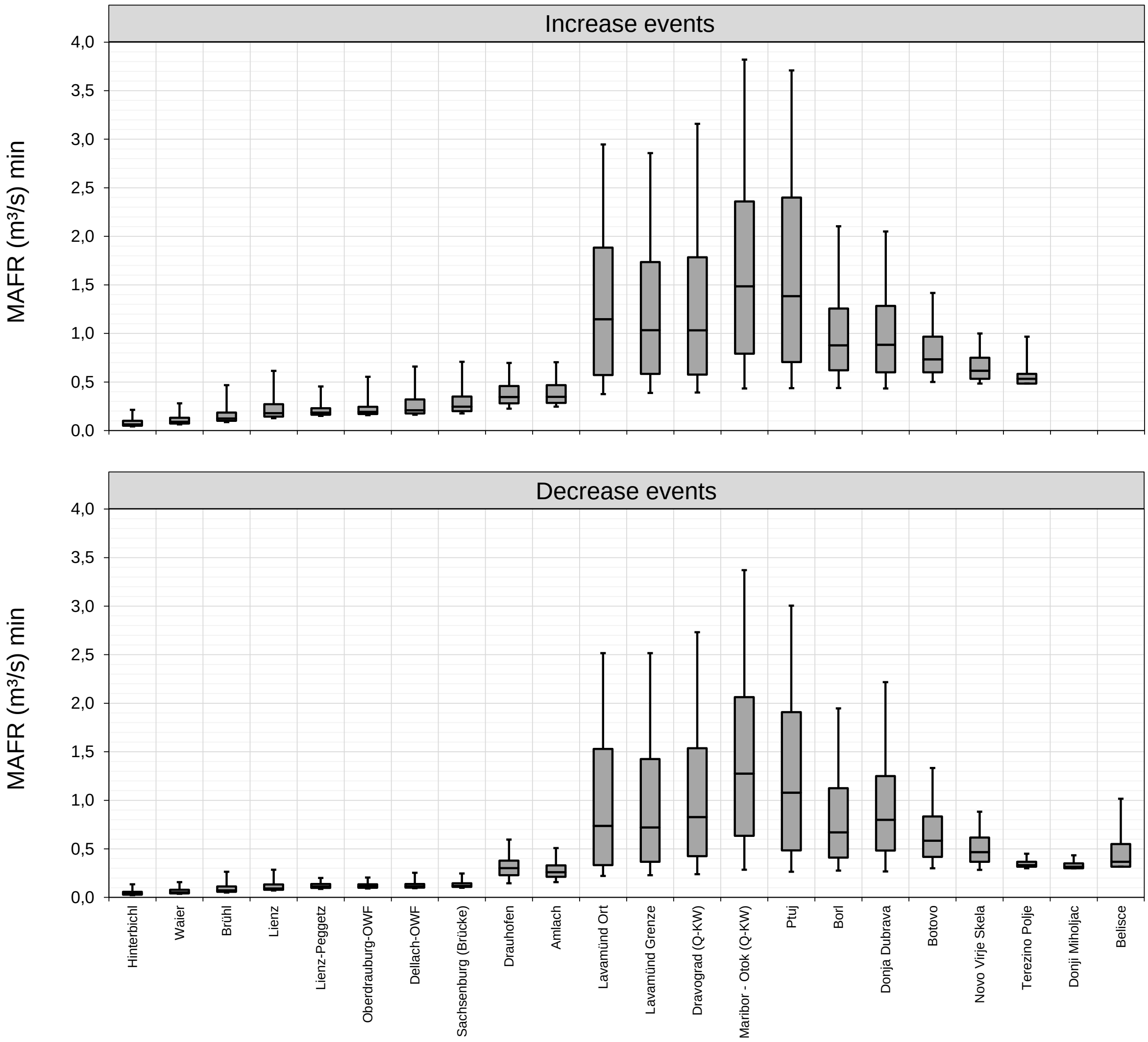


Figure 26: Maximum flow rate (MAFR) of sub-daily flow fluctuations with a maximum flow rate >GW10 (Data basis: 60 minutes resolution, whiskers correspond to 5% and 95% percentile)

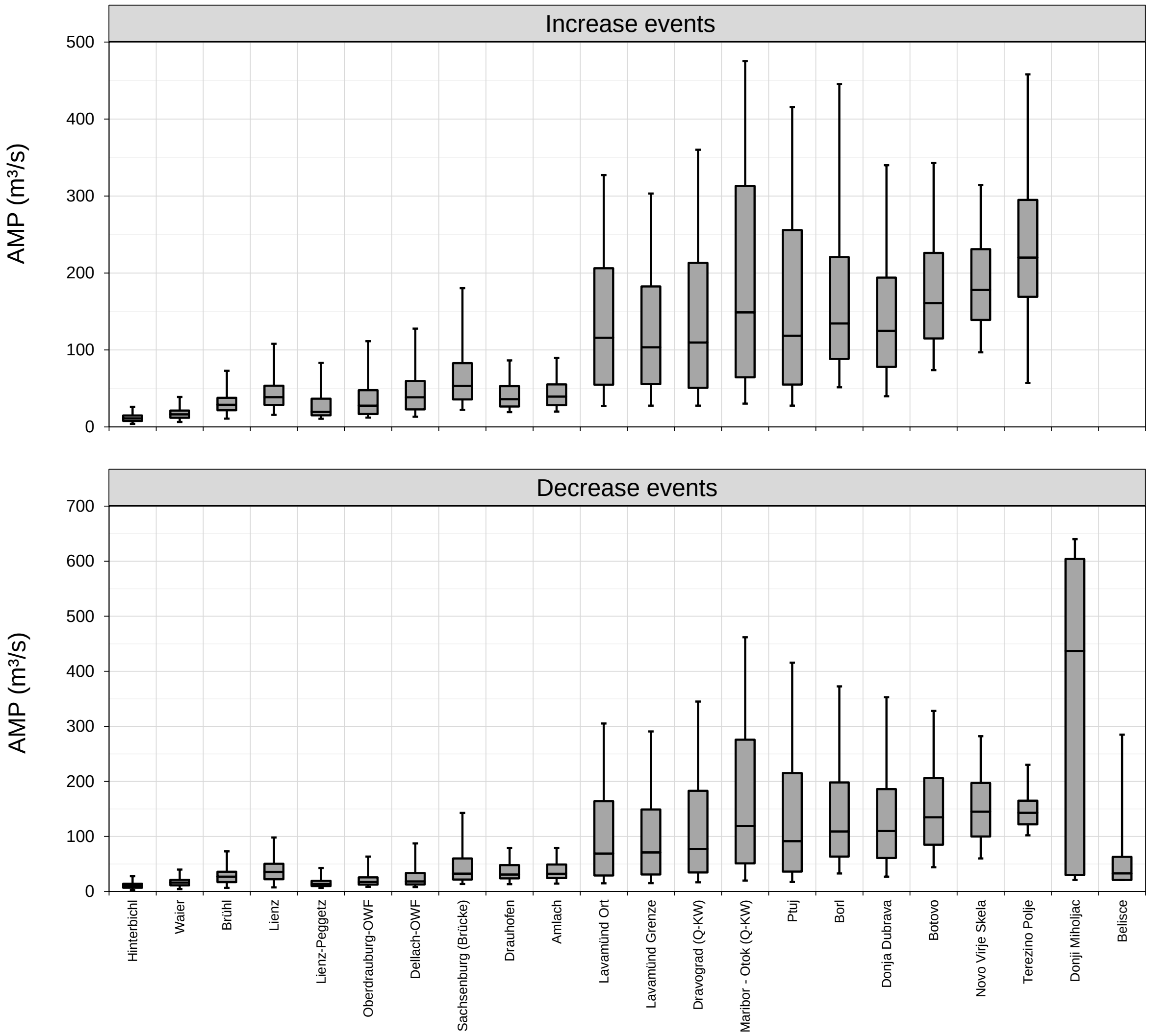


Figure 27: Amplitude (AMP) of sub-daily flow fluctuations with a maximum flow rate >GW10 (Data basis: 60 minutes resolution, whiskers correspond to 5% and 95% percentile)

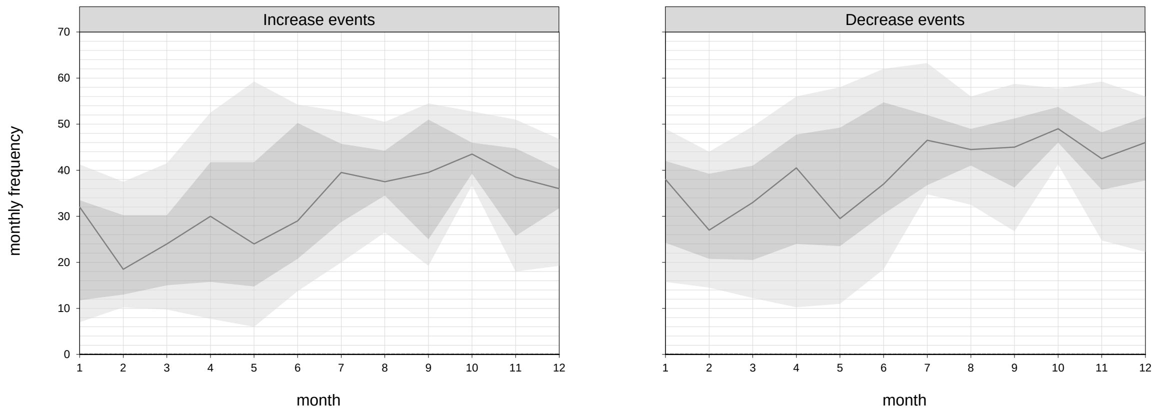


Figure 28: Donja Dubrava – monthly frequency of increase (left) and decrease (right) events with a maximum flow rate >GW10 (Data basis: 60 minutes resolution, grey line – median, interpercentile range: light grey – 5 to 95% percentile, dark grey – 25 to 75% percentile)

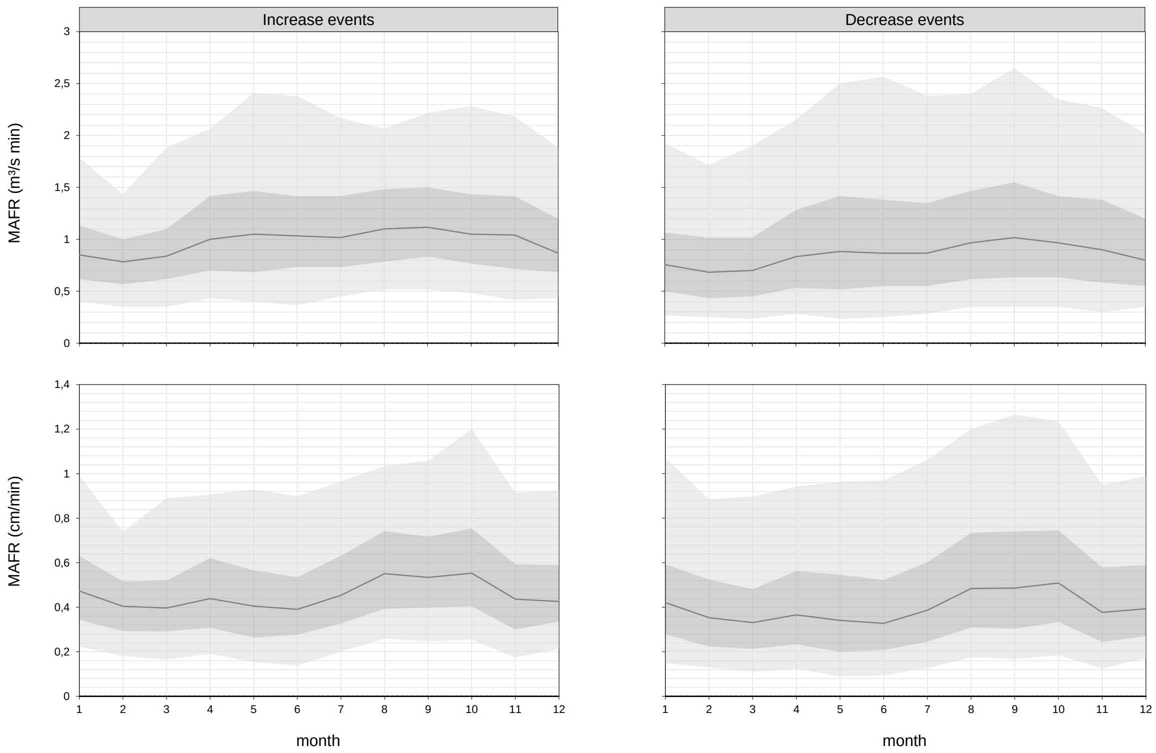


Figure 29: Donja Dubrava – maximum flow rates of increase (left) and decrease (right) events with a maximum flow rate >GW10 related to flow (top) and stage (bottom) (Data basis: 60 minutes resolution, grey line – median, interpercentile range: light grey – 5 to 95% percentile, dark grey – 25 to 75% percentile)

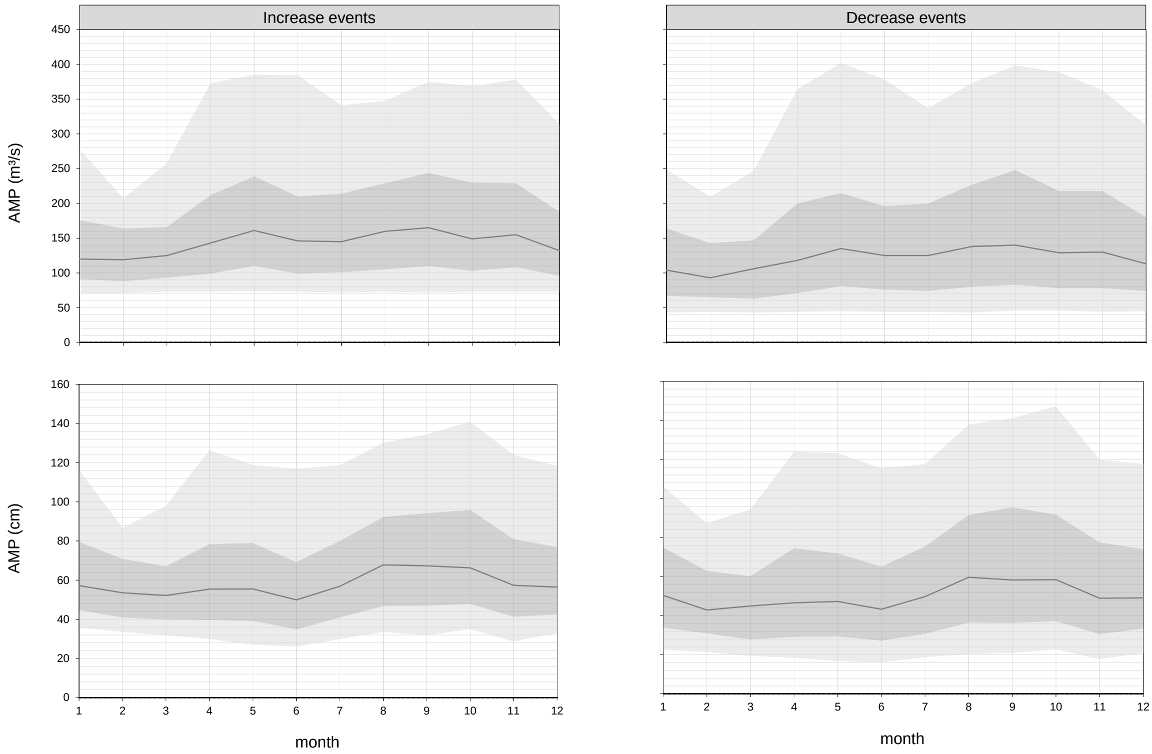


Figure 30: Donja Dubrava – amplitudes of increase (left) and decrease (right) events with a maximum flow rate >GW10 related to flow (top) and stage (bottom) (Data basis: 60 minutes resolution, grey line – median, interpercentile range: light grey – 5 to 95% percentile, dark grey – 25 to 75% percentile)

B. Frequency and Intensity of flow fluctuations – data basis 15 minutes

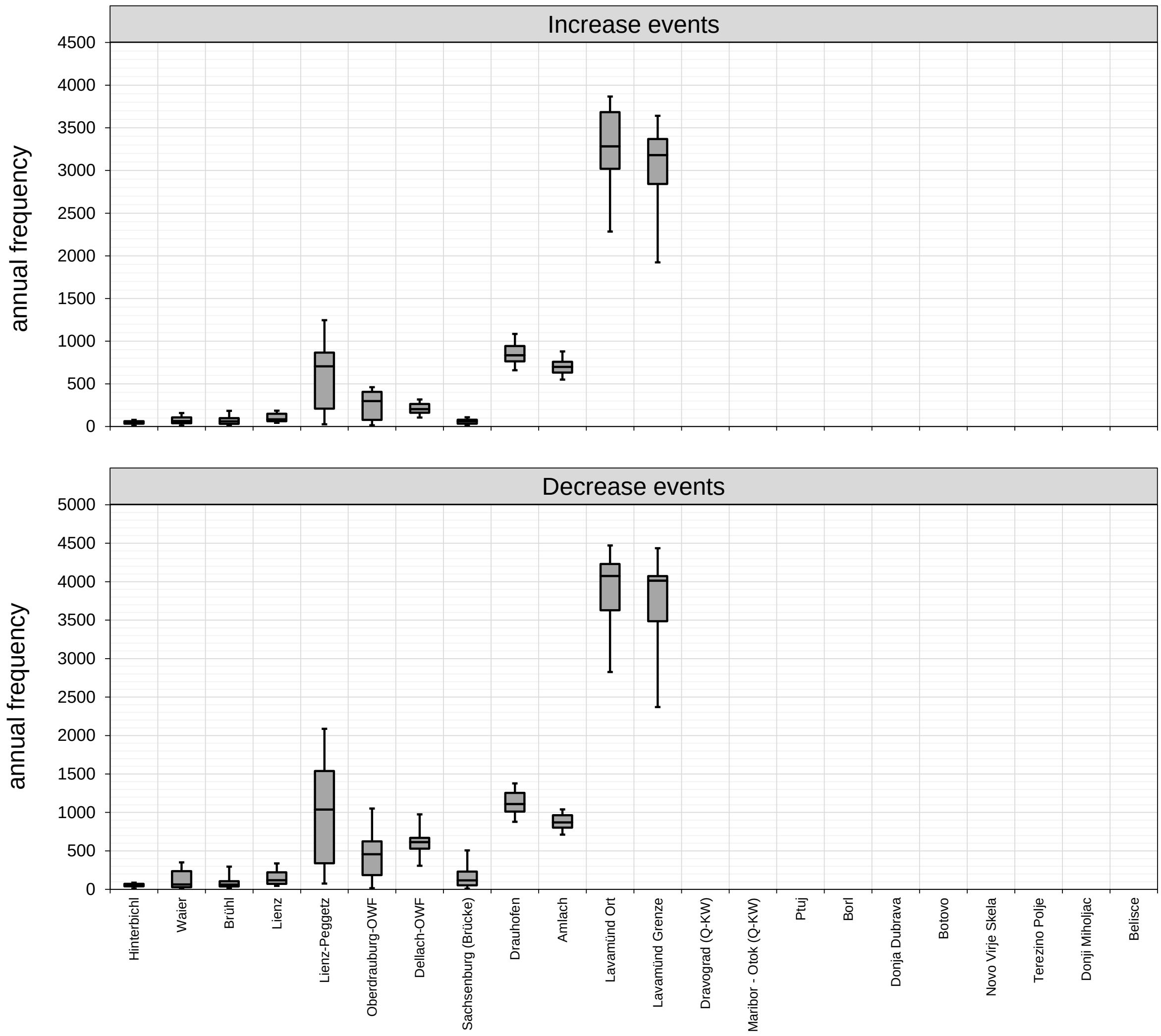


Figure 31: Annual frequency of sub-daily flow fluctuations with a maximum flow rate >GW10 (Data basis: 15 minutes resolution, whiskers correspond to annual 5% and 95% percentile)

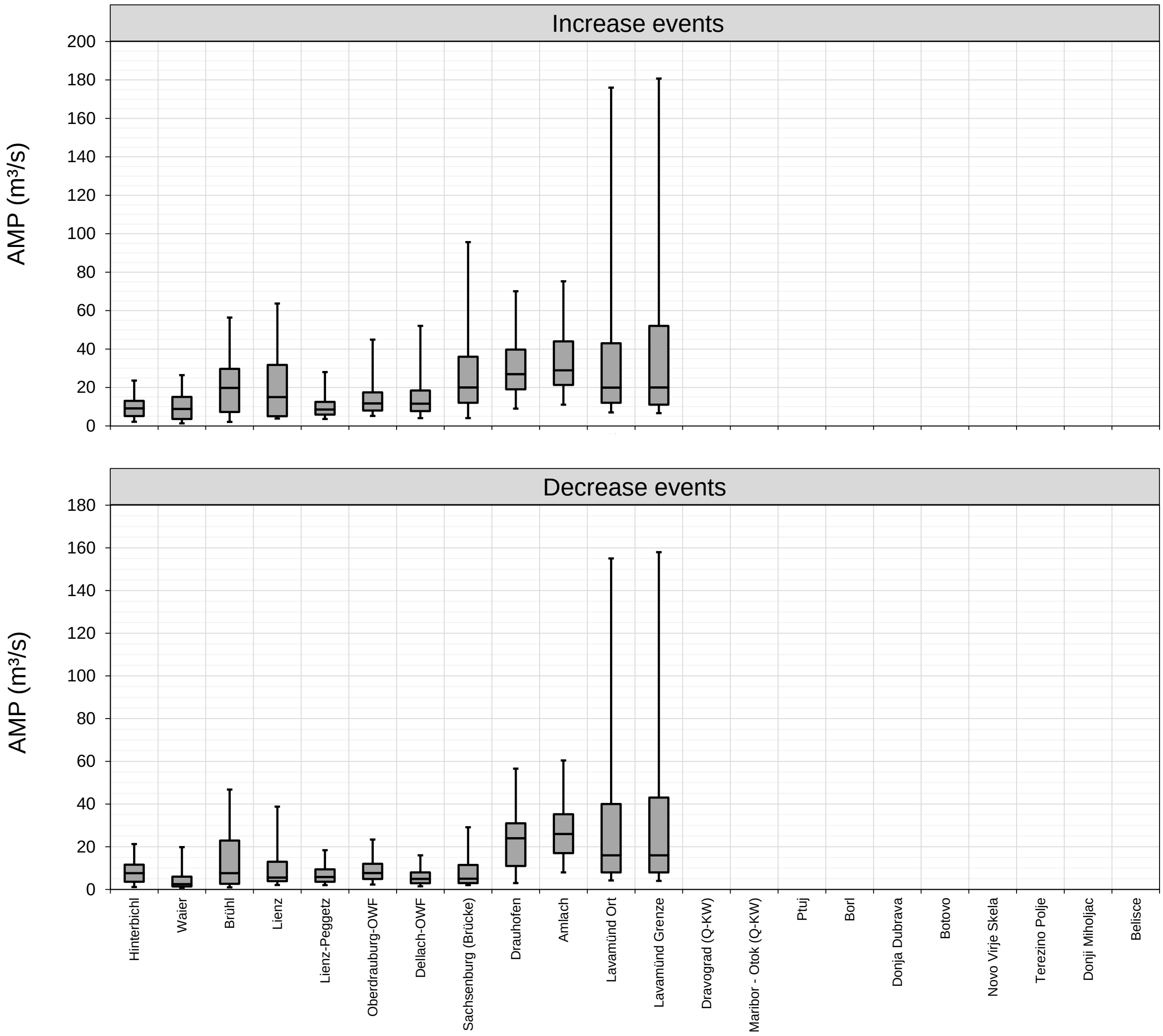


Figure 32: Amplitude (AMP) of sub-daily flow fluctuations with a maximum flow rate >GW10 (Data basis: 15 minutes resolution, whiskers correspond to 5% and 95% percentile)

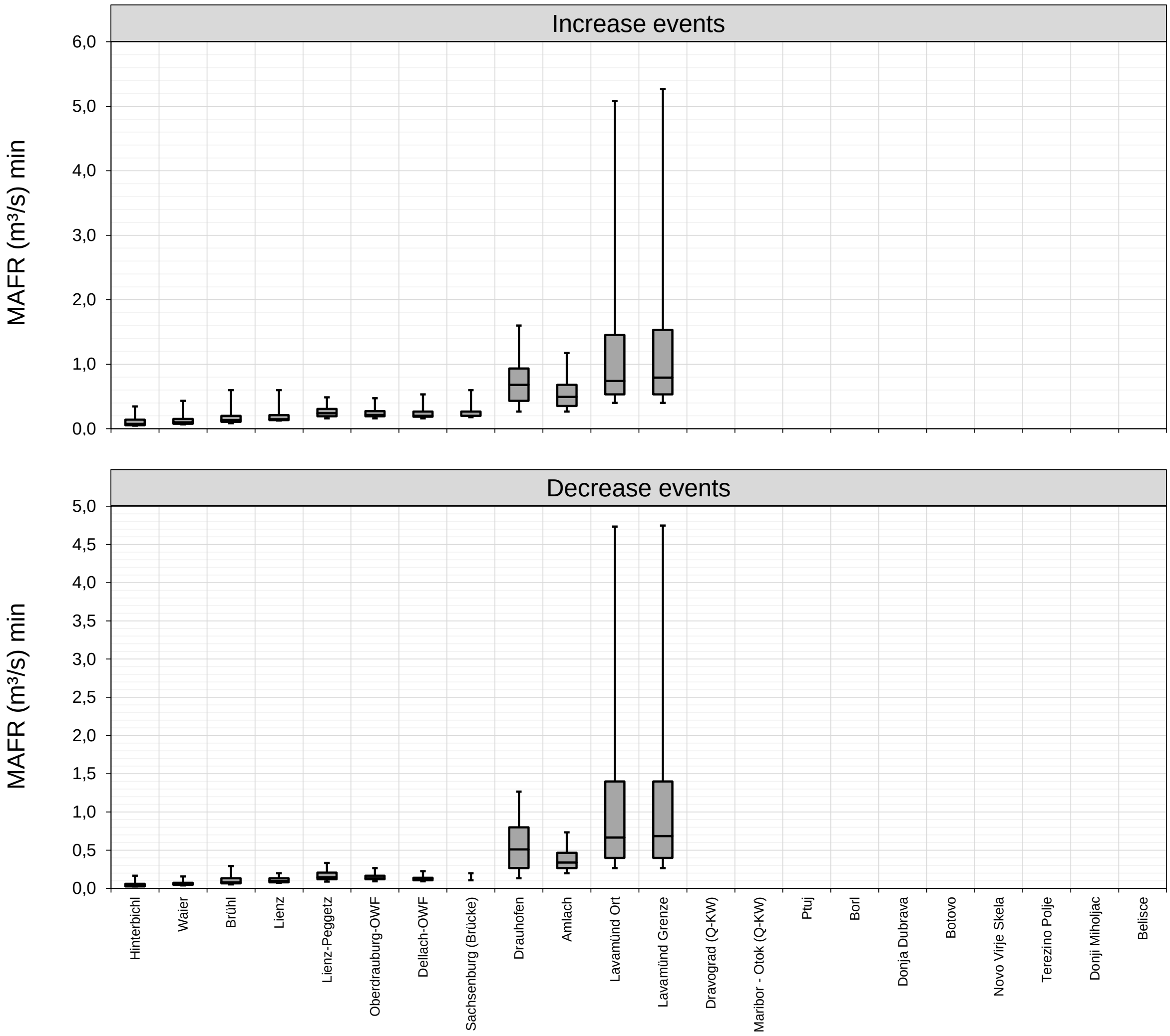


Figure 33: Maximum flow rate (MAFR) of sub-daily flow fluctuations with a maximum flow rate >GW10 (Data basis: 15 minutes resolution, whiskers correspond to 5% and 95% percentile)

C. Exemplary time series – 2019

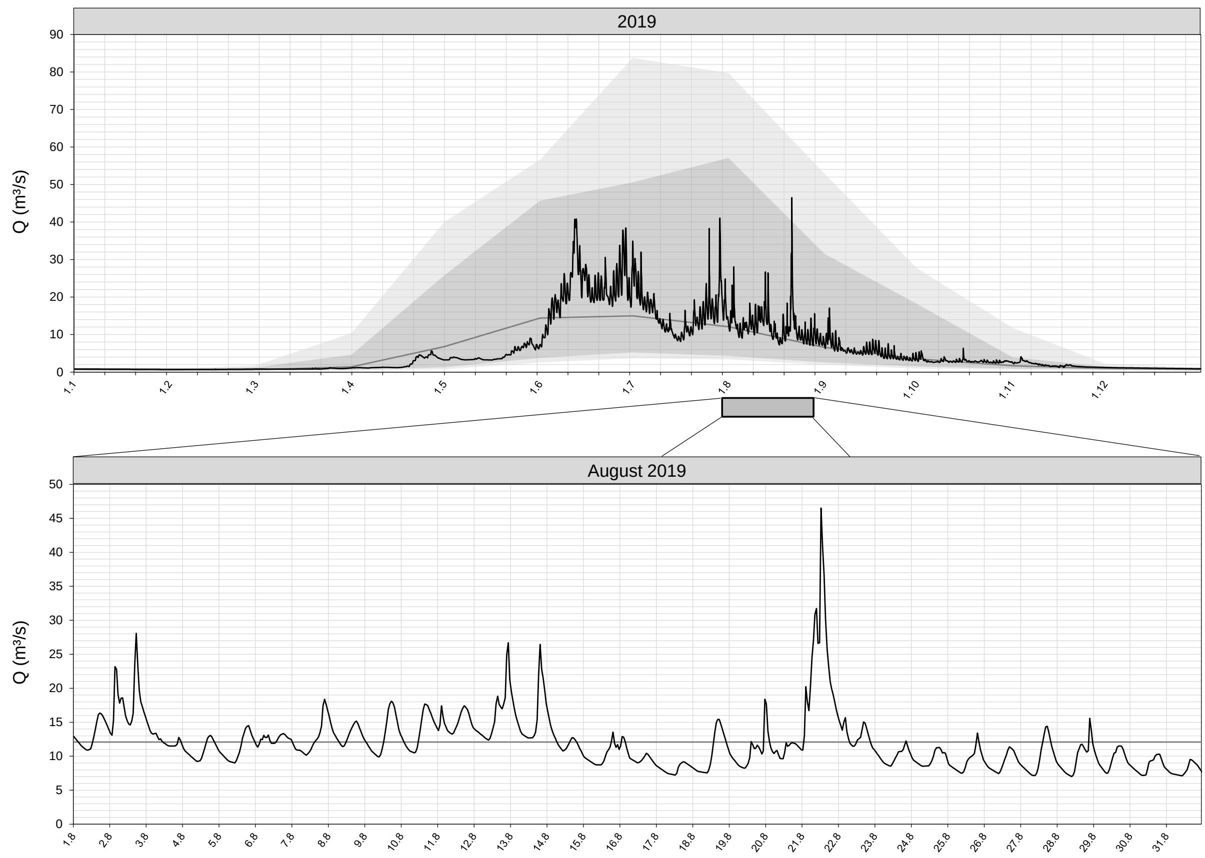


Figure 34: Isel – 212043, Hinterbichl (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

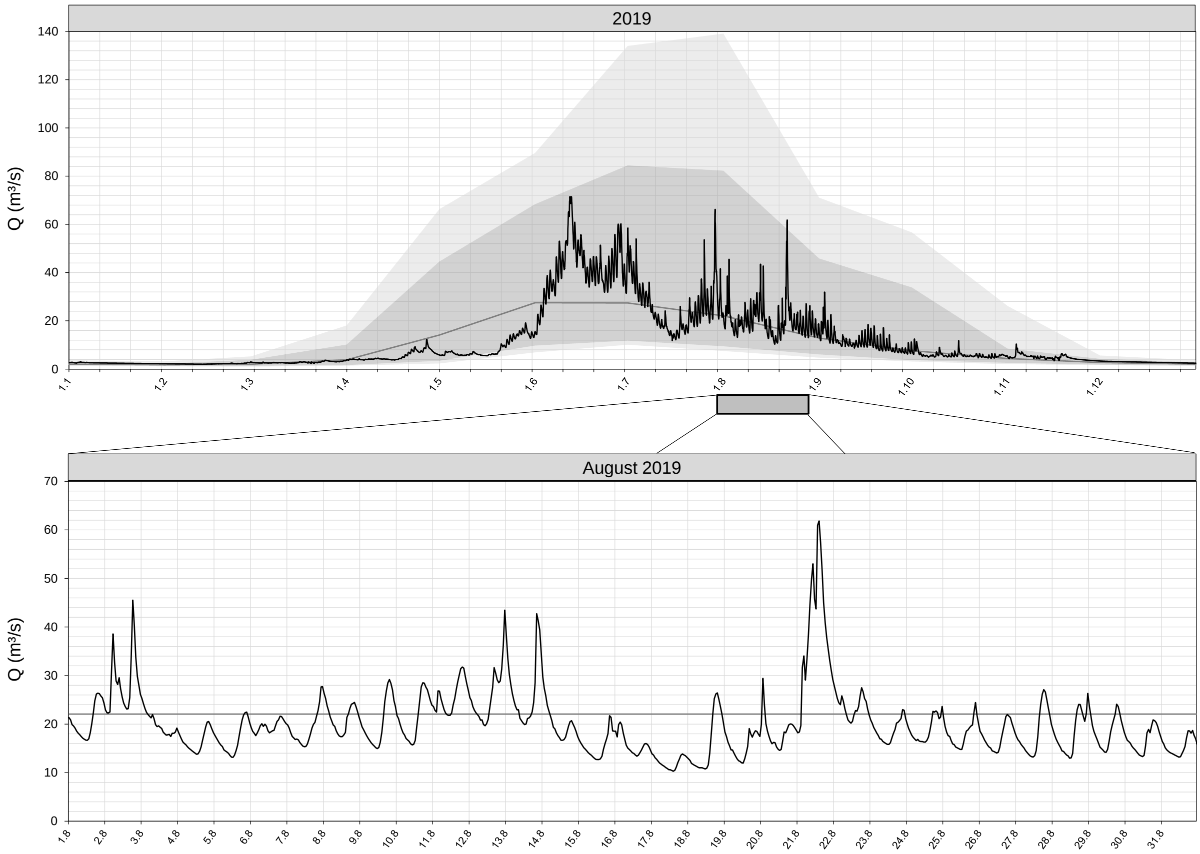


Figure 35: Isel – 212183, Waier (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

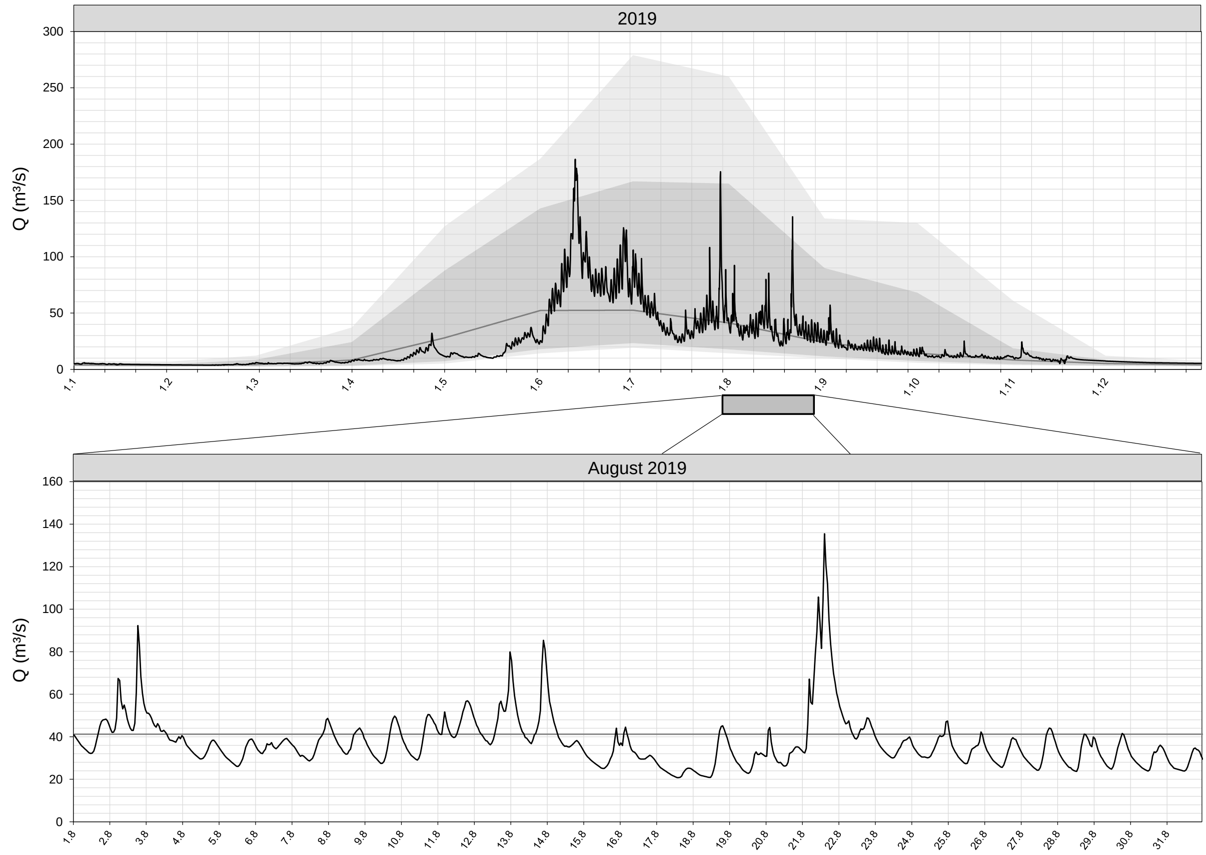


Figure 36: Isel – 212092, Brühl (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

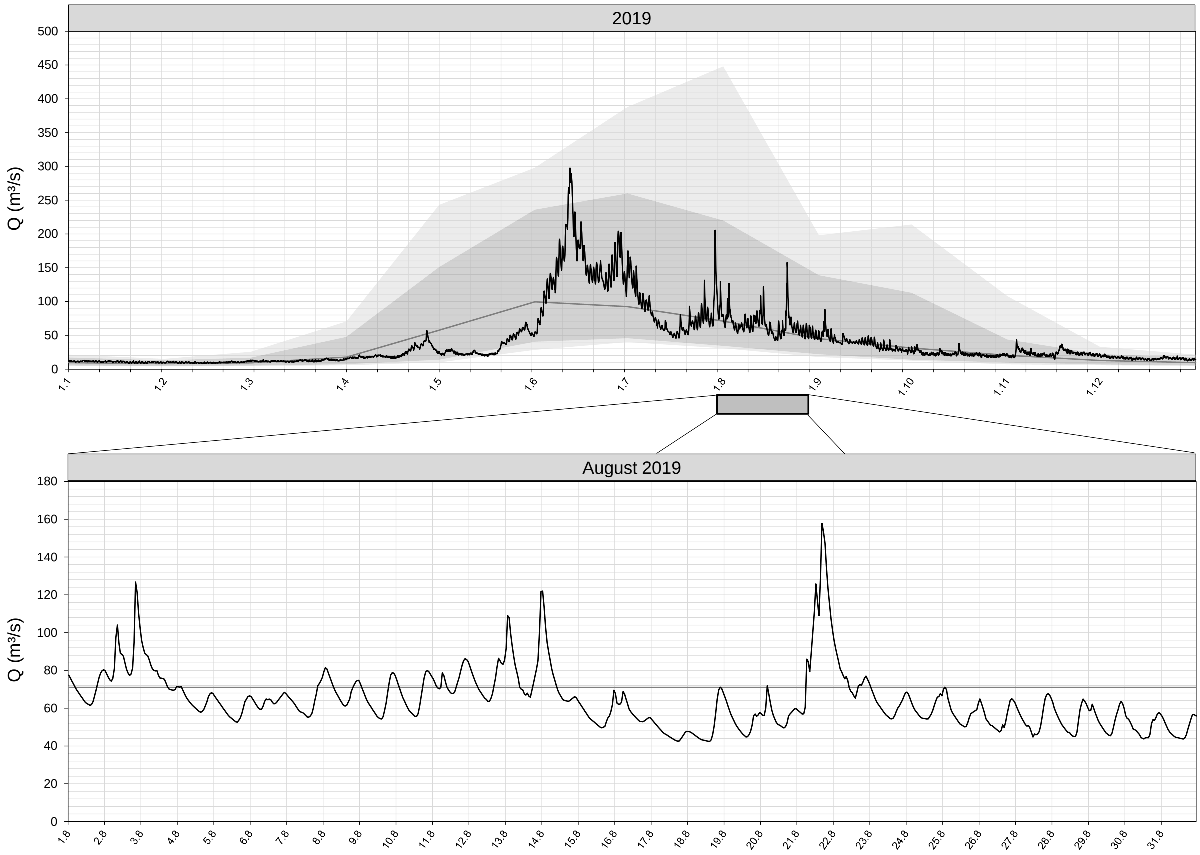


Figure 37: Isel – 212167, Lienz (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

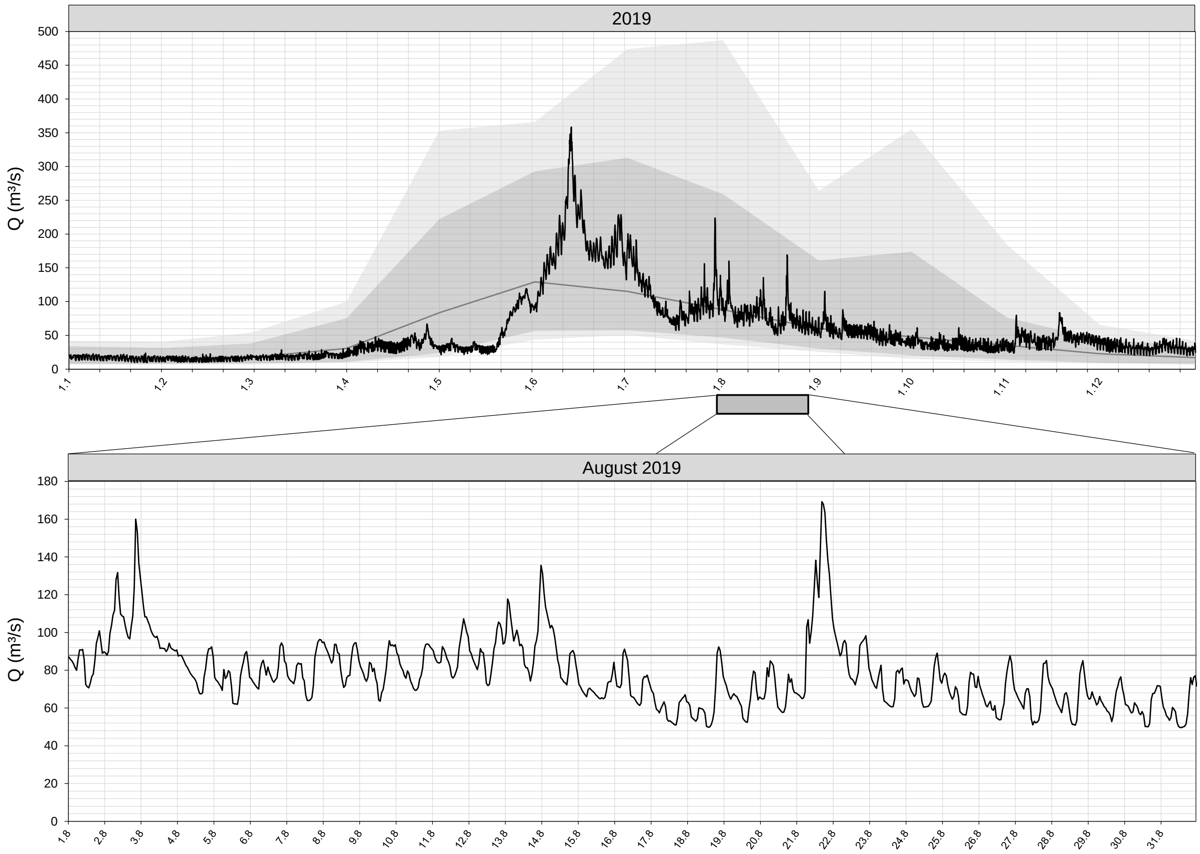


Figure 38: Drava – 212316, Lienz (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

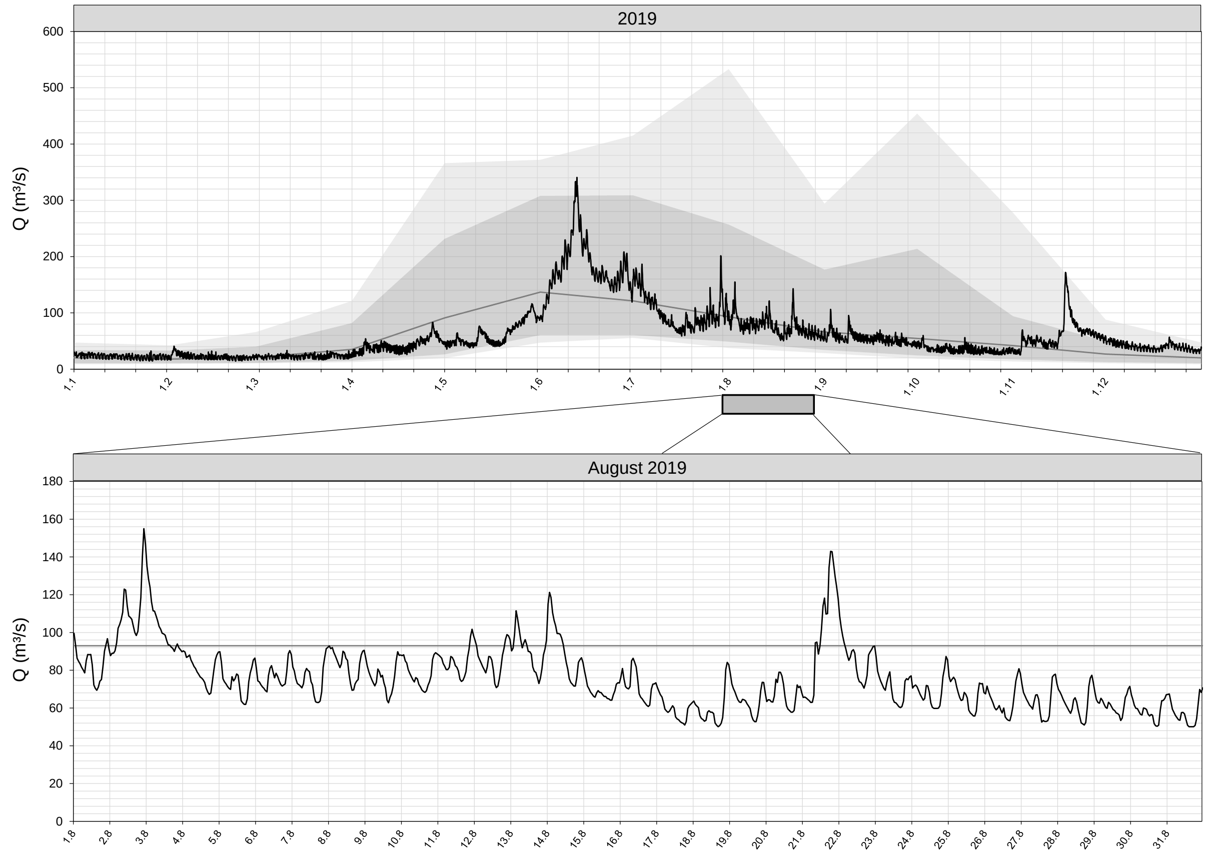


Figure 39: Drava – 212324, Oberdrauburg (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

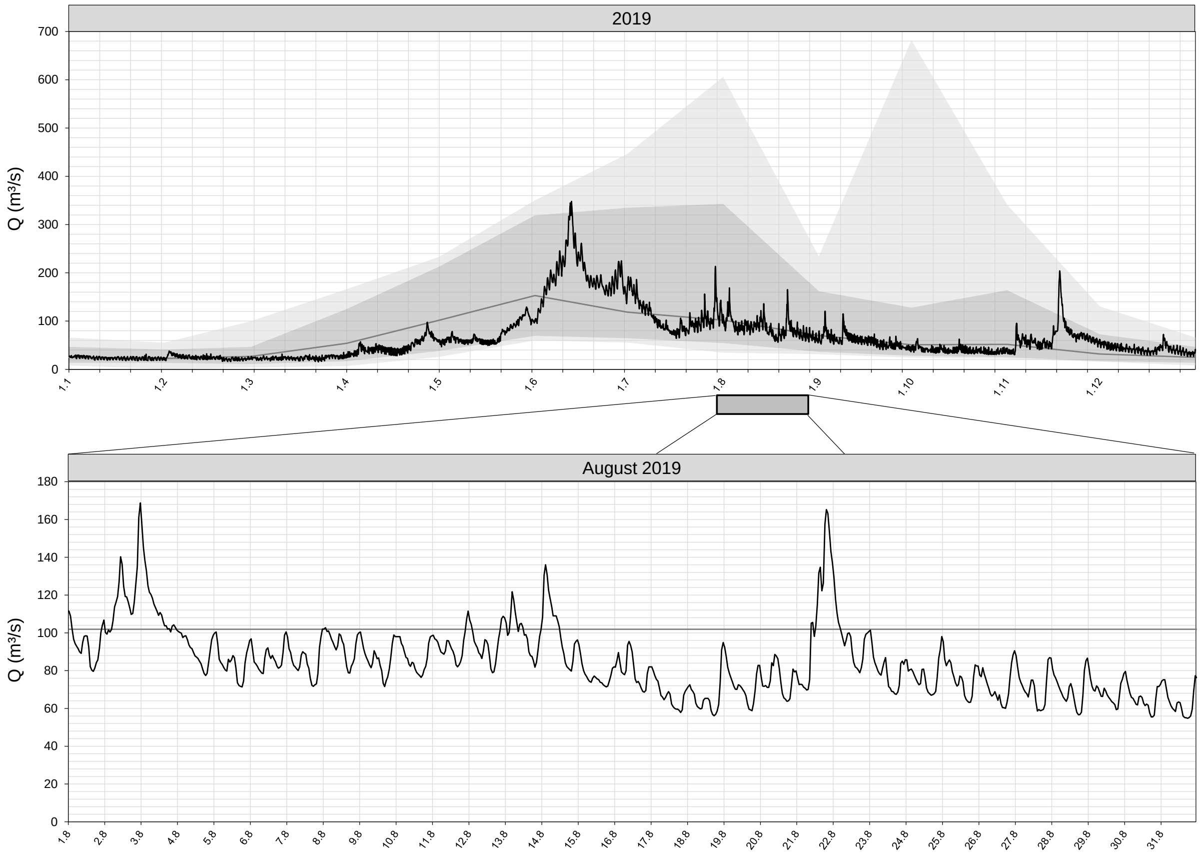


Figure 40: Drava – 213660, Dellach (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

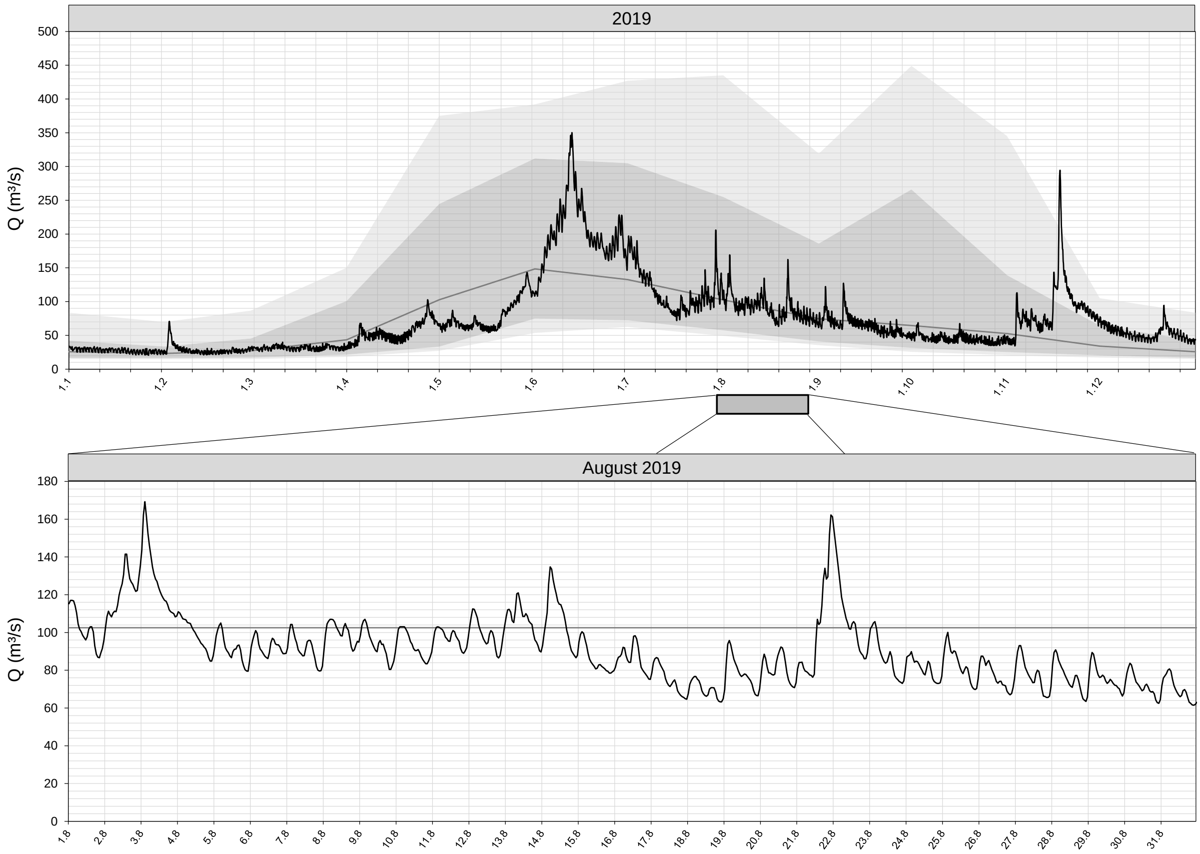


Figure 41: Drava – 212357, Sachsenburg (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

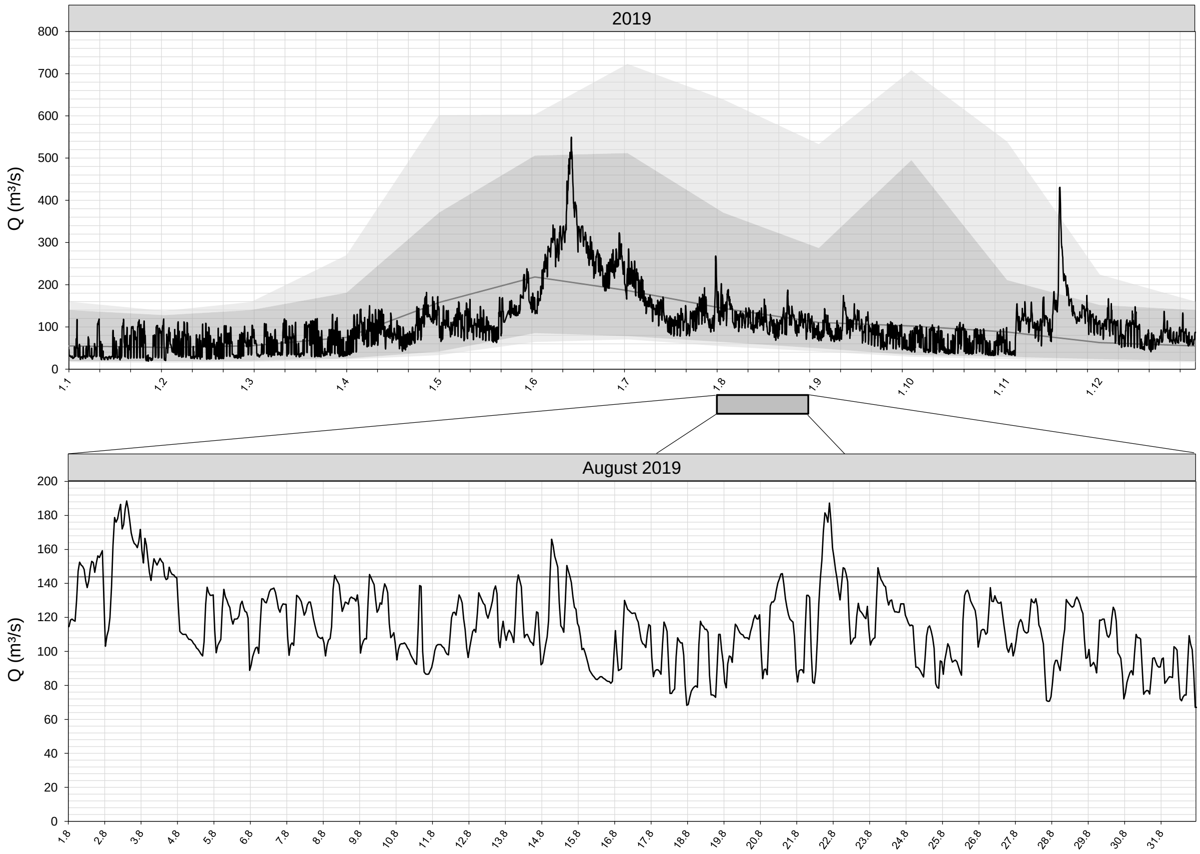


Figure 42: Drava – 213199, Drauhofen (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

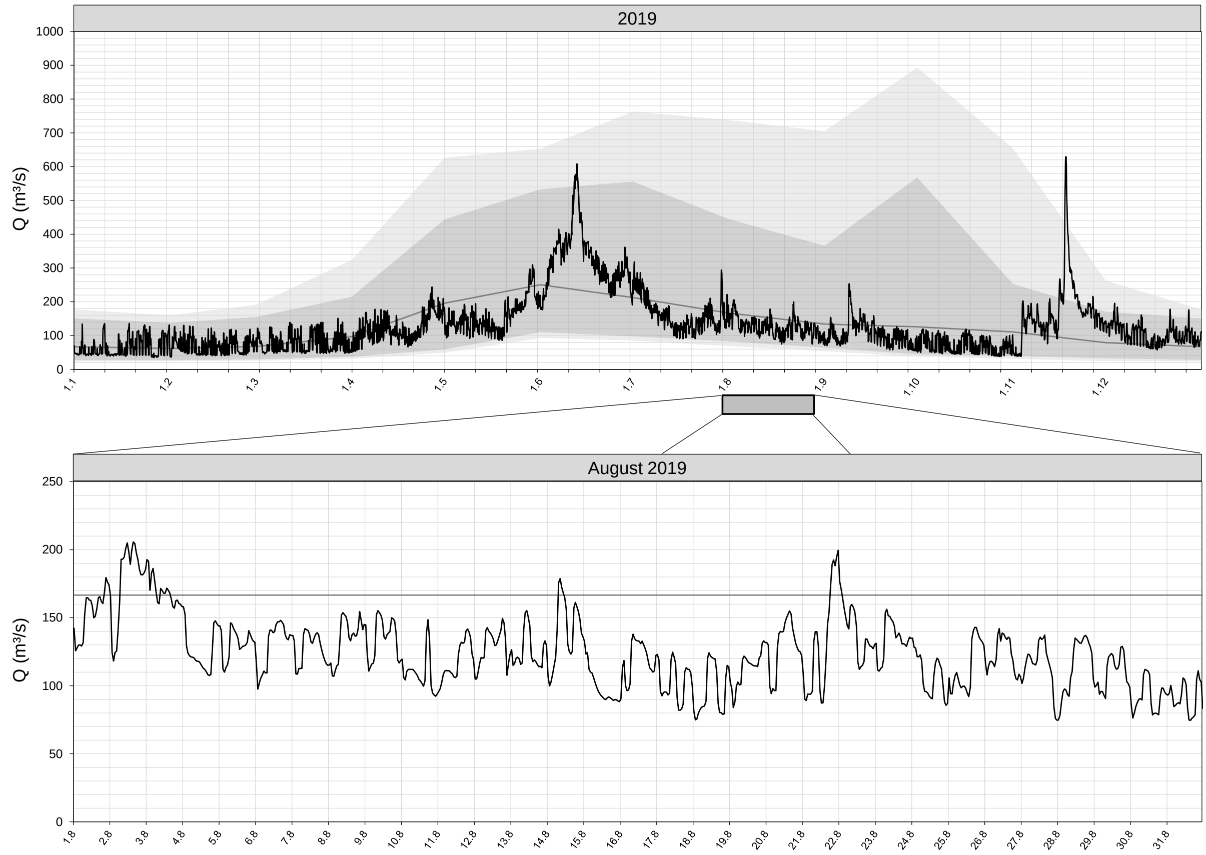


Figure 43: Drava – 213215, Amlach (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

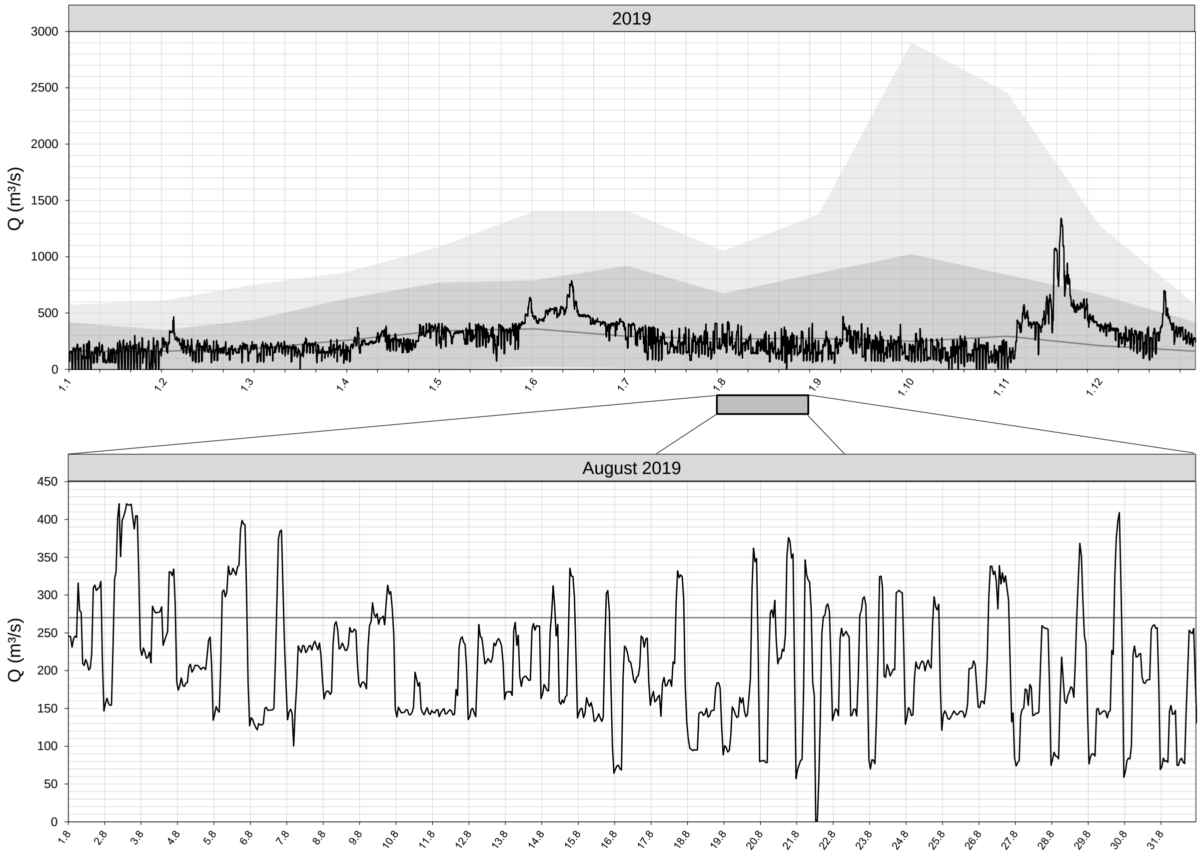


Figure 44: Drava – 213173, Lavamünd Ort (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

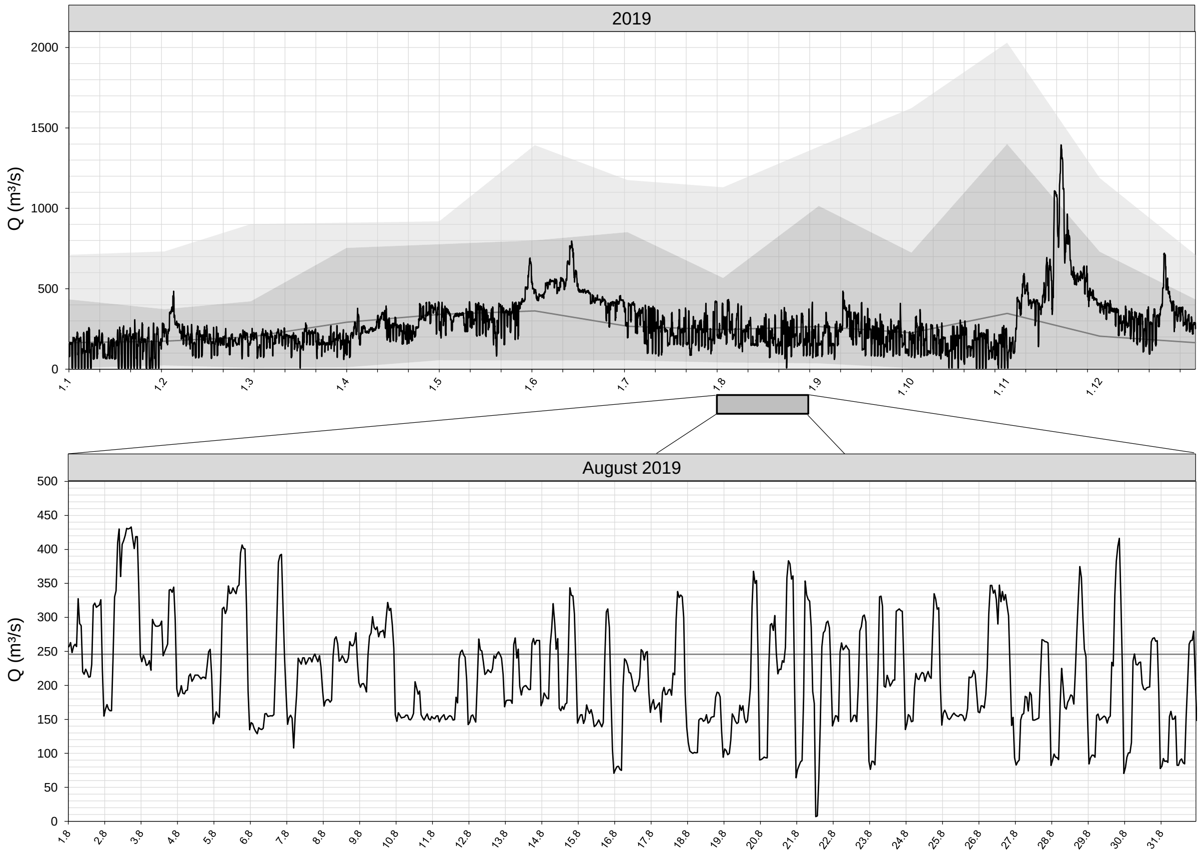


Figure 45: Drava – 213595, Lavamünd Grenze (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

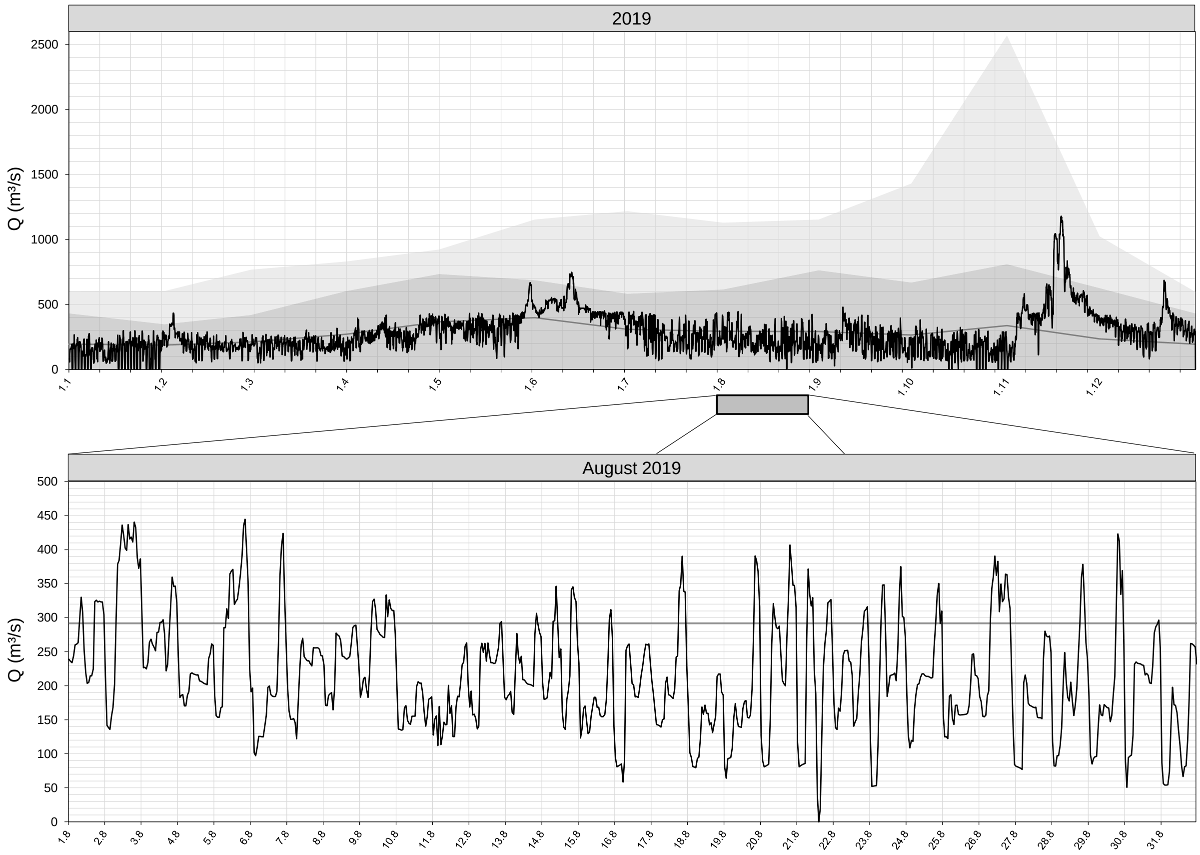


Figure 46: Drava – 600420, Dravograd (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

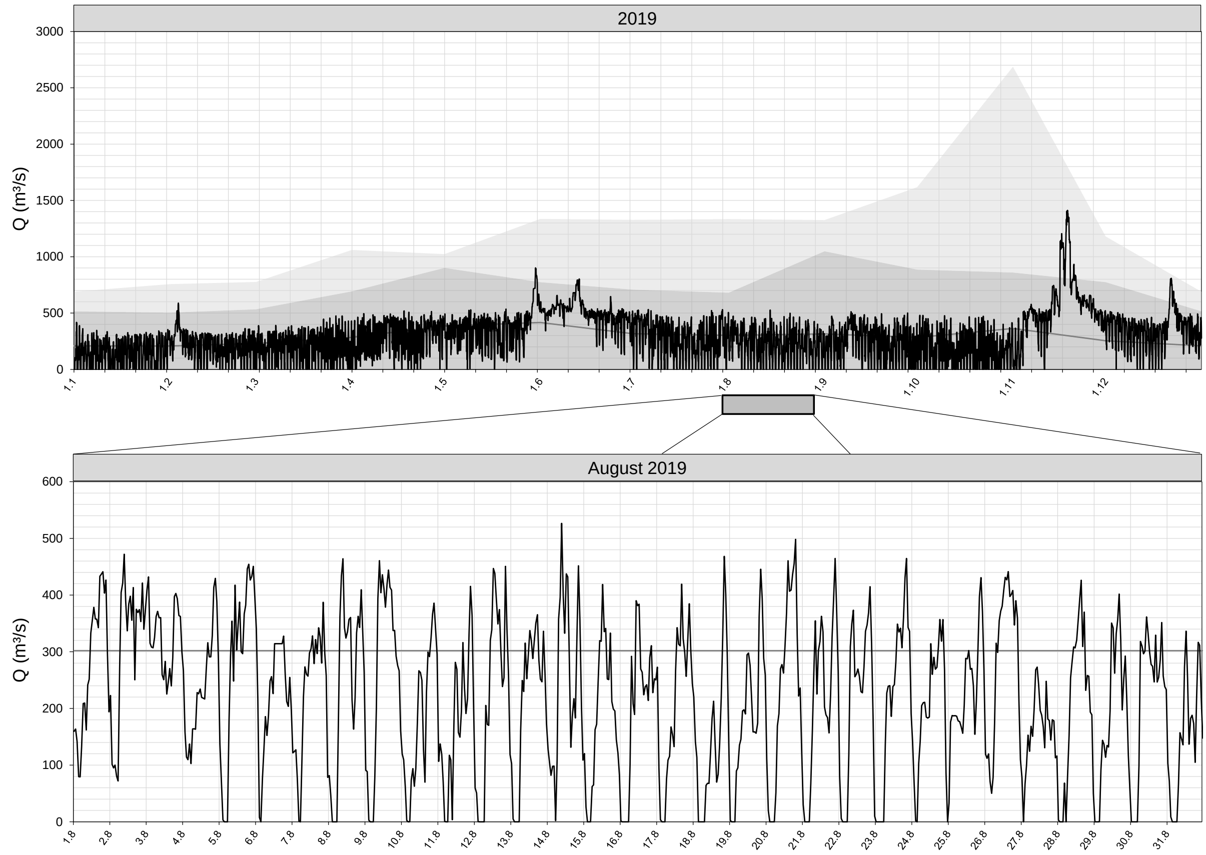


Figure 47: Drava – 600421, Maribor (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

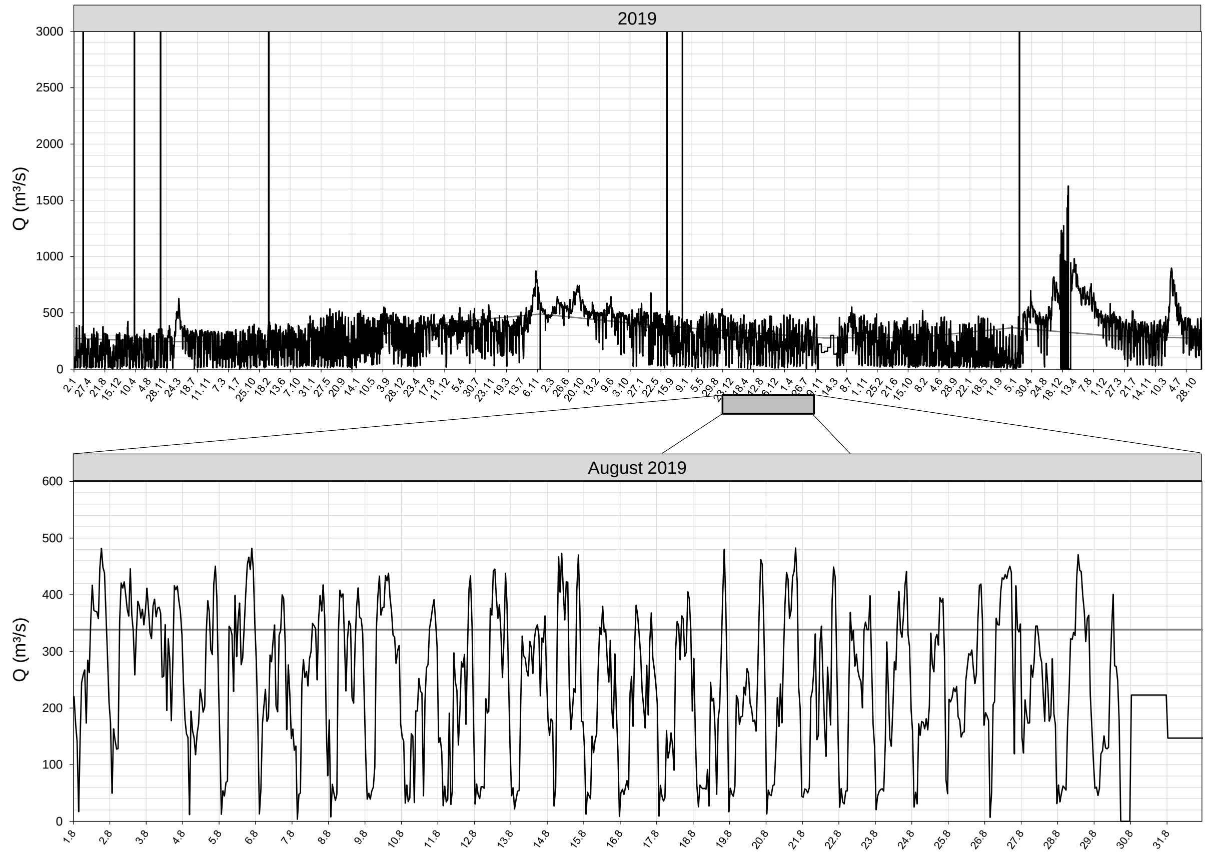


Figure 48: Drava – 600422, Ptui (black line – flow, grey line – monthly mean flow (data partly implausible))

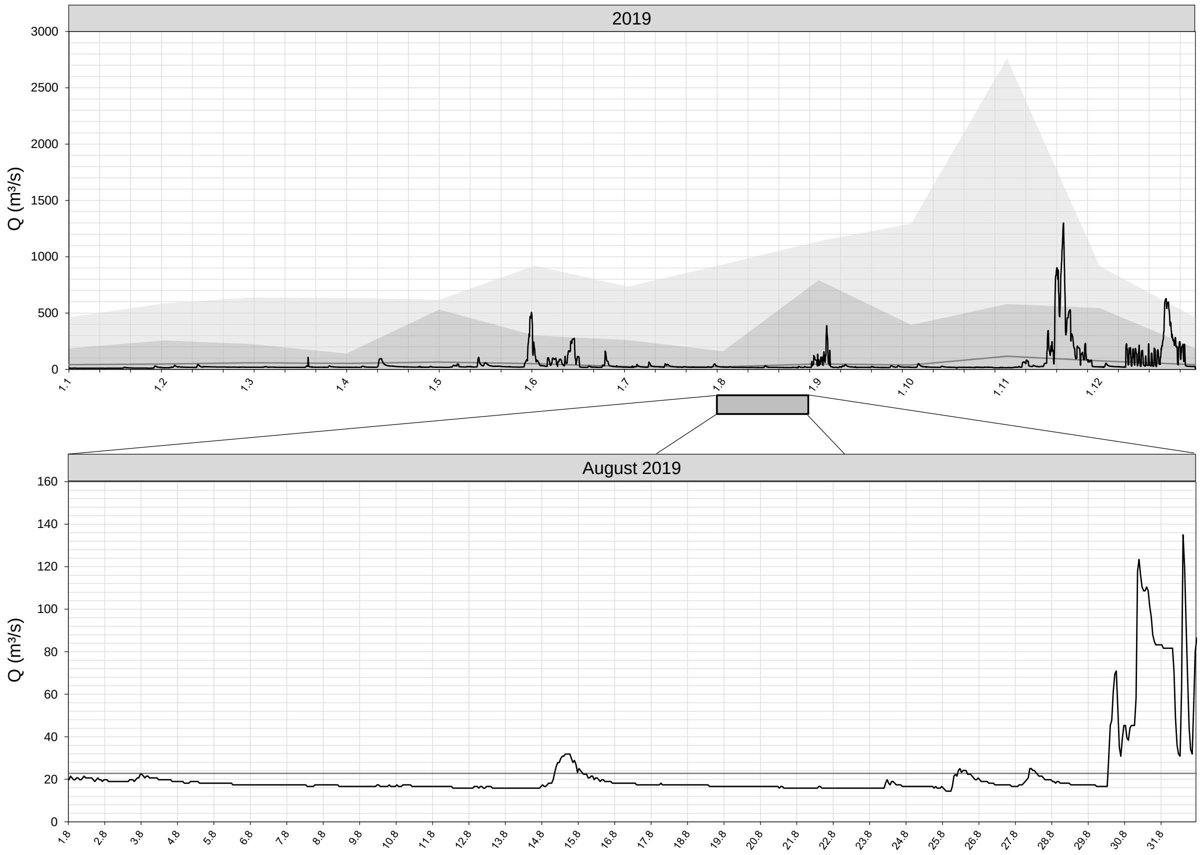


Figure 49: Drava – 600423, Borl (residual flow) (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

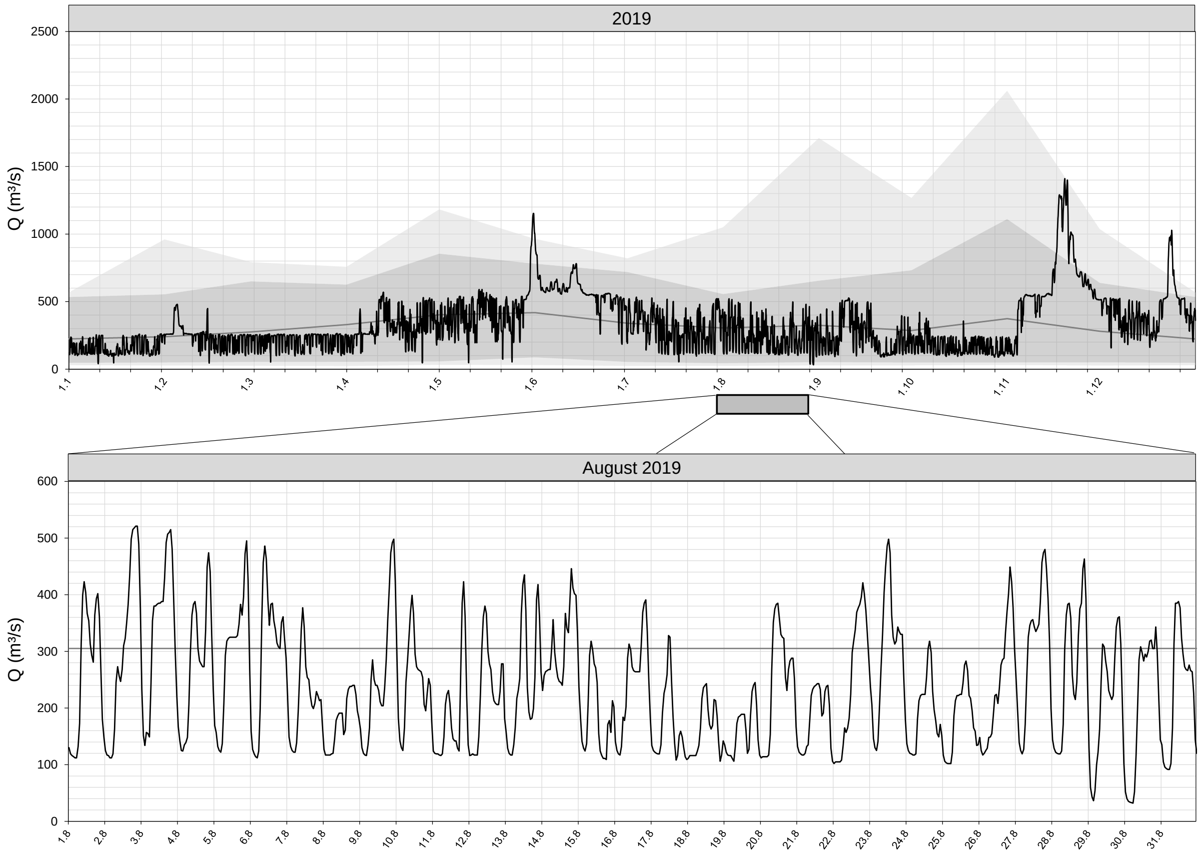


Figure 50: Drava – 600412, Donja Dubrava (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

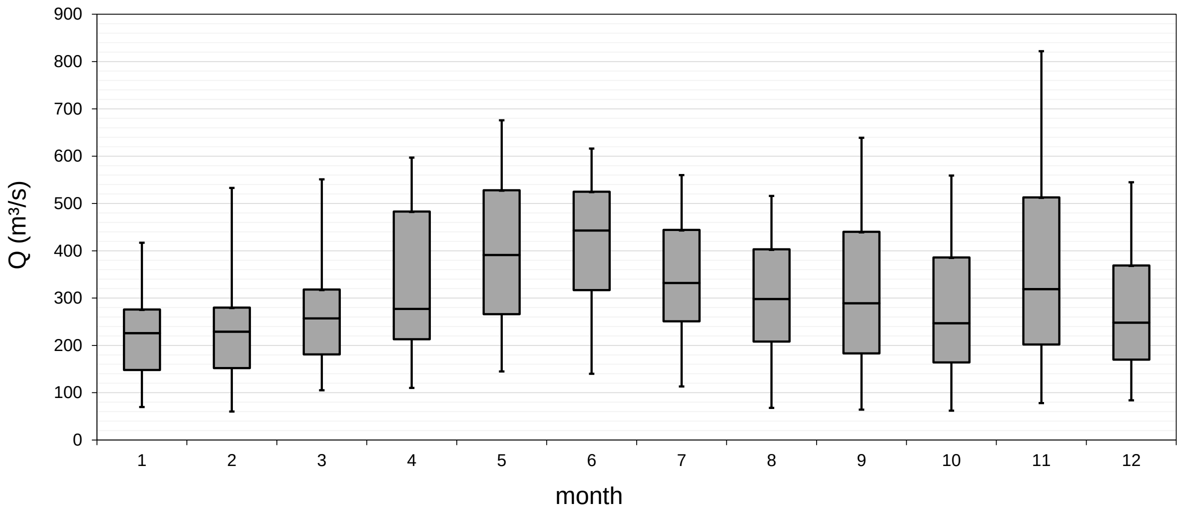


Figure 51: Drava – 600412, Donja Dubrava, monthly flow distribution (whiskers correspond to 5% and 95% percentiles)

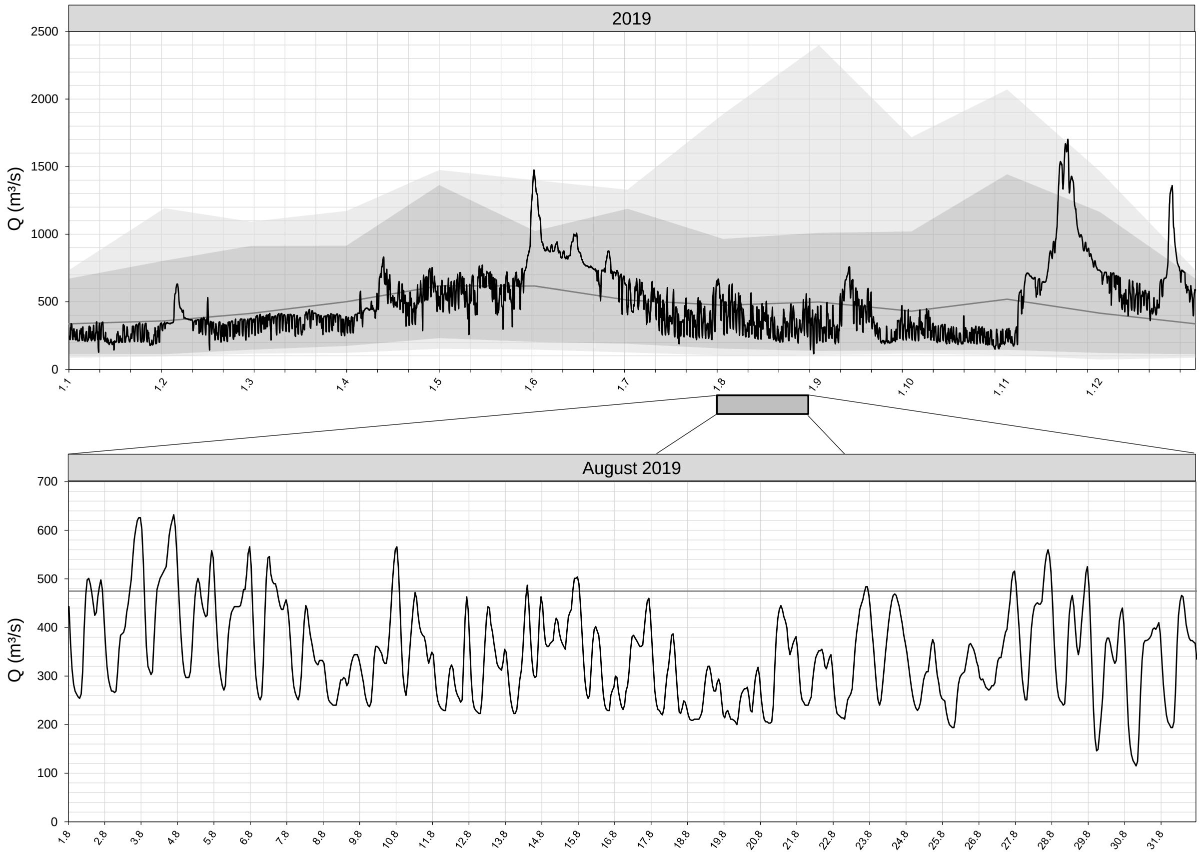


Figure 52: Drava – 600413, Botovo (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

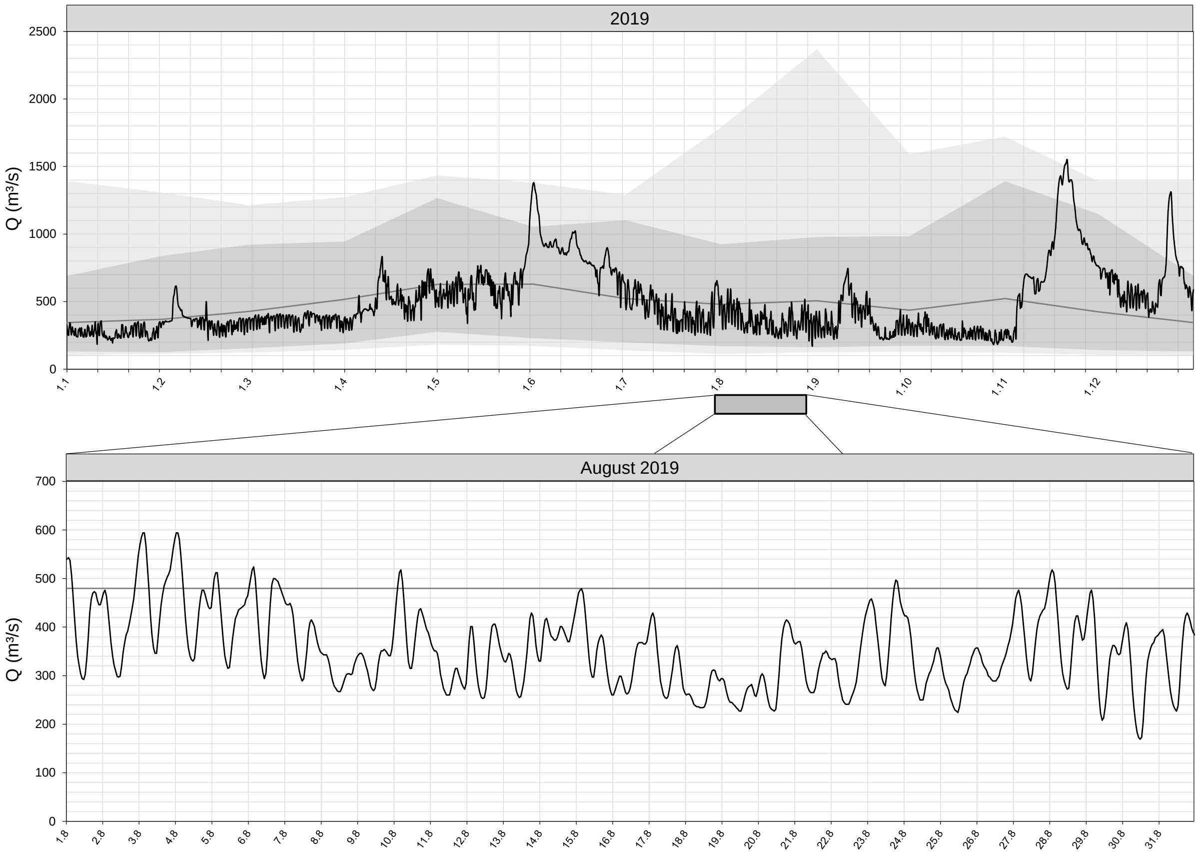


Figure 53: Drava – 600414, Novo Virje Skela (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

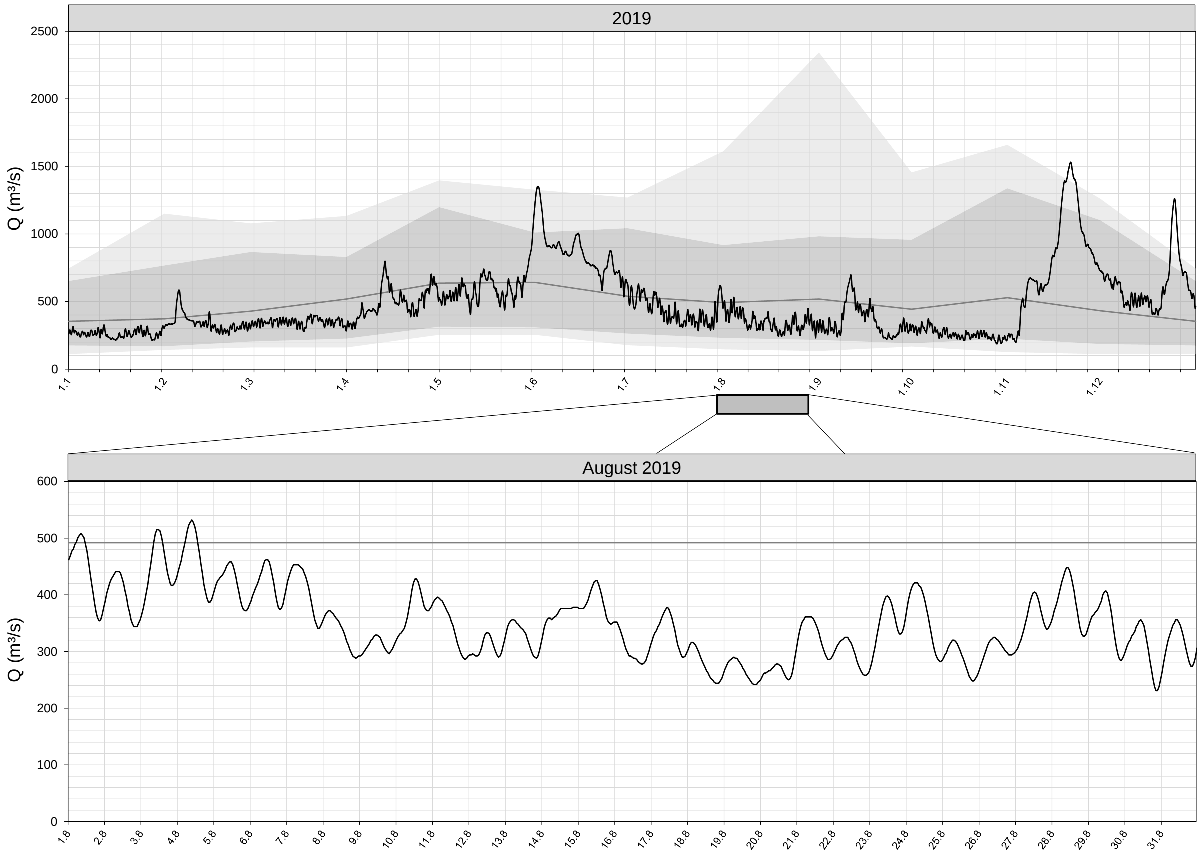


Figure 54: Drava – 600414, Terezino Polje (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

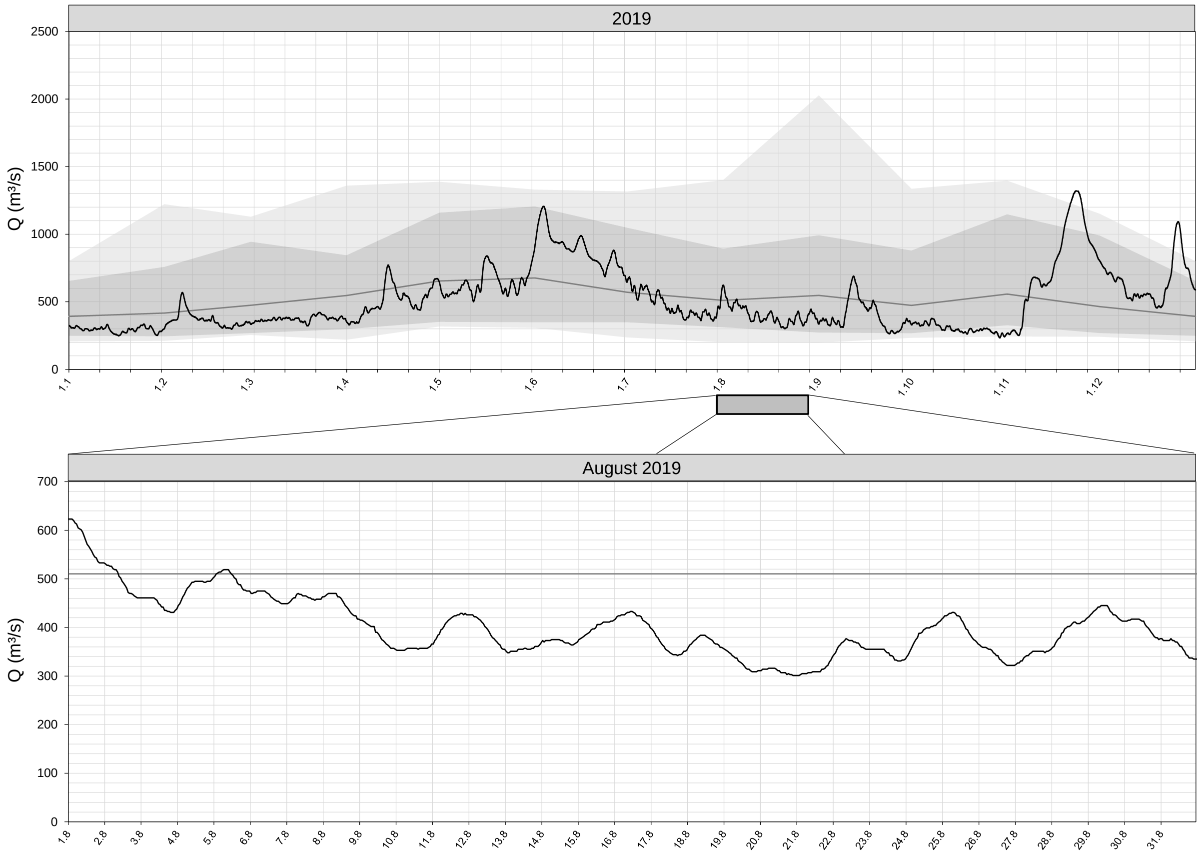


Figure 55: Drava – 600417, Belisce (black line – flow, grey line – monthly mean flow, Interpercentile range: light grey – monthly minimum flow (5% percentile) to monthly maximum flow (95% percentile), dark grey – monthly minimum flow (25% percentile) to monthly maximum flow (75% percentile)

D. Further aspects

Temperature

The authors were provided with extensive data sets (partly several decades) on the water temperatures of the Croatian Drava. However, all data refer to the Drava River from Donja Dubrava downstream and are exclusively daily temperature mean values. Hydropeaking operations can strongly influence temperature patterns in the downstream reach (Greimel et al. 2018, Hayes et al. 2019). However, an analysis of the temperature influence on the Drava by the Dubrava hydropower plant is not possible on the basis of the present data set, since higher resolution data (e.g. quarter-hour values or hourly values) are required for this purpose in order to be able to derive statements in correlation with the flow data.

For a detailed analysis of the consequences of the Dubrava hydropower plant on the river ecology of the Drava, however, detailed temperature data must be collected in the future. Detailed temperature data in the vicinity of the power plant, but also in sections upstream and downstream, can be generated relatively easily using permanently recording temperature probes.

Changes in hydro-chemical conditions:

In addition to the changes in flow, the Dubrava hydropower plant also has an influence on the hydro-chemical conditions of the downstream section of the Drava. The large reservoir of Donja Dubrava and the other dams upstream interrupt the natural bedload regime and also lead to sedimentation of suspended matter and fine sediments in the reservoir. Therefore, the Drava River is much clearer in the downstream section than in the unaffected state. Presumably, the transported nutrient load will also be significantly reduced, which could affect rates of primary and secondary production and thus the food supply for juvenile fish. The substantial absence of fine sediments, at least in the flood-free period of the year, causes the gravel banks between the power plant and the mouth of the river Mur to have particularly loose gravel and the water is very clear (Figure 56).

As mentioned above for water temperature, the establishment of a series of measurements for hydro-chemical changes would also be advisable, since no corresponding data are currently available to discuss potential consequences for the ecology of the affected section.

Figure 56: Gravelbank along the Drava upstream the Drava-Mura confluence. Noticeable is the loose gravel and clear water (picture date: 17.07.2021).