

Case Study 3 – Annex

Danube River Basin – harmonising inland, coastal and marine ecosystem management to achieve aquatic biodiversity targets[1]

[1]See full case study report for author and project information. Further information at https://aquacross.eu/content/case-study-3-danube-river-basin-harmonising-inland-coastal-and-marine-ecosystem-management

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Annex 1: Danube tributaries: Impact of hydropower

Southeast Europe (SEE) represents one of the hotspots of aquatic biodiversity worldwide (Griffiths, Kryštufek, & Reed, 2004). In the same time, the area sees a boom of hydropower development, with more than 2500 dams being planned, even in nature conservation areas (EU Natura 2000 areas). Thus, the construction of hydropower dams represents a clear threat to the regional aquatic biodiversity and ecosystem services, while there is hardly any data available so far on the environmental effects of hydropower plants in that region featuring high aquatic biodiversity.

So far, there is no nationally available overviews on the number of existing and planned HP plants for the most countries of SEE Europe. As data on the operation type of HP plants are often lacking, too, as well as the environmental flows provided, the impacts of existing HP plants on the flow regimes of rivers are largely unknown, and in consequence the ecological impacts, too. Especially, potentially valuable hydrological and ecological studies comparing the situations before and after dam construction are rare. There are missing national strategies for hydropower development which are legally binding.

Selection of the relevant indicators, metrics and indices for assessing the pressure induced by hydropower activity

Based on data availability for Danube tributaries indicators for the D-P-S analyses in SEE were selected according with the AQUACROSS concept on drivers, human activities, pressures and ecosystem state, which was specified for indicators, metrics and indices in WP4 and WP5.

Water abstraction, water flow changes and interruption of longitudinal river continuity for energy production by hydroelectric dams were selected as indicators for physical changes by human activities (Table AI 1), and fish communities were selected to describe state/ecosystem components (Table AI 2)

Table AI 1 Available integrative indicators describing selected pressure induced by hydropower activity

Pressures	Indicator	Available metric/Index	Data availability
Water flow rate changes, Water abstraction	Water flow changes, hydrological alteration - local, including sediment transport considerations	Extent of area affected by permanent hydrographical alterations River water bodies significantly affected by impoundments, water	Slovenia, Croatia, Montenegro, Serbia, Bosnia and Herzegovina, Bulgaria, Romania

		abstraction or hydropeaking	
	ditto	Collated database of future infrastructure projects (hydrological alteration)	Slovenia, Croatia, Montenegro, Serbia, Bosnia and Herzegovina, Bulgaria, Romania
Water flow rate changes, Water abstraction	Water flow changes, hydrological alteration	The ecodifference method (ecodeficit and ecosurplus metrics)	5 rivers in Slovenia and Croatia affected by hydropower operation in different ways
	ditto	The Indicators of Hydrologic Alteration model	5 rivers in Slovenia and Croatia affected by hydropower operation in different ways
	ditto	Method for the assessment of flow alteration by hydropeaking	5 rivers in Slovenia and Croatia affected by hydropower operation in different ways

Table AI 2: Available integrative indicators describing state/ecosystem components.

State	Component /indicator	Metric/Index examples	Data availability
Biological state	Fish	composition, abundance; population	Romania

Mapping the pressures represented by hydroelectric dams in SEE

The known locations of current and planned dams based on available data sets, which are partially known to be incomplete (e.g. for Romania), were mapped (Figure AI 1).The map hence shows the minimum extent of potential effects of hydropower on rivers in SEE, which hence may hamper or prevent reaching the goals of the Water Framework Directive (WFD) and Natura 2000 Directive there.

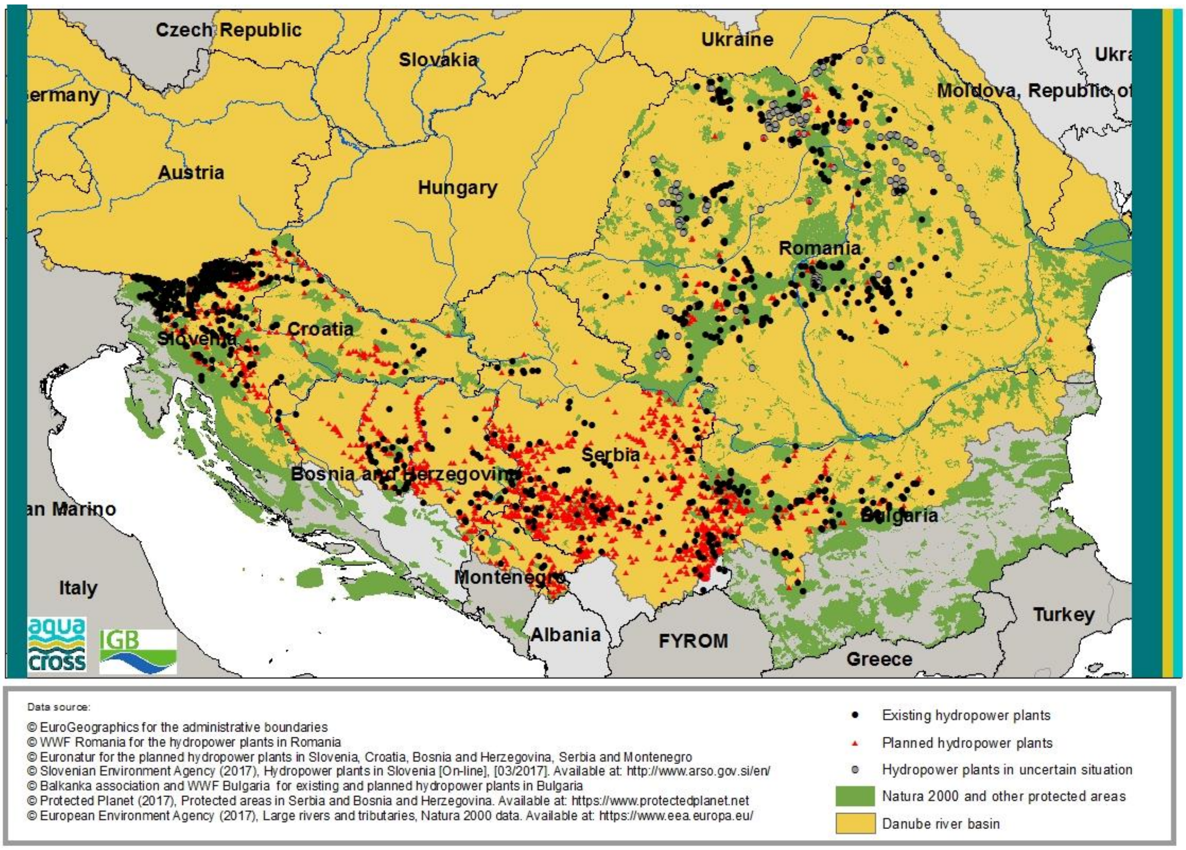


Figure AI 1: Map of operating and planed hydropower plants in Slovenia, Croatia, Bosnia and Herzegovina, Serbia, Montenegro, Bulgaria and Romania. Please note that shown available data are probably incomplete, especially for Romania.

The map is based on a database with 2372 hydropower plants in various stages of approval, construction, or operation which was collated based on various information sources from Euronatur, Slovenian Environment Agency (www.arso.gov.si/en/), http://balkanka.bg), WWF Romania based on information provided by the Romanian Environmental Protection Agency (http://www.raurileromaniei.ro/harta/), Balkanka association (https://dams.reki.bg/Dams/Map), WWF Bulgaria (http://www.wwf.bg/) and others which cover 7 countries situated in the middle and lower Danube catchment (Slovenia, Croatia, Bosnia and Herzegovina, Serbia, Montenegro, Bulgaria and Romania).

An analysis of this database shows that from 1044 operational HP plants, 333 (32%) are located in Natura 2000 areas, and from 1501 planned HP plants, 345 (23 %) would be located in Natura 2000 or other protected areas (Table AI 3).

Table AI 3: Number of the operating and planned HP plans in 7 countries from SEE (based on available data)

SEE countries	Existing	Planned	In Natura 2000 areas and other protected areas	Planned in Natura 2000 and other protected areas)
Bulgaria	84	82	51	42
Slovenia	419	150	110	67
Croatia	23	106	22	57
Romania	326	64	116	31
BiH	68	266	9	18
Serbia	113	780	25	126
Montenegro	11	53	0	4
Total	**1044**	**1501**	**333**	**345**

The fact that 23% of all new HP projects are planned in protected areas shows that this practice is in a contradiction to some guidelines for hydropower development that are highlighting protected sites as “no-go” areas such as the “Sustainable Hydropower Development” approach in the Danube Basin (ICPDR, 2014). The territory of protected areas in Bosnia and Herzegovina and Serbia is low and significantly below the European average (aprox. 2%) (Appleton et al. 2015), therefore percentage of planned HP projects in protected area there is lower than for example in Croatia or Slovenia.

Hydropower installed to date on rivers in the Danube basin in Slovenia, Croatia, Bosnia and Herzegovina, Serbia and Montenegro

Large HP facilities provide a dominant share (95%) of total installed capacity in the rivers from the studied area (Slovenia, Croatia, Bosnia and Herzegovina, Serbia and Montenegro) which sums up to 5148 MW. This capacity is contributed by only 7% of the total number of HP plants. Small HP plants represent 82% of the total number and provide only 2% of total installed capacity (Figure AI 2).

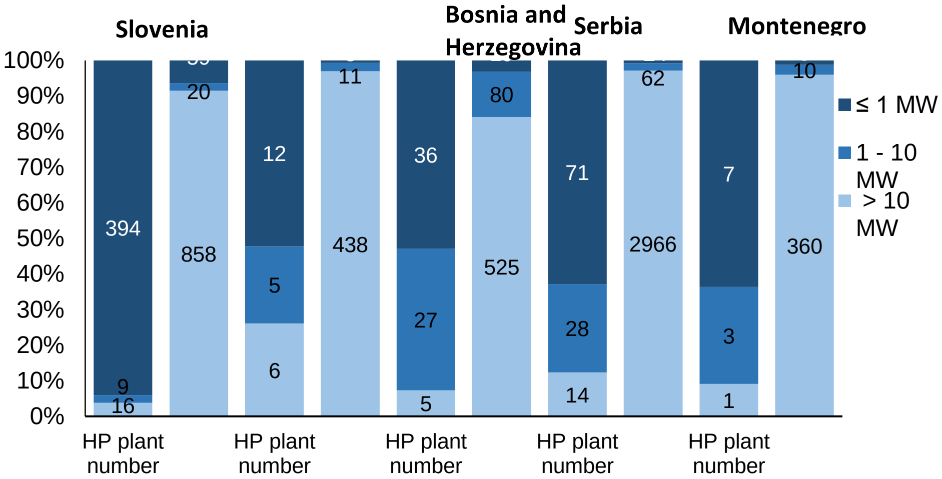


Figure AI 2: Country-specific distribution of installed electricity generation capacity (MW) among hydropower size classes, as compared to the respective distribution of the numbers of hydropower plants in Slovenia, Croatia, Bosnia and Herzegovina, Serbia and Montenegro in 2017. The numbers represent the respective numbers of HPPs. For Bulgaria and Romania such analyses were not possible because of data lack.

The high number of small HPPs with small electricity output raises the question whether these financial incentives provided at national level for small HPPs are efficient to increase the share of renewable electricity production (Abbasi & Abbasi, 2011). Most planned HPPs in the study region are small sized, although they cause significant damage since they extend to almost every river and are unfortunately often projected on rivers with high ecological value (Kelly-Richards et al. 2017; Schwarz, 2015).

The construction of hydropower plants of a certain size in last years may be determined by several factors, as the availability of so far unused hydropower potential, by regional electricity demand, by the availability of a high voltage electric grid, and by the structure of financial subsidy programs (IRENA, 2017; Liu, Masera, & Esser, 2013). In order to achieve the objectives from the EU Renewable Energy Directive, most EU member states have established financial support schemes for renewable electricity production, as fixed feed-in tariffs and feed-in premiums. These financial incentives are the most beneficial for small HPPs (Bosnia and Herzegovina Government, 2016; Croatia Government, 2013; Montenegro Government, 2014; Republic of Serbia Government, 2013; Slovenia Government, 2010), and seem to be sufficiently attractive to trigger the present boom of small sized HP facilities in the study area (Schwarz, 2015). According to a study of the International Monetary Fund (IMF), Serbia and Bosnia and Herzegovina are among the world's top ten countries with the highest percentage of energy subsidies in the Gross Domestic Product (Coady, Parry, Sears, & Shang, 2015).

Analysis of the impact of hydropower plants on river hydrology in Slovenia and Croatia

Assessments of assumed environmental effects of future HPPs in SEE are hampered by the fact that even the basic effects of HPPs on the hydrology of rivers have hardly been studied in that region (Bonacci & Oskoruš, 2010; Bonacci, Tadic, & Trninic, 1992; Globevnik & Mikoš, 2009; Žganec, 2012).

The alteration of flow regimes is often claimed to be the most serious and continuing threat to ecological sustainability of rivers and their associated floodplain wetlands (Sparks, 1995; Tockner, Pennetzdorfer, Reiner, Schiemer, & Ward, 1999). All species of the fauna and flora of rivers and their floodplains have adapted during their evolution to specific flow regimes. Correspondingly, the biotic communities colonizing certain river systems have been shaped by adaptation to their typical discharge levels, as well as to specific short-term and long-term dynamics of flow (Allan, 1995; Bunn & Arthington, 2002; Lytle & Poff, 2004; Townsend & Hildrew, 1994). Hydrological alterations may result in reduced or increased water levels, flow velocities and in artificial short-term or seasonal dynamics of those variables, which have direct effects on habitat features and availability both in the river channel and in the floodplain, as well as on sediment transport and sediment colmation (Magilligan & Nislow, 2005; Nislow, Magilligan, Fassnacht, Bechtel, & Ruesink, 2002). These impacts usually result in the alteration and homogenization of aquatic and water-dependent habitats in the affected river corridor, in the loss of lateral and longitudinal connectivity, leading to a disruption of life cycles (Kinsolving & Bain, 1993; Scheidegger & Bain, 1995). In consequence, the diversity of typical riverine biota decreases, exotic species spread, and many ecosystem dwindle not only at the reservoir site, but are additionally significantly degraded in most of the downstream river sections (Bunn & Arthington, 2002; Grill et al., 2015; Renöfält, Jansson, & Nilsson, 2010).

Knowledge on the impacts of planned HPPs on the hydrological regime of rivers in SEE would also represent a pre-requisite to develop approaches aiming at the mitigation or optimization of HPP operation to reduce environmental effects of flow regime alterations (B. Gao, Yang, Zhao, & Yang, 2012).

The study covers several river sub-basins within the Danube river basin located in Slovenia and Croatia which were selected due to the relatively good availability of gauging data there (Table AI 4, Figure AI 3). The hydrology of the studied rivers in Slovenia and Croatia is shaped by the Alpine and Continental climate components of the area, the marked orography, and by the widespread karstification of the river catchments. Rivers range from Alpine (e.g. Drava, Sava) to Continental karstic rivers (e.g. Gojacka Dobra).

Hence, for Slovenia and Croatia a complete database of the existing HPPs and gauging stations including their precise positions was collated. From there, longstanding hydrological gauging stations were chosen that are located downstream of the HPP, with daily data before and after HPP construction. If available, sub-daily (hourly) data were obtained. Data were provided by

Slovenian Environment Agency (www.arso.gov.si/en/) and Croatian Meteorological and Hydrological Service (http://meteo.hr/index_en.php).

Discharge data were available for 11 river reaches located downstream of several HPP types (Table AI 4, Figure AI 3). Among them, there are depleted river reaches (DR), reaches downstream of storage dams either with water withdrawal (STW), reaches downstream of diversion storage either with water withdrawal (STDW), or without water withdrawal (STD), and reaches downstream of run-of-river (RoR) HPP types (Table AI 4). The length of the daily discharge records for pre-impact periods (9 - 52 years) and post-impact (6 - 54 years) periods varied among hydrological gauging stations. For 13 presumably impacted gauging stations, sub-daily (hourly) data were available. Additionally, sub-daily data from 7 unimpacted gauging stations were obtained, which represent in total 106 years of non-altered discharge.

For three gauging stations with relatively short hydrological records, there were data for longer time spans available from nearby other gauging stations, which were hence included into analyses (Jesenice and Blejski Most (6U and 6D), Medno and Sentjakob (10U and 10D), and Varazdin and Dubrava (15U and 16D)) (Table AI 4). These stations were combined as there are no tributaries entering in between, and as the distance is max. 15 km, so that no significant difference in flow dynamics is assumed. During the gauging station selection process it became apparent that most gauging stations were constructed concurrently with HPPs, and many of these stations were decommissioned soon after HPPs were completed or they are operated by HPP owner, which thus greatly limits the number of acceptable data sets.

Table AI 4: Hydrological gauging stations selected due to assumed flow alterations by upstream hydropower plants, and hydrological basic information. Abbreviations: DR depleted river reach; STW - river reach downstream of storage hydropower plant which withdraw water from other rivers. STDW - reach downstream of diversion storage hydropower plant (after confluence of diversion and river bed) which withdraw water from other rivers; STD - reach downstream of diversion storage hydropower plant after confluence of diversion and river bed; RoR - reach downstream of run-of-river hydropower plant.

ID	HPP name	Gauging station	River (Country)	Location	River type	Pre-impact period	Post-impact period	H(m a. s. l.)	Catchment area [km2]
1	Formin	Borl	Drava (SI)	DR	Alpine nival-pluvial	1954-1977	1978-2016	322	14 662
5	Golica	Muta	Bistrica (SI)	DR	Alpine pluvial-nival	1954-1990	1991 - 2011	326	146
6A	Moste	Jesenice	Sava Dolinka (SI)	STW	Alpine high mountain nival-pluvial	1918-1952	6B	566	258

6B	Moste	Blejski most	Sava Dolinka (SI)	STW	Alpine high mountain nival-pluvial	6A	1953 - 2015	428	505
7G	Gojak	Lesce	Gojacka Dobra (HR)	STDW	Continental pluvial-nival	1946-1959	1960-2010	140	608
7L	Lesce	Lesce	Gojacka Dobra (HR)	STW	Continental pluvial-nival	1946-1959	2010-2016	140	608
8G	Gojak	Stative	Gojacka Dobra (HR)	STDW	Continental pluvial-nival	1946-1959	1960-2010	117	1 008
8L	Lesce	Stative	Gojacka Dobra (HR)	STW	Contínetal pluvial-nival	1946-1959	2010-2016	117	1 008
10A	Medvode	Sentjakob	Sava (SI)	RoR	Alpine medium mountain nival-pluvial	1926-1953	10B	267	2 201
10B	Medvode	Medno	Sava (SI)	RoR	Alpine medium mountain nival-pluvial	10A	1953 - 2015	300	2 285
11	Maribor-ski otok	Maribor	Drava (SI)	RoR	Alpine nival-pluvial	1926-1948	1949-2012	364	13 415
13	Zlatolicje	Ptuj	Drava (SI)	STD	Alpine nival-pluvial	1959-1968	1969-2014	335	13 664
14	Formin	Ormoz	Drava (SI)	STD	Alpine nival-pluvial	1962-1974	1991-2009	308	15 356
15	Varazdin	Varazdin	Drava (HR)	STD	Alpine nival-pluvial	1954-1974	1975-1982	166	15 616
16	Dubrava	Donja Dubrava	Drava (HR)	STD	Alpine nival-pluvial	15	1982-2015	130	16 000

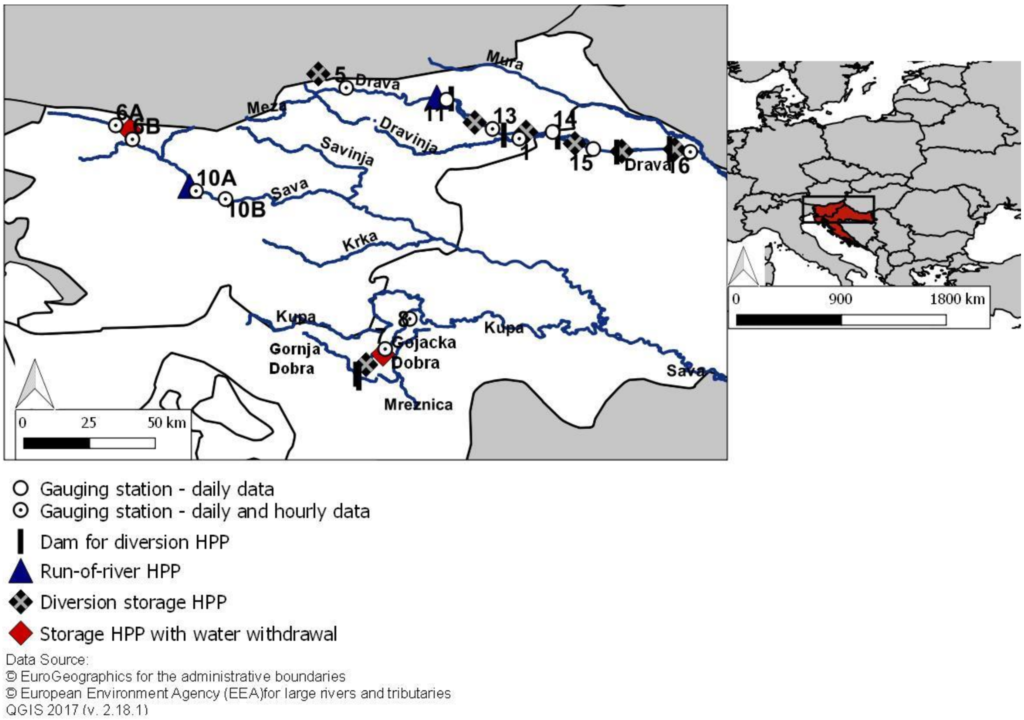


Figure AI 3: Hydrological gauging stations selected due to assumed flow alterations by upstream hydropower plants, and hydrological details

We analysed the type, magnitude, and direction of hydrological shifts across several types of hydropower plants (run-of-river, storage, diversion) based on gauging data at different temporal scales with three approaches, as (1) the ecodifference method (ecodeficit and ecosurplus metrics), (2) the Indicators of Hydrologic Alteration model and (3) a method for the assessment of hydropeaking flow alteration. Thereby, we applied these analyses to 5 rivers in Slovenia and Croatia affected by hydropower operation in different ways.

The methods differ in respect to data resolution and the time-scale of hydrological alterations which may be detected. Required data are short term (at least one year) daily discharge data for pre- and post-impact periods for method (1), long term (preferable more than 10 years) daily data from pre- and post-impact for method (2) and short term (at least one year) sub daily data for method (3).

The Ecodifference metrics (Vogel et al. 2007), including the ecodeficit (ED) and ecosurplus (ES) parameters, evaluate alterations to the flow regime of a river based on flow duration curves (FDCs). FDCs are calculated from daily stream flow data and provide a measure of the percentage of time duration that stream flow equals or exceeds a given value (Y. Gao, Vogel, Kroll, Poff, & Olden, 2009). Available hydrological time series were subdivided into the period before HPP construction and the period after that, and consequently two FCDs can be obtained for each HPP, i.e., a regulated FDC and an unregulated FDC. The ecodeficit is the percent area between the FCDs where the regulated FDC is below the unregulated FDC (Zhang et al., 2016a), while the ecosurplus is the percent area where the regulated FDC is above the unregulated.

Finally, the ecodifference, which mirrors the total change of flow regime, was computed as the sum of the ecodeficit and ecosurplus (Y. Gao et al., 2009; Zhang, Huang, & Huang, 2016).

When calculated on an overall percentage basis, ecodifference provides a measure of relative change from the unaltered condition. If ecodifference is higher than 15%, this river section is estimated as highly altered.

The Indicators of Hydrologic Alteration (IHA) method (IHA 7.1 software) may demonstrate the hydrologic alterations associated with HPP operation which will clearly affect the functioning of river ecosystems (Richter, Baumgartner, Powell, & Braun, 1996). Based on daily discharge data, IHA calculates more than 30 indices which describe the hydrologic regime of a certain gauging station. The indices generated by IHA consist of five major categories: (1) magnitude of monthly flows; (2) magnitude and duration of annual extreme and base flow conditions; (3) timing of annual extreme conditions; (4) frequency and duration of high and low pulses; and (5) rate and frequency of flow changes (Table AI 5) (Richter et al., 1996).

Thereby, non-parametric statistics were applied to skewed data distributions, which is common in hydrological data. In order to compare impacts of HPPs on quantitative way, we calculated for each HPP median value and degree of hydrological alteration (D) which was calculated according to (Richter, Baumgartner, Braun, & Powell, 1998).

Thereby, it is suggested that a level of D < 33% compared to the unaltered flow regime represents little or no alteration, 34% > D < 67% moderate alteration, and D > 68% high alteration (Richter et al., 1998).

Table AI 5: Output parameters for the IHA model (the 32 output parameters are grouped into five major categories; see Richter et al., 1996)

Indicator category	Description of categories	Indicators of Hydrological Alteration
Category 1	Magnitude of monthly flow	Average/Median flow of each calendar month
Category 2	Magnitude and duration of annual extreme flows, and the base flow conditions	Annual minimum 1-, 3-, 7-, 30-, 90-, day means/medians. Annual maximum 1-, 3-, 7-, 30-, 90-, day means/medians. Base flow index. Number of zero days
Category 3	Timing of annual extreme flow conditions	Julian date of annual 1-day minimum. Julian date of annual 1-day maximum
Category 4	Frequency and duration of high and low pulses	Number of low pulses each year. Mean duration of low pulse with each year. Number of high pulses each year. Mean duration of high pulse with each year
Category 5	Rate and frequency of flow changes	Up- and down rate. Number of flow reversals

The HP indicators software and method developed by Carolli et al., (2015) considers two of three indicators proposed by Meile, Boillat, & Schleiss, (2011), as HP1, which is a dimensionless measure of the magnitude of hydropeaking, and HP2 which reflects the temporal rate of discharge change. For both metrics the thresholds TRHP1 and TRHP2 were established based on the analysis of natural or near-natural flow series which enabled to identify the presence of hydropeaking. Thereby, the degrees of hydropeaking intensity were identified, as hydropeaking class 1 (absent or low alteration), hydropeaking class 2a and 2b (medium alteration) and hydropeaking class (strong alteration), following Carolli et al., (2015).

Results show that the various hydropower plant types have generally strong but varying effects on flow regime, producing a flow regime differing from the pre-impact natural flow regime. Flow regime was detected to be altered at all investigated river reaches downstream of hydropower plants (HPPs), according to the overall degree of hydrological alteration of the IHA model. However, degree of alteration vary: 8 river reaches were characterized as highly altered, and five as medium altered (Table AI 6). Medium altered river stretches are located downstream of diversion storage HPPs (STD) and run-of-river (RoR) HPPs (Table AI 6), while highly altered river stretches are located in depleted river reaches and downstream of storage HPPs with water withdrawal (STW and STDW) (Figure AI 4).

Flow regime within downstream of STW and STDW is the most severely changed as compared to the pre-impact flow regime. There are observed the highest degree of hydrological alteration of all IHA model's categories as compared to other HPP types (Figure AI 4). The most severe changes across these investigated sites occur in the rate and frequency of flow changes (Figure AI 4). Moreover only rate and frequency of flow changes is highly altered downstream of STD and ROR HPPs while other IHA model's categories downstream of these HPP types are medium altered (Figure AI 4). Within DRs magnitude of monthly flows is the most altered by drastic decrease of monthly discharge throughout all months (Figure AI 4, Table AI 6). Furthermore, there is a discharge reduced up to 11% of average pre-impact annual flow.

Similar results were revealed by ecodifference method where river reaches downstream of diversion storage and run-of-river HPPs exhibit less alteration than river reaches located in depleted river reaches and downstream of STW and STDW HPPs. Depleted river reaches reveal a strong change of flow duration curve resulting in a very high ecodeficit values. STW, STDW HPPs cause an increase in ecosurplus metric, while STD and RoR HPPs show increase in ecodeficit metric as compared to pre-impact conditions.

Moreover, hydropeaking (i.e. rapid variations of flow regime) was evident only at sub-daily scale downstream of storage, diversion storage and run-of-river hydropower plants (Table AI 6). Even 50 km downstream of STW HPP, hydropeaking is very strong (Table AI 6; GSs 8L, 8G). RoR HPPs in our study area produce hydropeaking, even that it is technically not possible to store large amounts of water in RoR HPPs. Therefore we explain our findings by the presence of HPPs with hydropeaking operation mode upstream of the RoR HPPs, which therefore still show discharge fluctuations shaped by hydropeaking. In contrast, depleted river reaches are not altered by hydropeaking (Table AI 7).

Thus, the total extent of flow alteration only gets visible with the availability of sub-daily hydrological data. As only a small fraction of all current gauging stations in the study area is actually recording at a sub-daily scale, the actual fraction of gauged river reaches which is affected by hydropower plants cannot be estimated to date. The combination of several methods could provide a practical and objective method for the analysis of hydrological alterations. Hydropeaking flow alteration method could be used complementary to other two used methods (Meile et al., 2011; Richter et al., 1996) in order to detected sub-daily changes which are obviously not detectable with other methods.

Table AI 6: The hydropeaking indicator values (HP1, HP2) and overall hydropeaking values for each gauging stations; gauging stations 11, 14 and 15 do not measure hourly data; THP1 = 0.4; THP2 = 1.6; *: Significant difference between unaltered and altered periods at the 5% level.

Gauging Station (GS)	1	5	6	7G	7L	8G	8L	10	13	15/16
HPP Type	**DR**	**DR**	**STW**	**STDW**	**STW**	**STDW**	**STW**	**RoR**	**STD**	**STD**
HP1	0.2*	0.1	0.8*	1.2*	1.3*	0.9*	1.2*	0.5*	1.3*	0.7*
HP2	3.1*	0.1*	5.2*	7.1*	15.6*	4.1*	12.2*	12.0*	94.2*	40.5*
Overall	2b	1	3	3	3	3	3	3	3	3

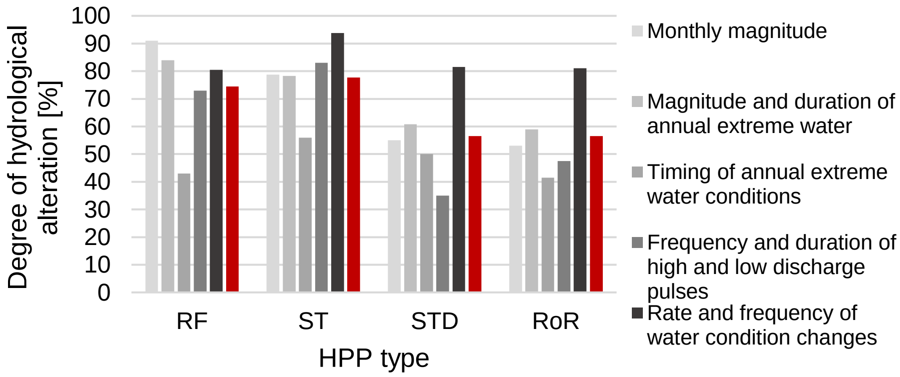


Figure AI 4: The degree of hydrological alteration of the IHA model's flow categories of different HPP types

Table AI 7: Degree of hydrological alteration of a flow regime (Equation 2); (1) ≤ 32% representing little or no alterations; (2) 33-66% representing moderate alteration; (3) 67-100% representing a high degree of alteration

Gauging Station (GS)/ parameters	1	5	6	7G	7L	8G	8L	10	11	13	14	15	15/16
Type of HPP	**DR**	**DR**	**STW**	**STDW**	**STW**	**STDW**	**STW**	**RoR**	**RoR**	**STD**	**STD**	**STD**	**STD**
October	100	100	80	80	100	35	61	8	23	33	26	88	12

November	100	43	30	65	100	86	100	70	41	67	13	63	21
December	100	14	78	61	67	30	61	19	15	50	13	63	24
January	100	62	86	70	61	56	100	5	41	50	24	25	21
February	100	81	100	24	22	30	61	26	36	83	26	100	56
March	100	43	78	80	61	72	61	32	4	67	13	25	16
April	90	62	86	70	61	91	61	22	2	33	13	13	29
May	100	62	77	61	67	53	61	8	62	33	38	36	24
June	100	100	72	73	100	21	100	8	49	17	26	13	6
July	90	43	86	25	4	31	100	2	69	67	38	13	12
August	100	81	69	16	42	55	71	39	20	33	26	29	47
September	100	62	83	30	67	62	100	5	23	33	26	63	21
Overall_Cat_1	99	83	89	68	83	74	90	52	54	68	32	77	43
1-day min	100	82	52	83	61	12	53	44	16	100	13	25	47
3-day min	100	81	56	52	61	7	61	51	2	67	1	25	3
7-day min	100	100	64	26	42	39	61	57	15	33	1	25	13
30-day min	100	100	100	54	100	67	22	62	15	83	73	25	29
90-day min	100	81	100	65	61	11	17	39	23	50	49	25	29
1-day max	30	5	53	83	100	49	100	73	77	67	36	50	24
3-day max	40	24	85	49	61	35	100	66	49	50	11	13	29
7-day max	80	43	85	90	61	7	61	53	28	50	26	63	74
30-day max	100	43	95	85	100	91	100	53	2	67	26	25	38
90-day max	100	62	100	85	61	86	61	26	28	100	26	13	6
#zero days	0	0	17	14	3	8	8	0	0	0	0	0	0
Base flow Ind.	50	5	45	70	22	81	61	5	62	50	75	63	65
Overall_Cat_2	88	80	87	78	83	70	82	60	58	82	56	49	56
Date of min	60	14	12	89	100	55	17	42	49	83	7	50	68
Date of max	7	43	50	9	61	12	17	22	36	17	38	13	24
Overall_Cat_3	49	37	41	71	91	45	17	37	46	69	31	42	58
#Low pulse	70	71	60	96	100	86	61	58	62	33	1	25	65
Low pulse L	93	14	100	42	17	92	100	54	12	40	13	59	9
#High pulse	94	73	80	65	100	12	61	1	4	0	13	13	21
High pulse L	52	23	20	53	48	38	74	24	29	27	11	75	35
Overall_Cat_4	86	60	84	82	85	77	88	48	47	33	12	61	34
Rise rate	92	81	5	70	100	75	100	100	36	33	7	63	74
Fall rate	90	81	98	85	100	100	100	21	87	83	26	36	85
#reversals	90	5	100	70	100	97	100	100	49	50	100	100	100

Overall Cat_5	91	70	97	80	100	95	100	88	74	71	77	85	93
Overall	83	66	80	76	88	72	75	57	56	65	41	63	57

1.1.1 Analysis of the impact of hydropower on fish communities in upper lotic systems in Romania

This section analyses the impacts of the small HPP on fish communities in rivers situated in the trout zone (upper lotic systems) in Romania.

Even small hydropower plants can have significant environmental impacts, which start during the construction phase: with habitat degradation, loss of riparian zone and destruction of wetlands (Başkaya, Başkaya, and Sari 2011).

The disruption of longitudinal connectivity by dams can have severe impacts on migratory fish, especially salmonids (Stakėnas and Skrupskelis 2009). Significant reductions in the numbers of salmonids were observed after the construction of small hydropower plants on small mountain rivers (Almodóvar and Nicola 1999, Ovidio et al. 2004).

The populations in upstream river reaches separated by dams from the lower reaches of the same river are often characterized by lower genetic diversity and a lower effective population size compared with populations below dams (Morita and Yokota 2002).

Another problem associated with small hydropower plants is the reduction of stream flow, which may cause profound ecological impacts. Flow abstractions to HPPs often result in a 90–95% reduction of the average annual discharge, which hence usually substantially affects key physical characteristics of the affected stream (e.g. water velocity, water temperature, suspended solids, fine particles and nutrients). Thereby, HPPs will also alter the quantity and quality of aquatic habitat, with cascading impacts on stream biota (Anderson, Freeman, and Pringle 2006, Vaikasas, Bastiene, and Pliuraite 2015).

The fish fauna of Romanian Carpathian first and second order streams (according to the Horton-Strahler classification system) has been studied by several ichthyologist generations, starting with Antipa (Antipa 1909), Bănărescu (Bănărescu 1964, Bănărescu 1969) and followed by others e.g. (Bănăduc et al. 2012).

In order to assess the impacts of a HPP, reference sites are needed to compare impacted with reference fish communities. In case the necessary reference sites are not present or accessible for sampling in the same stream system, an alternative solution is chosen by switching to other similar streams which must be located within the same ecoregion and also in the same longitudinal fish community zone. The Carpathians areas fortunately still harbor such river sectors or even rivers which can be used as reference rivers or river sectors (Bănăduc et al. 2012).

The available scientific information on Romanian ichthyofauna before the 1960's offer the possibility of a comparison of these documents fish communities, which are taken as reference data, with the present situation in order to assess the impact generated by the construction of the HP plants.

A review of scientific publication for Romania was conducted in order to assess the impact of HP plants on the biodiversity. We identified 44 relevant publications analyzing the effects of hydropower on Romanians rivers in terms of fish, 9 on macroinvertebrates and 4 on other biota.

Starting from the review of the scientific publications for Romania, a database for 55 hydropower plants situated in various rivers from Romania was created with information related to the presence and dominance of the fish species from these river reaches in historic reference time (Bănărescu 1964) and after the construction of the hydropower (upstream and downstream) (Bănăduc 1999, 2000, 2005, 2006, 2010, Bănăduc, Mărginean, and Curtean-Bănăduc 2013, Bănăduc et al. 2014, Curtean-Bănăduc, Costea, and Bănăduc 2008, Curtean-Bănăduc et al. 2014, Davideanu et al. 2006, Florea 2017, Momeu et al. 2007, Momeu et al. 2009, Voicu and Bănăduc 2014, Pricope et al. 2009, Telcean and Cupsa 2015, Ureche, Battes, and Pricope 2004, Voicu and Merten 2014, Voicu et al. 2016, Voicu et al. 2017). The database was completed by data provided by personal communication from the experts who published the mentioned studies (Bănăduc personal communication).

From these 55 HP plants situated in various river types in terms of fish zonation, 32 are situated in the trout zone after (Bănărescu 1964). For analyses that river type was selected because:

- the sampling methodology was similar in all case studies,

- in this river type other human pressures, as water pollution, bias are less frequent than in larger streams,

- there is a similar type of micro hydropower plant with diversion which has a installed power < 10 MW which is commonly installed on the streams in the trout zone.

Recorded dominances of the present fish species were assessed according to (Šorić 1996): ED – eudominant (> 20% of total fish number), D – dominant (10 – 20%), SD – subdominant (4 – 10%), R – recedent (1 – 3%), SR – subrecedent (< 1%).

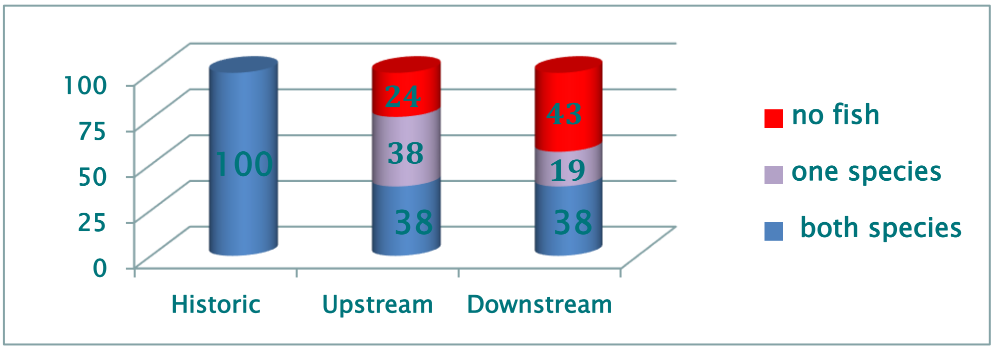
For statistical evaluation these dominance were coded into numbers 5 to 1, and the nonparametric Wilcoxon signed rank test for paired data was applied.

Two fish species are characteristic for the trout zone: brown trout (*Salmo trutta fario*) and bullhead (*Cottus gobio*). Brown trout was found in the reference state (based on the historic data) in all 32 stations, and the bullhead in 21 (60%) of the stations. Analyses of presence-absence data reveal that among the latter 21 stations harboring both species in the reference state, only in 38% both species remained either in the upstream or downstream stations after the construction of the HP plants (

Figure AI 5).

Hence, both the upstream and the downstream reaches of these streams near hydropower plants have clearly less fish species than in reference state: 24% - 43% lack one fish species, and 62% lack both fish species which can be expected there (

Figure AI 5). Presence of brown trout and bullhead in the reference state and presently in upstream and downstream reaches of HPPs at 21 selected sites where in the reference state



both species occur.

Figure AI 5: Comparative analyses of presence-absence data reveal among the 21 stations harbouring both fish species in the reference state with upstream and downstream reaches of HPPs

Analyses dominance records of both fish species at the same sites show that the dominances both of brown trout and bullhead are significantly decreased ($p < 0.005$) both in upstream and downstream reaches near HPPs in comparison with the historical reference state (Table AI 8, Figure AI 6, Figure AI 7). Thereby, the dominance of both species did not differ significantly between upstream and downstream reaches.

In the studied headwater streams other human impacts are improbable, so that the demonstrated relative effects on the fish communities (alteration of dominance) and the absolute reduction of the number of fish species may be mainly attributed to the micro hydropower plant constructed there.

Table AI 8: Wilcoxon signed rank test for paired data on dominance data of Salmo trutta fario and Cottus gobio

Wilcoxon signed rank test for paired data	Salmo trutta fario	Cottus gobio
	P value	P value
Reference state versus upstream	0.00222	0.000851
Reference state versus downstream	0.0003	0.000186
Upstream versus downstream	Not significant	Not significant

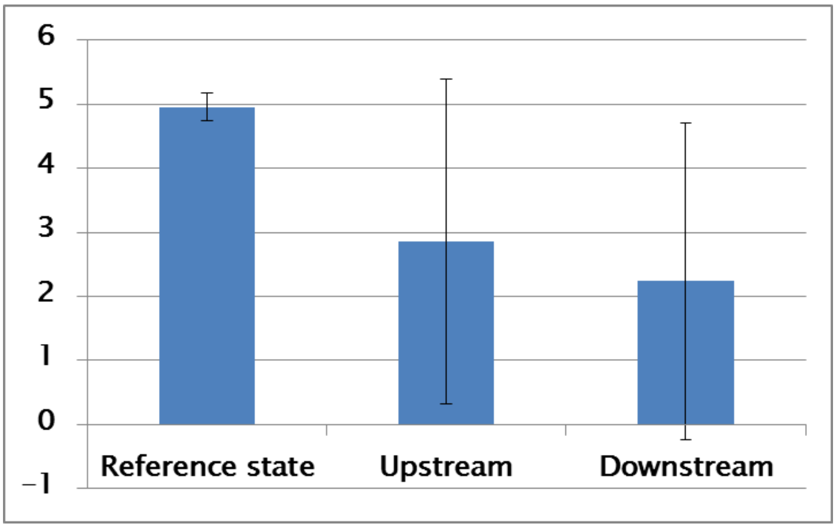
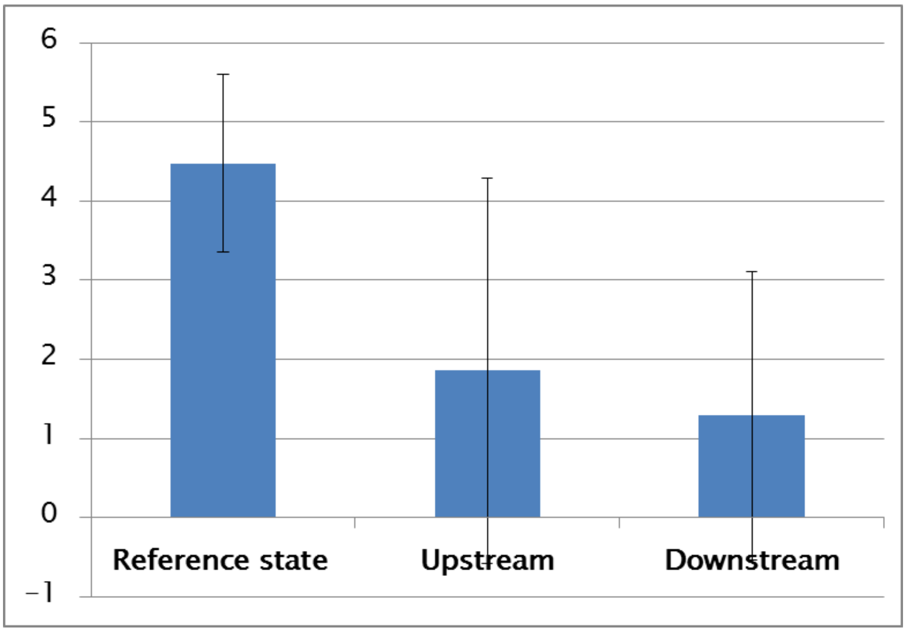


Figure AI 6: Dominance (average and standard deviation) of Salmo trutta in 32 Romanian streams of the trout zone in the historic reference status (left) and according to current records in the upstream and downstream reaches of HP plants located there. Dominance values were coded as follows: ED – eudominant (> 20% number) = 5, D – dominant (10 – 20%)= 4, SD – subdominant (4 – 10)= 3, R – recedent (1 – 3%)= 2, SR – subrecedent (< 1%)= 1, EX–extinct from that river streach = 0

Figure AI 7: Dominance (average and standard deviation) of Cottus gobio in 21 Ro streams of the trout zone in the historic reference status and according to current records in the upstream and downstream reaches of HP plants (right) located there. Dominance values were coded as follows: ED – eudominant (> 20% number) = 5, D – dominant (10 – 20%)= 4, SD – subdominant (4 – 10)= 3, R – recedent (1 – 3%)= 2, SR – subrecedent (< 1%)= 1, EX–extinct from that river streach = 0



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Annex 2: Impact of algal (Cyanobacterial) blooms on the social-ecological system of the Danube Delta

This chapter summarises the supply and demand side for ecosystem services in the Danube Delta. Further, a specific analysis was accomplished on the current state of biodiversity conservation of aquatic ecosystems in the Danube Delta, by engaging stakeholders in the knowledge, combat or mitigation of eutrophication, climate change and the most visible effects in surface waters: algal (Cyanobacterial) blooms.

Building the knowledge base of the socio-ecological system

Danube Delta, part of the Danube Delta Biosphere Reserve (DDBR) is the second largest delta of Europe, that combines important natural heritage characteristics of an ecosystem with a rich diversity of wetland habitats, lakes ponds and marshes with a community of 12,638 inhabitants (2011 Census) (Figure AII 1). In terms of legal status, more than 80% of the Reserve's lands belong to the public domain of national interest being administered by the Danube Delta Biosphere Reserve Authority, the rest of the area being the public domain of local interest (about 19%) and private (***, 2009).

The Danube Delta acts as a complex Social-Ecological System where the main driving forces of wetland changes include human activities. A total of 13 ecosystem services and 10 sub-services including provisioning services, cultural services, regulating services and habitat/supporting services were identified, described and assessed in Danube Delta Biosphere Reserve.

The reference configuration of the Inland Danube Delta-Socio Ecological System based on an integrated model of socioeconomic biodiversity drivers, pressures and impacts have:

- a high degree of complementarity between local socioeconomic metabolism and major ecosystem and landscape functions, e.g. over 50% of the region's total supply with resources and services are delivered by the local natural capital, and less than 10% of the total amount of energy (high quality energy content of the biomass which reflects the useful work that can be performed) accumulated by primary producers (NPP) was directly or indirectly diverted towards humans.

- a strong resilience against local and catchment-wide socioeconomic drivers and pressures and the hydrological pulse of the Danube river (Haberl H. *et. al.* 2009).

Despite growing recognition of their societal and ecological importance, deltaic flood plains are declining worldwide at alarming rates (Tockner K. *et al.* 2008). Loss of wetland ecosystem services is strongly related to the climate change and eutrophication, two major anthropogenic stressors that work dependently to favour cyanobacterial blooms in freshwater bodies (Moss *et al.* 2011; Mantzouki *et al.* 2014).

Figure AII 1: Map of Danube Delta Biosphere Reserve case study

When it comes to manage the occurrence of this major problem in freshwater ecosystems, the socio-economic dimensions of cyanobacteria blooms and the benefits of mitigation measures on ecosystem services in the delta are being totally ignored.

The assessment of Danube delta's ecosystem services and trends was accomplished under Norwegian-Romanian cooperation, emphasizing two periods characterized by fundamentally different socio-political and economic frames: the socialist period (1960-1989) where policies focused on economic development and the market-economy period where policies shifted towards ecological restoration after 1990.

The Danube Delta provides critically important services which benefits accrue from local communities to humanity. In this respect, over 60% of the Delta's ecosystem services have declined over the studied period. The socio-economic benefits from ecological restoration policies are already becoming apparent (***, 2013), but must be improved because of the nitrogen cycling in Danube Delta lakes (Figure AII 2) which will continue to maintained high pressure on the capacity of aquatic ecosystem to produce ecosystem services.

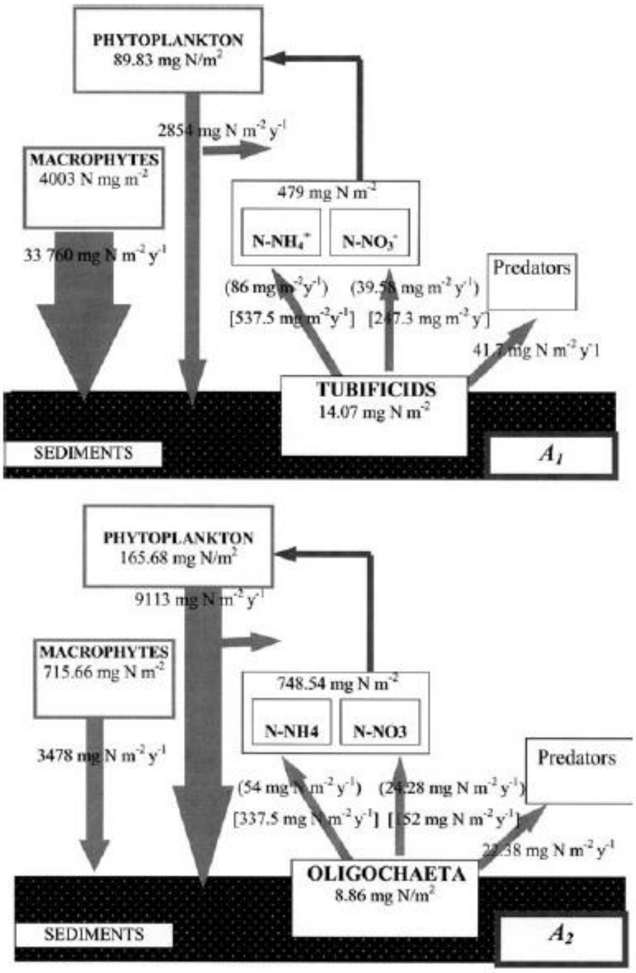

Figure AII 2: Nitrogen cycling in Danube Delta lakes (sources: Rîșnoveanu et. al. 2004)

A characteristic feature of the Delta socio-economic system, as part of the socio-ecological system, is the scarcity of Delta settlements (only 23) and the alternation of low populated areas with unpopulated areas, lack of waste disposal platforms and presence of drinking water networks in only six settlements, lack of services to meet the locals' and the tourists' demands and the high migrations of population (Petrișor *et al.* 2016; Tătar *et al.* 2017).

The interdiction of industrial-scale fishing, failure to fit into the job market due to little access to education and the absence of professional facilities, refusal to attend requalification courses offered by the Labour Employment Tulcea County Agency make this area one with a low income among the population. Poverty in the Delta shows up in poor health and high the risk for disease, due to pollution over the past decade which make the water improper for drinking, lack of collection and evacuation of domestic waste waters and uncontrolled waste dumping; reduced life expectancy due to heart diseases and improper diet (Damian N. & Dumitrescu B., 2009).

Apart from these, there are a small number of local entrepreneurs, with neither the expertise nor the funds to embark upon the development of local sustainable and eco-friendly ventures.

In the Danube Delta the industrial activities are poorly represented and the private agricultural production is taking place in various forms: intensive, organic, traditional-primitive for the subsistence of its inhabit-ants (Lup *et al.* 2016).

Agricultural land accounts 21.6% of the territory of Danube delta (see Table AII 1). In the structure of agricultural land use, the largest share belongs to permanent pastures with agricultural use (24,8%), followed by agricultural land without vegetation (6,87%) and shrub areas used for agriculture (3.05%). The vineyards and orchards occupy insignificant areas (2.67%), on the private land of the inhabitants (***, 2007).

Agricultural land used	Surface	
Land cover classes	hectares	% of used agricultural area
wheat and rye	6,060	5.73
barley and two-row barley	6,464	6.11
maize	6,464	6.11
potatoes	0	0.00
sunflower	8,080	7.63
soy	2,424	2.29
grain legumes	0	0.00
tomatoes and other fresh vegetables	0	0.00
temporary artificial pasture	2,424	2.29
orchards	0	0.00
vineyard	2,828	2.67
other agricultural crops including greenhouses	0	0.00
uncultivated land	29,896	28.24
agricultural lands without vegetation (fallow land)	7,272	6.87
permanent grassland, used for agriculture	26,260	24.81
areas with shrubs used for agriculture	3,232	3.05
woodlands, used for agriculture	0	0
Wetlands, used for agriculture	4,444	4.20
Total agricultural area	105,848	100,0

Table AII 1: Surface situation at the delta level of the main land cover, grouped on agricultural land (data taken from the Statistical Survey on land use in 2005)

Most industrial facilities are concentrated in urban areas adjacent to Danube Delta Biosphere Reserve. In the Danube Delta Biosphere Reserve area is developing an industry based on exploitation and valorisation of natural resources, primarily fisheries, agricultural and reed. (***, 2013)

Aquaculture in the Danube Delta was established in 1961 on an area of 560 ha but due to the poor results obtained in terms of productivity the development of this sector has declined significantly. The yield in fish farms is between 100-200 kg/ha, while the yield of the carp under natural conditions can exceeds 700 kg/ ha (Lup *et al*. 2016a).

Case study specific analysis going beyond: D -P -S Danube Delta and Co-Design

Background

Danube Delta is facing serious cyanobacterial bloom risks due to eutrophication and climate change, thus being vulnerable to ecological decline, which also involves challenging issues of biodiversity conservation, restructuration of the wetlands and improving the human well-being. Due to the hydro-morphological structure of the delta, to the release of sedimentary phosphorus and the opportunity of cyanobacteria to use nitrogen from atmosphere as a nutrient source, cyanobacteria have been spread in all available niches (Török *et al.* 2017). Further, aggregation of cyanobacteria - concentrated by wind activity - could have high impact on aquatic biodiversity- considering its potential toxic effect, which increases the risk of toxin related health problems - in resting or feeding areas of the wildlife protected species if no action to mitigate their effect is taken.

Recent seasonal analyses of distribution of cyanobacteria in Danube Delta's lakes revealed high concentration of biomass values (Figure AII 3) exceeding the risk of thresholds, spotted after the warm season. The lakes can be included in the risk category both for cyanobacterial occurrence and for the total algal biomass. The gelatinous mass in which cyanobacterial cells are anchored, leads to blocking gills of fish and their inevitable mortality during algal blooms For both spring and fall seasons were identified traces of microcystin in the water mass. (Török *et al.* 2018).

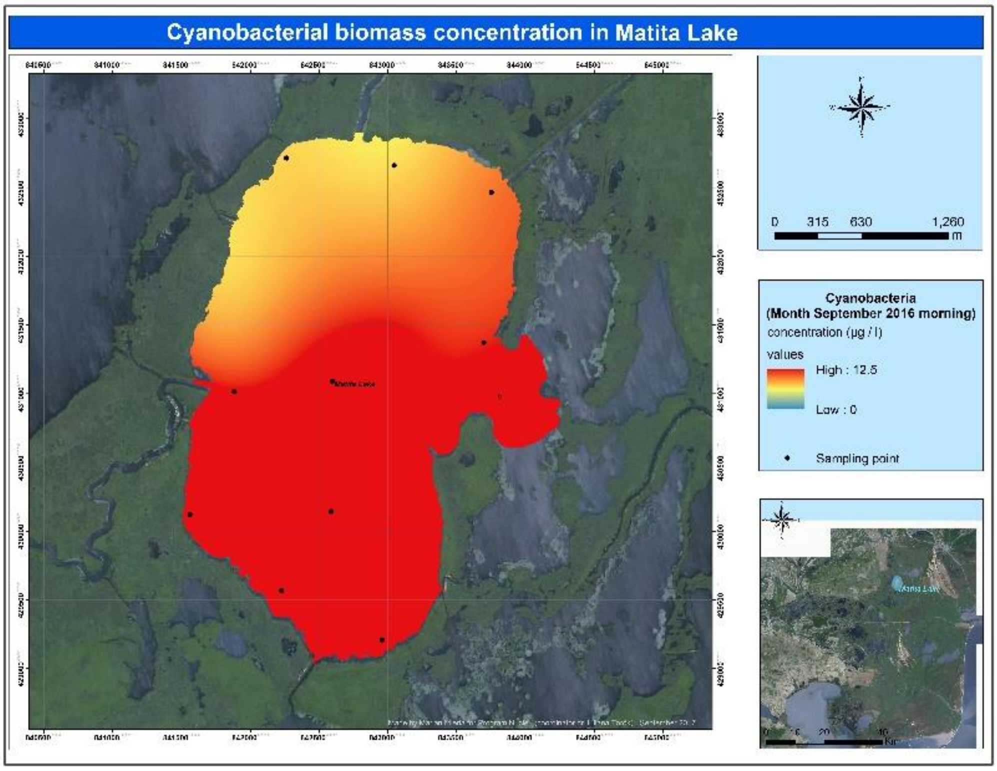

Figure AII 3. Circadian (September morning) highlighting of cyanobacterial biomass concentration zones in the Matita Lake

Co-design objective

The awarness and the effects of algal (cyanobacterial) blooms on ecosystem services and human society represent an issue of stakeholders interest, mainly for administrators of protected area, but as well for water resource managers.

Romania has made remarkable progress over the last 20 years, but some issues addressed and discussed at the European level, such as those related to the management of the expansion of cyanobacterian blooming in surface waters, have remained little known at the level of environmental agencies, and responsible agencies for monitoring and management of surface water quality (Török *et al.* 2018a).

The co-design process for Danube Delta focuses on engaging different stakeholders with interest in the topic of algal (cyanobacterial) blooms, by using qualitative approaches – questionnaire, to assess how they perceive the severity of aforementioned phenomen in aquatic ecosystems, if they have common understandings of the impact and risks arisen and if there is an institutional collaboration that can influence decision-making at the political level to develop adaptation and mitigation strategies for the future. Do they have a role in achieving ecological sustainability of aquatic ecosystems and can the management of the area be an Ecosystem-Based one?

We have involved in the co-design process 24 stakeholders divided in 5 group of stakeholders, representing public authorities, natural resource management, inspection and environmental control, research and environmental related NGO (see Table AII 2).

Group of stakeholders	Organisation	Responsibilities related to algal blooms
Natural resource management	Danube Delta Biosphere Reserve Authority (DDBRA)	A management body that is subordinated directly to the Ministry of Environment with responsibilities in creating and applying a special regime of management to conserve and protect the biodiversity in the natural ecosystems of the Danube Delta Biosphere Reserve (Vaidianu *et al*. 2015)
	National Administration „Romanian Waters" (NARW), Dobrogea Water Branch	It is a public institution of national interest that manages the waters from the state public domain and the infrastructure of the National System of Water Management. Based on Law 107/1996 is responsible, *inter alia*, for implementing EU directives related to water, sustainable development of aquatic ecosystems and their protection against depletion and degradation.
Inspection and environmental control	National Environmental Guard (NEG)	It is the main enforcement authority, having competences mainly in respect of verifying compliance with environmental laws and regulations. Has attributions regarding the environmental supervision, prevention and/or contravention including penalties, as well as informing the legal authorities in the case of offences committed in the environment (Condrea & Bostan, 2009)
Public authorities	Tulcea County Environmental Protection Agency (EPA)	Responsible for the environmental protection at county level, environmental legislation and policies implementation, issuing permits for activities having environmental impact, monitoring environmental factors.
	11 Local Councils within the territory of Danube Delta Biosphere Reserve: (Ceatalchioi, C.A.Rosetti, Chilia Veche, Crisan, Maliuc, Mahmudia, Murighiol, Nufaru, Pardina, Sfantu Gheorghe, Sulina)	Based on Law 215/ 2001, Local Councils take measure for the protection and rehabilitation of the environment, aimed at the increase in the quality of life. Contribute to the protection, conservation, restoration and turning to good account parks and natural reservations, under the terms of the law.
Research	National Institute for Marine Research and Development "Grigore Antipa" (NIMRD)	National institution involved in basic research and applied technology, with main areas of activity that cover, among others, protecting and ecologically improving coastal lakes, marine pollution, sedimentology and coastal morpho dynamics.

	National Institute for Research and Development in Electrical Engineering (ICPE-CA)	National institute carrying out accredited research, developing and validating viable solutions, exploring renewable resources.
	Eco Museum Research	Its purpose is to develop fundamental and applied research of the natural heritage, especially of Northern Dobrudja, includinf Danube Delta, in order to protect and enhance the value of its scientific, educational, cultural and tourism values.
NGO	Mare Nostrum	Promotes and ensures the sustainable development of the coastal zone, contributing to the specific environmental policies.

Table AII 2: List of stakeholder groups involved in co-design and their responsibilities relevant to algal (Cyanobacterial) blooms

Steps and outcomes of co-design process

Data collection to analyse perception of different stakeholders on algal (Cyanobacterial) blooms in aquatic systems in Danube Delta was carried out by means of questionnaire surveys. The questionnaire contained 18 opened and closed questions in order to provide the survey write-up with quantifiable and in-depth results (D.K.Bird, 2009). The first section was designed to capture stakeholders' awarness on algal (Cyanobacterial) blooms. The aim of the second section was to assess the perception on legislation and governance with role in preventing / combating / diminishing algal blooms. The third section tackled the issue of measures, from stakeholders' point of view, which could be implemented to control/mitigate the phenomenon. In the last section, stakeholders were asked to assess if they can support decision-making at political level to develop strategies for the management of algal blooms and if they have the meanings to apply an ecosystem-based management. The participants responded to the designed algal bloom questionnaire through person to person questionnaire deliveries.

Standard descriptive statistics were used to define the stakeholders' perception of algal and cyanobacterial bloom in aquatic systems in Danube Delta. The answers of both opened and closed questions were coded and analysed by category of stakeholders. Responses to closed questions were recorded as binomial (yes/no), or appreciated with Likert scale, having a 1-5 range (where "not really important / not really serious/major negative" =1, "little important / litlle serious / negative" =2, "important / serious / without" =3, "considerable important / serious / positive" =4, "very important / very serious / major positive"- 5). Further, the scores were calculatted through sume or average: e.g. average level of perception of main factors, the scores were totalled for each factor and divided by the number of respondents for that factor.

Section I: Awareness on algal (cyanobacterial) blooms

Stakeholders were asked about their knowledge related to algal (Cyanobacterial) blooms in aquatic ecosystems of Danube Delta. Almost all respondents indicated that they know about the occurrence of the phenomenon in aquatic ecosystems (82% for algal bloom and 60% for cyanobacterial bloom), being able to recognize it, but they are not familiar with the scientific terminology (Figure AII 4). The respondents with limited knowledge in the aforementioned phenomenon are representatives of public authorities and environmental control groups. The follow up question concerning their willing to attend seminars or meetings with specialists, in case they are not familiar with the topic, indicated their lack of interest in the algal bloom phenomenon.

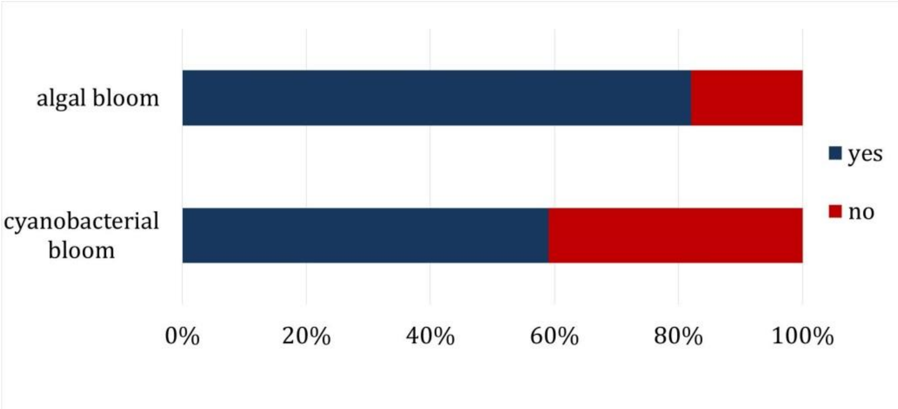

Figure AII 4: Awareness of stakeholders on algal (cyanobacterial) blooms

Even though the results of the survey indicated that not all respondents are aware with the terminology, it was an overall consensus that algal (cyanobacterial) blooms represent more than a serious issue for deltaic aquatic ecosystems. Public authorities, natural resource management and research groups assessed the severity of the issue as "very serious", meanwhile representatives of environmental control group stated it as a "considerable serious" issue and only the NGO group found it "serious" (Figure AII 5).

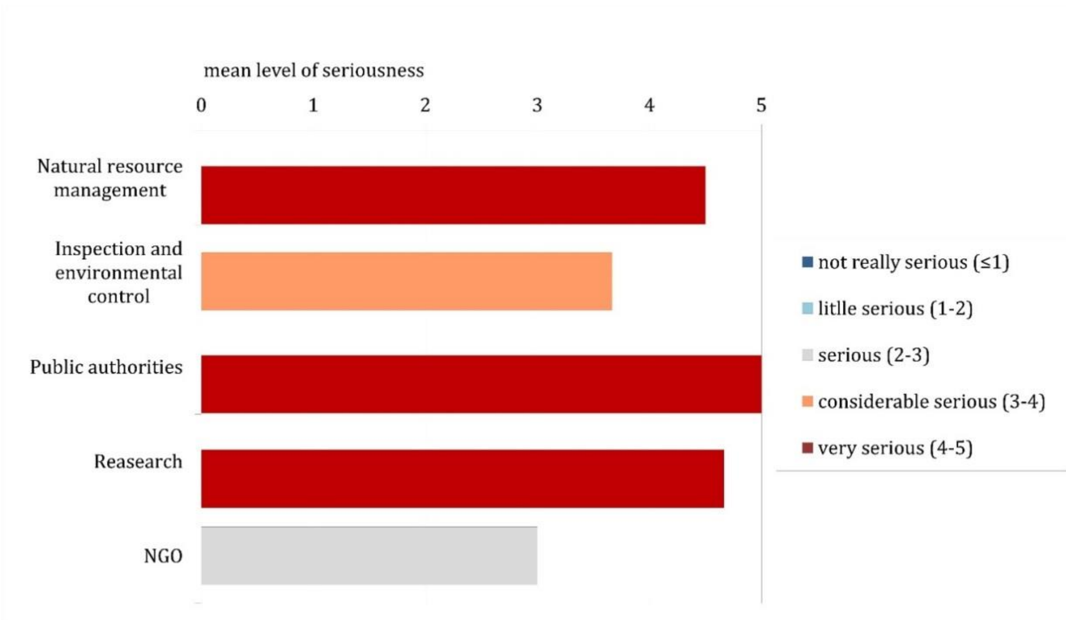

Figure AII 5: Perception of the severity of algal (cyanobacterial) blooms, ordered by group of stakeholders. The mean level of severity was calculated using a Likert scale, where "not really serious" =1, "little serious" =2, "serious" =3, "considerable serious" =4, "very serious" =5. Average = 4, 2; Standard Deviation (SD) = 0.73

The development and proliferation of algal (cyanobecterial) blooms in Danube's aquatic ecosystems result from a combination of natural and anthropic factors (Pinay 1992, Gils *et al.* 2005, Miloradov *et al.* 2014). Respondents were given 6 choices of such factors, of which they had to highlight the perspective that best suits with theirs, by using Likert scale. Overall, stakeholders considered that waste water discharges (average=3.8) and lack of waterbody connectivity (average=3.6) represent the most important trigger factors for algal blooms in the delta, followed by climate change (average=3.0) and agriculture (average=2.9) – Figure AII 6.

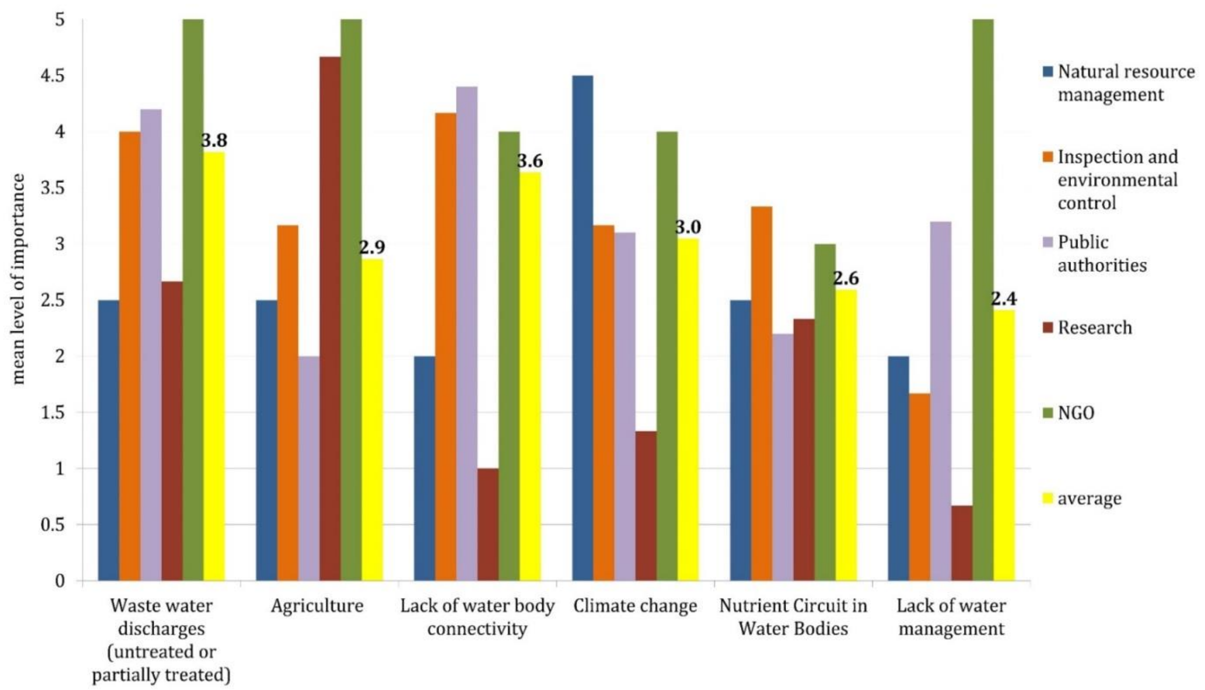

Figure AII 6: Perception of main factors of algal blooms, ordered by group of stakeholders. The mean level of importance was calculated using a Likert scale, where "not really important" =1, "little important" =2, "important" =3, "considerable important" =4, "very important" =5.

The main concerning factor for public authorities is the lack of water body connectivity (average=4.4), an issue also mentioned as a priority within Danube Delta Integrated Development Strategy (DDISD,2016) which require physical interventions to restore natural water circulation and key habitat areas, either by dredging /desilting of selected channels and lakes, either breaching of dykes and dams to allow flooding of disused agriculture/aquaculture/ forestry polders (renaturalization). The fact that Danube Delta is facing the aquatic ecosystems pollution through untreated sewage/waste water from the inhabited islands (DDISD, 2016a) has led public authorities to position waste water discharges on a second position in terms of importance (average=4.2) when it comes to algal blooms' factors. At the opposite side lies the natural resource management group that considered water body connectivity (average=2.2) the least important trigger factor mainly because these institutions are the ones responsible for maintaining water quality within Danube Delta.

Instead they have considered climate change (average=4.5) as the most important factor followed by nutrient circuit (average=2.5), waste water discharges (average=2.5) and agriculture (average=2.5).

Water pollution from pesticides and fertilizers used in the agricultural polders was thought to have a high impact on aquatic ecosystems, mainly by NGO, research and Environmental control groups, although data on the extent of the use and impact are generally lacking (DDISD, 2016).

According to EPA, Yang *et al*. 2008, Huisman *et al.* 2011, Sharma *et al.* 2011, Bennet, 2017, Thorburn *at al.* 2017, algal (cyanobacterial) blooms have direct and indirect socio-economical and ecological impact on the aquatic ecosystems. Based on that, was constructed the closed question on perceived level of impact of algal (cyanobacterial) blooms on deltaic aquatic ecosystems and services. As shown in figure AII 7, most respondents are aware of the negative impact of algal (cyanobacterial) blooms, mainly on aquatic biodiversity (average=4.4), human communities that depende on fish resource (average=4.3), water quality and human body through toxins bioaccumulation. Several representatives of inspection and environmental control body appreciated the impact as positive on all the components taken into account, which could be translated can be translated as an unawareness of the impact of the phenomenon, event though *a-priori* they haye rated the issue as a "very serious" one.

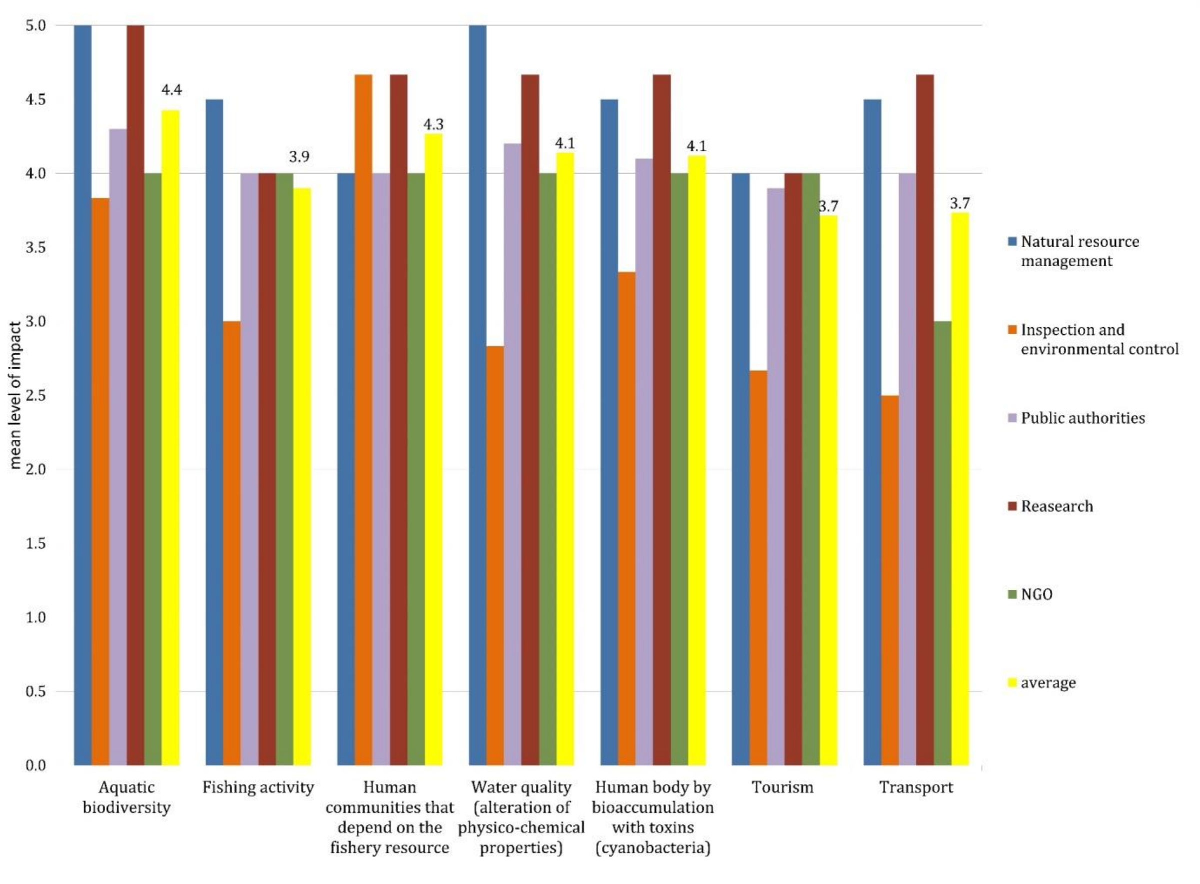

Figure AII 7: Perceived level of impact of algal (cyanobacterial) blooms on aquatic ecosystems, ordered by group of stakeholders. The mean level of impact was calculated using a Likert scale, where "major negative" =5, "negative" =4, "without" =3, "positive" =2, "major positive" =1.

Section II: Legislation and Governance

Over the years, the EU has adopted a suite of legislation that aims to protect and manage European waters. In the 1990s, the Urban Waste Water Treatment Directive (UWWTD, 91/271/EEC; EC, 1991a) and the Nitrates Directive (NiD, 91/676/EEC; EC, 1991b) came into force, focused on protecting human health, whereas the NiD targeted agriculture as the source of emissions, to protect aquatic resources. The Water Framework Directive (WFD, 2000/60/EC; EC, 2000) introduced a more holistic approach to ecosystem-based management in 2000. It focuses on the multiple relationships between the many different causes of pollution and their various impacts on water in a river basin, with the aim to achieve "a good status" of European waters (EEA, 2016). In 2008, with similar objectives of WFD, was launched the Marine Strategy Framework Directive (MSFD; 2008/56/EC) addressed to marine waters. Directive 2010/75/EU on industrial emissions (integrated pollution prevention and control) has one of the main goal to improve water quality by reducing substances which contribute to eutrophication.

Assessing the risk of non-compliance with environmental objectives has become an extremely important issue for European Community countries. Romania has made remarkable progress over the last 20 years, but some issues addressed and discussed at the European level, such as those related to the management of the expansion of cyanobacterian bloom in surface waters have remained little known at the level of environmental agencies, and responsible agencies for monitoring and management of surface water quality.

Based on the average scores between 2.14 and 4.00, all group of stakeholders thought most legal frameworks with role in dimishing/combating algal blooms are relatively important. Due to the fact that Danube Delta is facing the aquatic ecosystems pollution through untreated sewage/waste water from the inhabited islands (DDISD, 2016b), among the most high scored EU directives were Urban Waste Water Treatement (average=4) and Water Framework Directive (average=3.82). Comparing stakeholders' perceptions (Figure AII 8), can be observed that public authorities show a certain lack of confidence in most directives, considering that the current policies and strategies for managing the algal blooms require revision and a better transposition and implementation at national level. They expressed a unanimous opinion that there is no local management strategy for algal blooms to guide their local prevention / combat actions. Representatives of 2 local councils claimed to be aware of the existence of the aforementioned directives by heaving heard abouth them briefly, but have no knowledge of their content.

Representative of natural resource management group mentioned that the governance is more top-down regulated, raising the issue of the need for legislative review by taking into account current local conditions, what has been done and what has been reported until now.

Research group consider that policies and directives with role in combating / diminishing algal blooms may require improvements in the achievement of certain regional objectives, and the transition to new water protection stages. Furthermore, the necessity of following the implementation plans of the directives after their transposition into the national legislation has been highlighted.

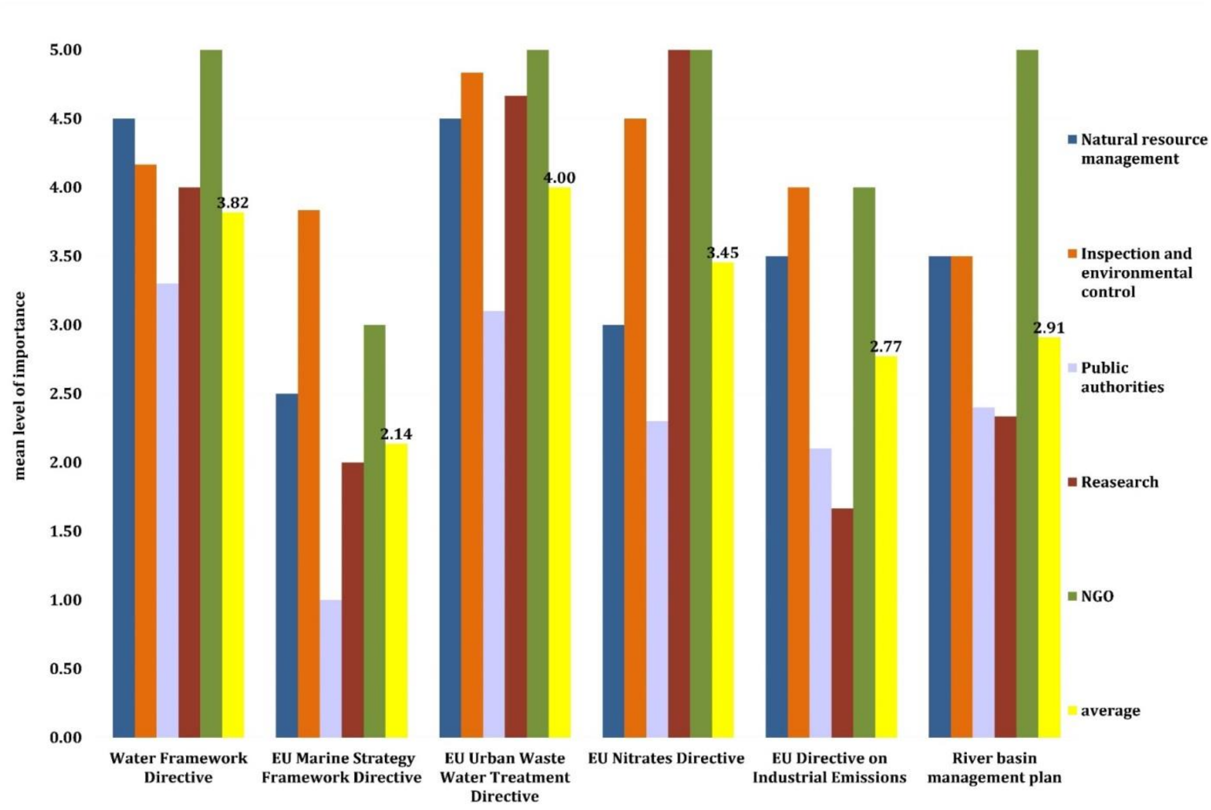

Fig AII 8: Perception of the importance of legal frameworks with a role in diminishing/combating algal blooms. The mean level of importance was calculated using a Likert scale, where "not really important" =1, "little important" =2, "important" =3, "considerable important" =4, "very important" =5.

Section III: Control & Mitigation measures

Based on both expert judgement and scientific review, the measures pre-prepared in the questionnaire, were designed to cover both control (to suppress or destroy algal blooms) and mitigation - dealing with an existing or ongoing bloom, and taking whatever steps are necessary or possible to reduce negative impacts (Anderson, 2009). The results show an agreement between respondents when it comes to control measure of improving the sewage treatment system (with the highest average score of 4.4), coming in response to the main driver factor identified (waste water discharges). This shows that it is a very important aspect in the studied area, the localities in Danube delta do not have centralized sewerage systems that collect the waste waters at the level of the whole locality, and the existing treatment plants perform only the mechanical pre-treatment of the domestic waters.

The second measure considered most important for deltaic aquatic ecosystems is reducing the use of chemical fertilisers (average=3.80), but with different perceptions among stakeholders. Meanwhile research and NGO groups are ranking it as very important measure for long term ecological improvement, public authorities and natural resource managers consider little important, as within the delta the it is stipulated by law that land users should ensure the fertilization of land only with organic fertilizers.

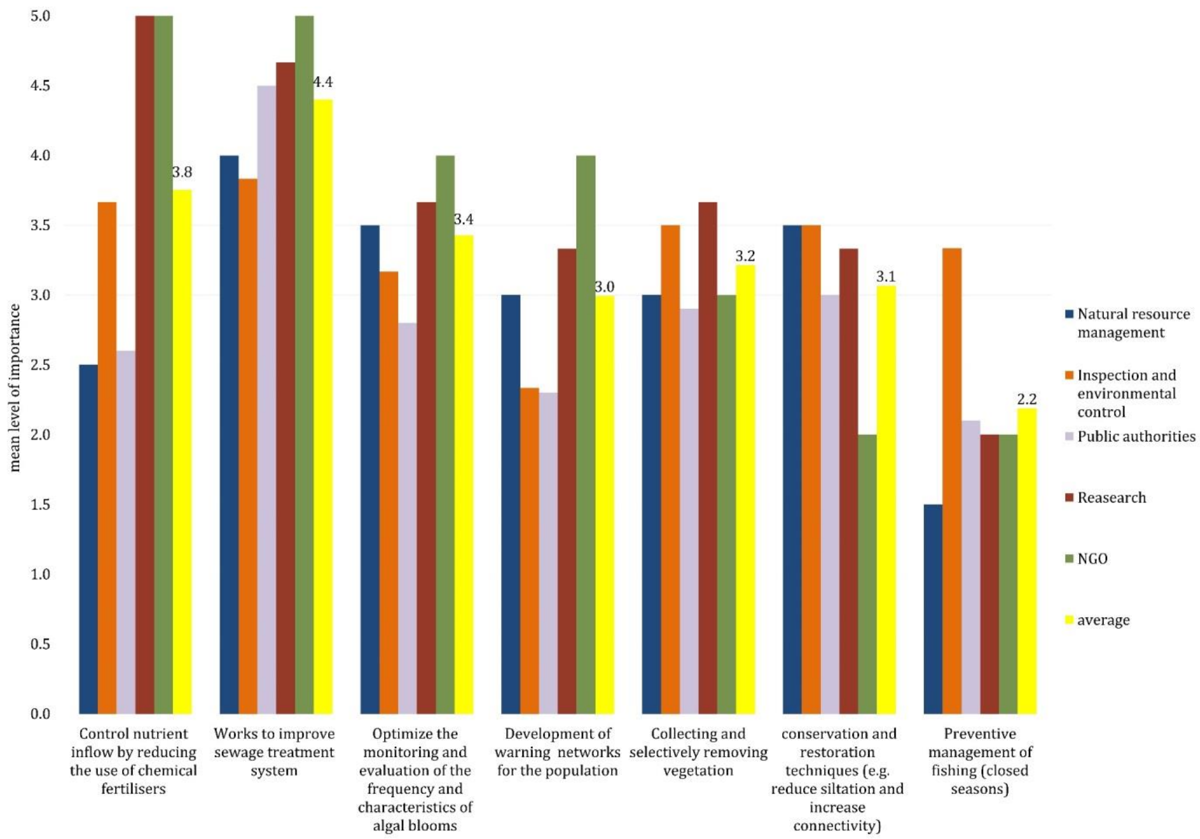

Fig AII 9: Perception of the importance of control/mitigation measures, ordered by group of stakeholders. The mean level of severity was calculated using a Likert scale, where "not really important" =1, "little important" =2, "important" =3, "considerable important" =4, "very important" =5.

Section IV: Management & Institutional Collaboration

The question whether the stakeholders have a strategy or an action plan to manage algal (cyanobacterial) blooms, revealed that they are not aware of such instruments in force for Danube delta area. Moreover, representatives of local councils mentioned that they are notified by local pople of the occurence of algal blooms in aquatic ecosystems on their commune's territory (e.g. in Holbina, Militova lakes, Cordon-Litoral channel), but they can not take actions because they are not the administrators of the affected water bodies. Hence, they consider that the entitled institutions to record and diminish the phenomenon are the ones that administer the natural resources, stressing the lack of institutional collaboration and harmonization of interests among stakeholders. Moreover, they have raised the problem of institutional overallaping when it comes to natural resource management, a true obstacol in achieving ecological goals.

Further, the representative of water management body mentioned that the institution is mainly responsible for carrying out routine water quality monitoring and maintenance of watercourses, without influence or control over the factors of algal blooms.

Researchers, NGO and natural resource management groups consider that they can influence decision-making at the political level to develop strategies for the management of algal bloom, through extensive efforts for monitoring and research activities carried out in the field, rising awareness and enhance communication of scientific recommendations to the decision-makers and general public. Representatives of public authorities specified that since they are not the owners of water bodies, they cannot influence political decision-making but can only report algal bloom situations when they occur and present the risks exposed.

In terms of applying ecosystem based management principles in the case study area, public authorities together with natural resouce management and inspection and environmental control groups believe that the stuff within their institutions do not have technical/scientifical competencies in the field of algal blooms and its management. Additionally, there is no local strategy for the management of algal blooms in the Danube delta. Another type of constraint encountered would be the lack of financial resources to support EBM management, related mainly to the priorities and need among decision-makers, in algal bloom topic. This can be attributed to the fact that stakeholders and decision-makers appreciate the importance of environmental damages in connection with social and economic interests, with risks and distribution of costs and benefits (Belacurencu, 2007).

Designing the Bow tie diagram – based on stakeholder process

A Bow Tiw diagram consists of a fault tree on the left side identifying the possible events causing the top event and an event tree on the right side showing the possible consequences of the top event based on the failure or success of safety barriers (Liu Z, 2017). In our case, the top event is represented by algal (cyanobacterial) blooms in aquatic ecosystems of Danube Delta. In the left side are mentioned the anthropogenic and natural pressures such as: hydrotechnical works, morphological alterations, waste water discharges partially threatened or untreated, lack of water body connectivity, climate change (increase in water/air temperature), that favour the occurrence of algal (cyanobacterial) blooms and in the right side are the consequences resulting from the event.

The controls measures positioned on the left are the solutions preventing the issue from occurring, meanwhile the mitigation column represent the measures which should be considered to recover once the event took place. Both control and mitigation measures use a mixture of legislation, water management plans and changes in behaviour and mentalities to manage the risk. Control and mitigation measures are specific to a certain cause or consequence and may not be applicable to all of them.

The escalation factors can be considered as restrictive ones that can damage the efficiency of both control and mitigation measures, such as institutional conflicts regarding the ownership status of water bodies that puts barriers to the implementation of control or mitigation measures.

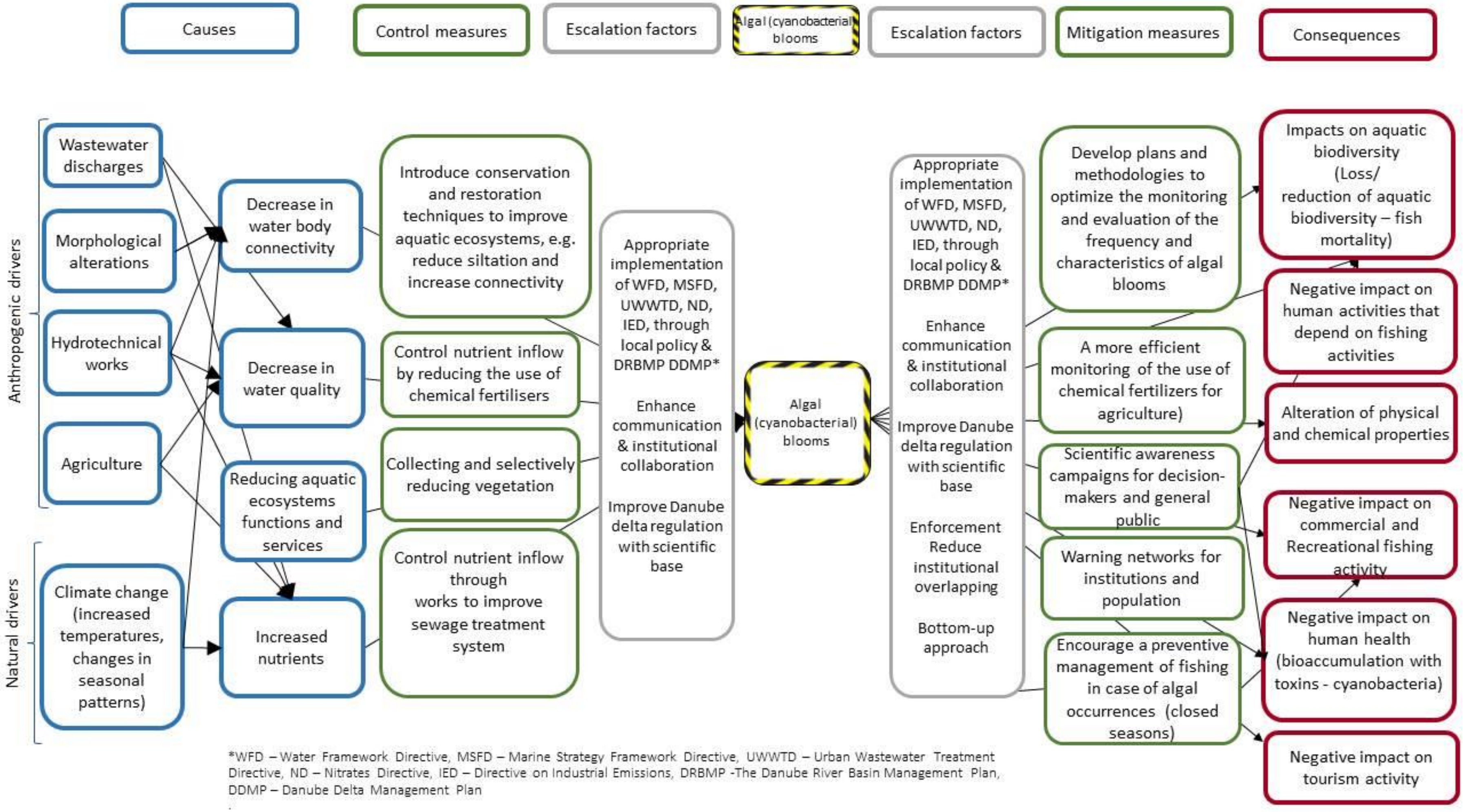

Figure AII 10: Bow-tie diagram for algal (cyanobacterial) blooms in Danube delta case, based on stakeholders process

Conclusions

This study analysed the perceptions of different group of stakeholders on algal (cyanobacterial) blooms in aquatic ecosystems in the Danube Delta in order to apprehend which are the vulnerabilities in terms of potential adaptation and mitigation strategies for the future, and to highlight what type of support is required for the adoption of these measures. The results could be used in other aquatic ecosytems to help plan and mitigate algal blooms in the future.

The research findings regarding stakeholders' limited knowledge and their lack of interest in algal bloom and cyanobacterial blooms occurring in aquatic ecosystems of Danube Delta should attract the attention of the biosphere reserve management. As stated by several group of stakeholders, this is mainly due to lack of institutional cooperation and communication within the case study area.

Several national and local institutions have overallaping roles when it comes to natural resource management. These overlapping situations can make it very difficult to agree upon and implement important management decisions for algal blooms. As stated in DDISD 2016, the institutional structure for managing the Danube delta territory is complex and insufficiently coordinated which might hinder conservation efforts. This is an obstacle to achieving the goals of ecological conservation and environmentally sustainable development.

Due to the strong linkage between Danube Delta and Danube River policymakers should exploit at local and regional level actions that can increase the institutional cooperation that is needed to mitigate the effect of cyanobacteria blooms and its potential toxic effect on aquatic diversity. Those actions must be address to reducing algal blooms all over the Danube Basin.

The capacity and effectiveness nature resource manager and other stakeholders need to be strengthened in order to improve aquatic ecological conditions. Strengthening steps could include both technical and institutional (human resources) aspects. Institutional initiatives should address building trust, communication and collaboration.

At local level, the base factor for EBM implementation relies on the priorities of stakeholders and decision-makers, whose financial and human resources will be focused on treating conservational and environmental issues depending in part on the strengths and interest on the impact and the effects of algal blooms that occur in deltaic aquatic ecosystems.

During the stakeholder involvement process it was identified that the main societal actors in the Danube Delta topic and some of the major sectors (e.g. mainly local authorities, research group, environmental resource management group, NGO) can be directly engaged in the co-design of the project.

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Annex 3: Analysis of causal linkages for the navigable Danube

Table AIII 1: Selected metrics and indices per indicator related to hydro-mophological alterations for the modelling approach

Code	Description of metric	Indicator	Source
Driver			
Hydropower	river stretch is situated within the reservoir area upstream of a hydropower plant	impact of hydropower plant	https://danubis.icpdr.org/
navigation1	navigation class according to the "Classification of European Inland Waterways"	status of waterway	(Economic Commission for Europe, 2012)
navigation2	critical locations for inland navigation where the fairway depth of 2.5m at Low Navigable Water Level was not achieved	status of waterway	(Fairway, Danube, 2014, 2016)
urban	percentage of the potential floodplain area covered by urban structures	Land cover/Land use	Copernicus Land Monitoring Services (land.copernicus.eu)
agriculture	percentage of the potential floodplain area covered by agricultural land	Land cover/Land use	Copernicus Land Monitoring Services (land.copernicus.eu)
Pressure			
Bank stabilization	Extent of reach affected by artificial bank material (% of bank length)	hydro-morphological assessment	Schwarz, 2014
planform	Planform of the River channel	hydro-morphological assessment	Schwarz, 2014
erosiondeposition	Erosion/deposition character	hydro-morphological assessment	Schwarz, 2014
engineeringstructures	Impacts of artificial in-channel structures within the reach (impoundments, groynes)	hydro-morphological assessment	Schwarz, 2014
flooding	Degree of lateral connectivity of the river and the floodplain (Extent of floodplain not allowed to flooded, regularly owing to engineering)	hydro-morphological assessment	Schwarz, 2014
connectivity	Degree of lateral movement of the river channel	hydro-morphological assessment	Schwarz, 2014
State			
Aspius	Conservation status of *Aspius aspius* (fish)	conservation status according to HBD	Natura 2000 database, www.eea.europa.eu
Bombina	Conservation status of *Bombina sp.* (amphibian)	conservation status according to HBD	Natura 2000 database, www.eea.europa.eu

Gymnocephalus_bal	Conservation status of *Gymnocephalus schraetzer*(fish)	conservation status according to HBD	Natura 2000 database, www.eea.europa.eu
Gymnocephalus_sch	Conservation status of *Gymnocephalus baloni* (fish)	conservation status according to HBD	Natura 2000 database, www.eea.europa.eu
Lutra	Conservation status of *Lutra lutra* (mammal)	conservation status according to HBD	Natura 2000 database, www.eea.europa.eu
Misgurnus	Conservation status of *Misgurnus fossilis* (fish)	conservation status according to HBD	Natura 2000 database, www.eea.europa.eu
Rhodeus	Conservation status of *Rhodeus amarus* (fish)	conservation status according to HBD	Natura 2000 database, www.eea.europa.eu
Triturus	Conservation status of *Triturus dobrogicus* (amphibian)	conservation status according to HBD	Natura 2000 database, www.eea.europa.eu
Zingel_st	Conservation status of *Zingel streber* (fish)	conservation status according to HBD	Natura 2000 database, www.eea.europa.eu
Zingel_zi	Conservation status of *Zingel zingel* (fish)	conservation status according to HBD	Natura 2000 database, www.eea.europa.eu
Haliaeetus	Population status of *Haliaeetus albicilla* (bird)	population according to HBD	Natura 2000 database, www.eea.europa.eu
Alcedo	Population status of *Alcedo atthis* (bird)	population according to HBD	Natura 2000 database, www.eea.europa.eu

Table AIII 2: Probabilities in the Bayesian Network on the P-S link (links with a probability >0.5 are shown in bold) for selected species. Causal links were calculated via bootstrapping following the approach of Friedman et al. (1999). For abbreviations see Table AIII 1.

	bank-stabilization	planform	erosion-deposition	engineering-structures	connectivity
Aspius	**0.66**	**0.70**	0.35	0.30	0.37
Bombina	0.13	**0.55**	**0.86**	**0.22**	0.57
Gymnocephalus_bal	0.34	**0.74**	**0.73**	0.32	**0.68**
Gymnocephalus_sch	0.49	**0.60**	**0.96**	**0.68**	0.43
Lutra	0.03	**0.77**	**0.76**	0.36	**0.50**
Misgurnus	0.08	**0.82**	0.25	0.38	**0.51**
Rhodeus	0.05	**0.93**	0.47	0.48	**0.54**

Triturus	0.18	**0.65**	**0.89**	0.48	**0.50**
Zingel_st	0.25	**0.73**	**0.51**	0.18	0.37
Zingel_zi	0.06	**0.83**	**0.78**	0.65	**0.55**

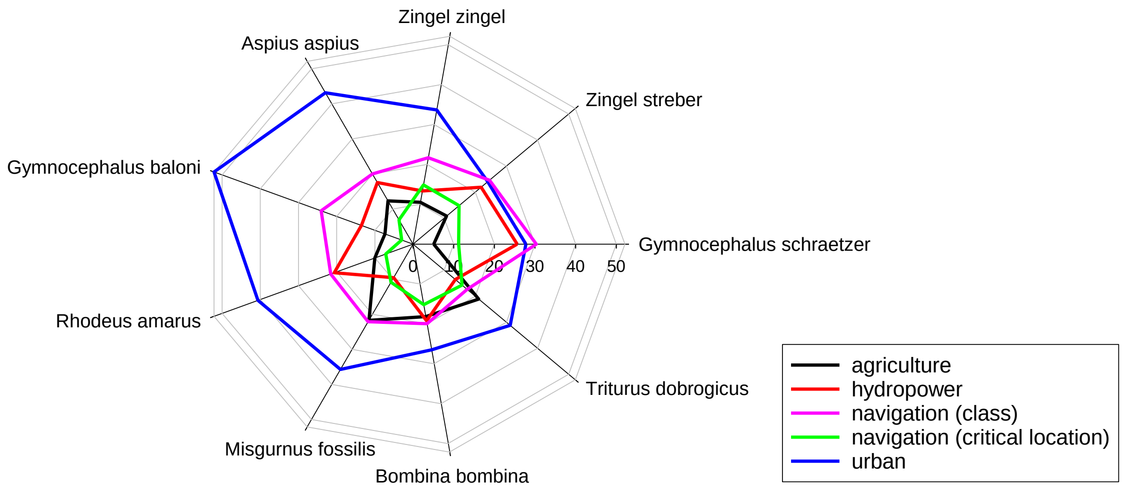
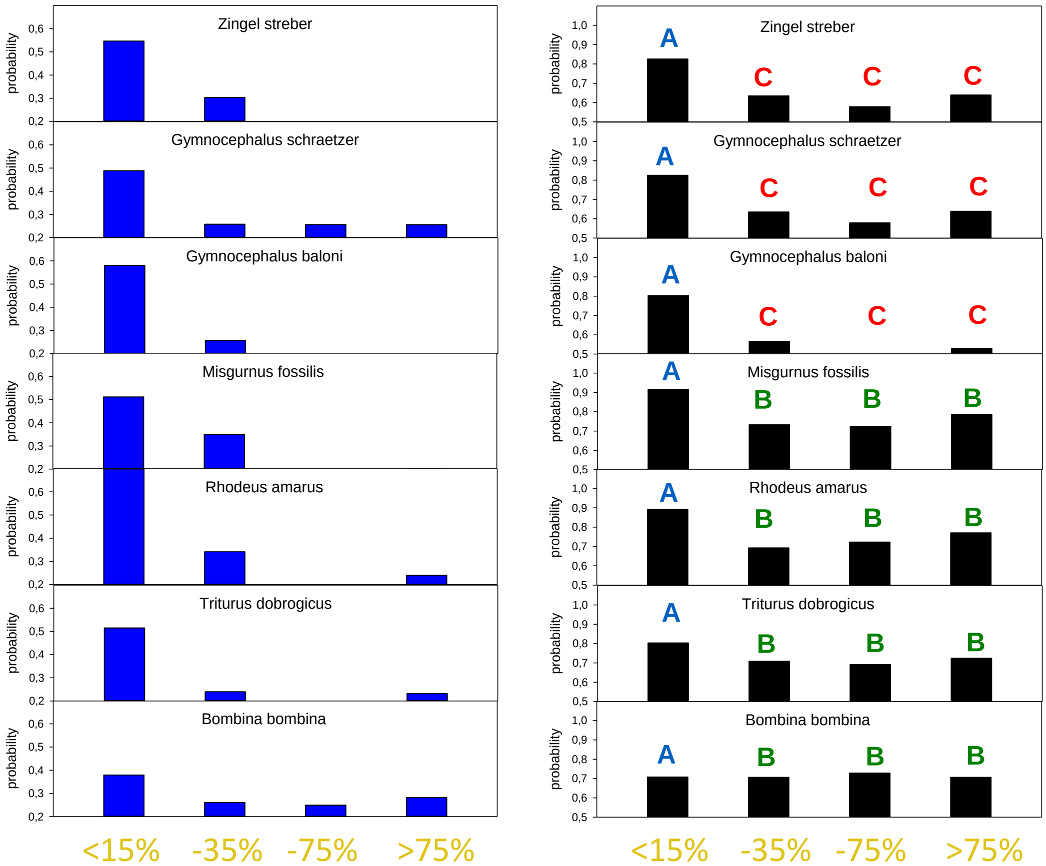


Figure AIII 1: Relative importance of drivers for the conservation status of selected species. Results of sensitivity analysis based on the boosted Bayesian networks for the D-P-S data for the selected species (see Table AIII 1).

Figure AIII 2: Conditional probabilities of the excellent conservation status (blue bars) and at least good conservation status (black bars) for selected species ranging from rheophilic (top graphs) to stagnophilic (lower graphs) species for the different levels of impact on the planform of the river (expressed in percentage of length of a stretch that has an altered planform). Capital letters mark highest probabilities for A: „excellent“, B: „good“, C: „average or reduced“ conservation status respectively.



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Identification of conservation and restoration priority areas in the Danube River based on the multi-functionality of river-floodplain systems

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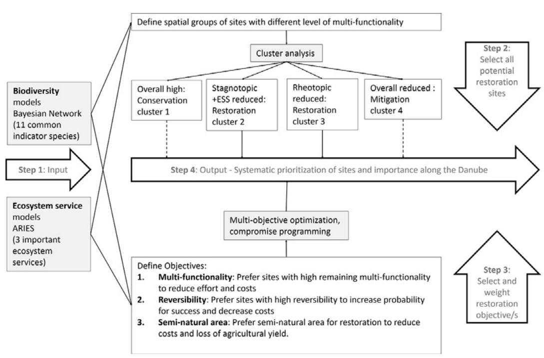
HIGHLIGHTS

- Large river-floodplains are multi-functional hotspots altered by multiple pressures.
- Restoring and conserving floodplains requires systematic planning.
- We prioritize reaches based on multi-functionality, reversibility and costs.
- Our framework can serve as a planning tool for conservation and restoration.

GRAPHICAL ABSTRACT



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ABSTRACT

Large river-floodplain systems are hotspots of biodiversity and ecosystem services but are also used for multiple human activities, making them one of the most threatened ecosystems worldwide. There is wide evidence that reconnecting river channels with their floodplains is an effective measure to increase their multi-functionality, i.e., ecological integrity, habitats for multiple species and the multiple functions and services of river-floodplain systems, although, the selection of promising sites for restoration projects can be a demanding task. In the case of the Danube River in Europe, planning and implementation of restoration projects is substantially hampered by the complexity and heterogeneity of the environmental problems, lack of data and strong differences in socio-economic conditions as well as inconsistencies in legislation related to river management. We take a quantitative approach based on best-available data to assess biodiversity using selected species and three ecosystem services (flood regulation, crop pollination, and recreation), focused on the navigable main stem of the Danube River and its floodplains. We spatially prioritize river-floodplain segments for conservation and restoration based on (1) multi-functionality related to biodiversity and ecosystem services, (2) availability of remaining

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semi-natural areas and (3) reversibility as it relates to multiple human activities (e.g. flood protection, hydropower and navigation). Our approach can thus serve as a strategic planning tool for the Danube and provide a method for similar analyses in other large river-floodplain systems.

1. Introduction

River-floodplain systems are among the most endangered ecosystems worldwide, with up to 90% of floodplains in Europe and North America strongly impaired by human activity (Tockner and Stanford, 2002). Loss of riparian and floodplain area due to agricultural encroachment or urbanization, often accompanied by pollution, are seen as the most relevant threats to their biodiversity and ecosystem services both worldwide (Vörösmarty et al., 2010) and in Europe (Schindler et al., 2014, 2016). The alteration of hydromorphological conditions due to conventional engineering works for hydropower generation, flood protection and infrastructure are additional pressures on remaining riverine habitats and biodiversity (Habersack et al., 2016).

Large river-floodplain systems are hotspots of global biodiversity (Shiel et al., 1998; Tockner and Stanford, 2002), and multiple regulating, provisioning and cultural ecosystem services (Tockner and Stanford, 2002; Tomscha et al., 2017). In addition, jointly conserving and restoring river and floodplain systems' flood retention capacity, biodiversity, and the ecological status of adjacent water bodies has become a priority in environmental and water policy in Europe (EU Flood Risk Directive, EU Biodiversity Strategy to 2020, EU Water Framework Directive respectively). Floodplains are also a key element of the EU Green Infrastructure Strategy (Schindler et al., 2014), where green infrastructure is defined as 'a network of natural and semi-natural areas that deliver a wide range of ecosystem services,' i.e., systems with high multi-functionality including provision of habitats, flood regulation or clean water (Garmendia et al., 2016; Schindler et al., 2014). Overall, natural ecosystems in general (Benayas et al., 2009; Bullock et al., 2011) and specifically floodplains (Schindler et al., 2014, 2016) show a high multi-functionality related to biodiversity and ecosystem services and well-directed ecological restoration efforts have the potential to simultaneously increase both.

Widespread evidence already shows that restoration of lateral hydrological connectivity (including removal, slotting or lowering of dykes and levees or reconnection of sidearms) can effectively reduce hydro-morphological pressures and restore multi-functionality of river-floodplain systems (Mueller et al., 2017; Paillex et al., 2009; Reckendorfer et al., 2006; Rumm et al., 2018; Schindler, et al., 2016; Straatsma et al., 2017). This includes the abandonment of intensively used agricultural land in floodplains and their conversion into natural habitats, which is widely practiced in forest restoration (Benayas et al., 2008), and is an important intervention to increase river-floodplain system multi-functionality (Schindler et al., 2014). Human stressors related to engineered structures (e.g., hydropower dams, flood regulation levees, and navigation infrastructure) restrict the potential for floodplain restoration by controlling flow and restricting natural geomorphic processes, including channel migration (Schiemer et al., 1999; Tockner et al., 1998). The selection of sites for successful conservation and restoration can thus be challenging as the knowledge required to disentangle these multiple stressors is still incomplete (Feld et al., 2016), particularly in large-river systems (De Leeuw et al., 2007). Contributing to the challenge, quantitative ecological data on floodplains are often scarce and heterogeneous, as many of the ecological status indices under the Water Framework Directive focus on the river's main stem and do not require sampling of its floodplains (Funk et al., 2017). Where it does exist, floodplain monitoring and reporting under EU Habitats and Birds Directives does not follow harmonized or optimized monitoring approaches (Borre et al., 2011; EEA, 2015a; Tsiripidis et al., 2018). In light of such data gaps, local expert knowledge is gaining importance in conservation biology and is believed to increase the quality of models for decision making (Balram et al., 2004; Drescher et al., 2013; Martin et al., 2012; Kuhnert et al., 2010).

Environmental management challenges are particularly acute for the Danube River, the longest and most international river in the EU. In the Danube's current state, deficits in the system's ecology are evident across the entire navigable stretch of the river, with a failure to achieve good ecological status or potential as defined by the Water Framework Directive (ICPDR, 2016). However, few countries within the Danube watershed have implemented or planned restoration through the year 2021. Danube watershed countries have also unevenly reported on floodplains of basin-wide importance having restoration potential (ICPDR, 2016). High restoration costs (Ebert et al., 2009), strong differences in socio-economic conditions (Domisch et al., this issue), inconsistencies in legislation among the different Danube watershed countries and the complexity of the environmental problems and the heterogeneity of drivers and pressures may hamper strategic planning and joint management efforts (Hein et al., 2016, 2018). For example, data from past restoration projects in Romania have shown that compensation costs to farmers (in terms of lost agricultural yield) can be higher than the restoration costs itself (Schwarz, 2010). By contrast, for river-floodplain areas impacted by multiple drivers, i.e., hydropower, navigation and flood regulation that have high restoration constraints (Hein et al., 2018), restoration costs can be expected to be even higher, as adaptive management may be required, which can extend over multiple decades. A more strategic and harmonized approach is required for conservation and restoration planning at the scale of large catchments (Hein et al., 2018; Seliger et al., 2016), which combines multiple data sources, including local expert knowledge as a source of best-available information and evidence (Gilliland and Laffoley, 2008). Such an approach also provides information that can enable synergies between multiple EU policies and targets towards ecosystem-based management approaches. Therefore, the core task of this study is to prioritize river-floodplain reaches of the navigable Danube for restoration and conservation by optimizing for highest multi-functionality at lowest cost and risk in failing this target. We do so by combining quantitative data for key biodiversity indicators generated using Bayesian networks and modelled ecosystem services data generated using the Artificial Intelligence for Ecosystem Services (ARIES, Villa et al., 2014) modelling platform. Finally, we applied trade-off analysis to support the identification of important areas with biodiversity and ecosystem services conservation and restoration potential, based on multi-functionality goals, reversibility, and restoration costs.

2. Methods

2.1. Study system

The Danube River Basin is the most international river basin in the world, and is shared by >80 million people from 19 countries. The Danube (Fig. 1) connects with 27 large and over 300 small tributaries on its way from the Black Forest to the Black Sea, with a catchment size of approximately 800,000 km^2. Accordingly, a huge variety of human activities and related pressures affect this area. The extent of floodplains in the Danube River Basin has been reduced by 68% (Hein et al., 2016).

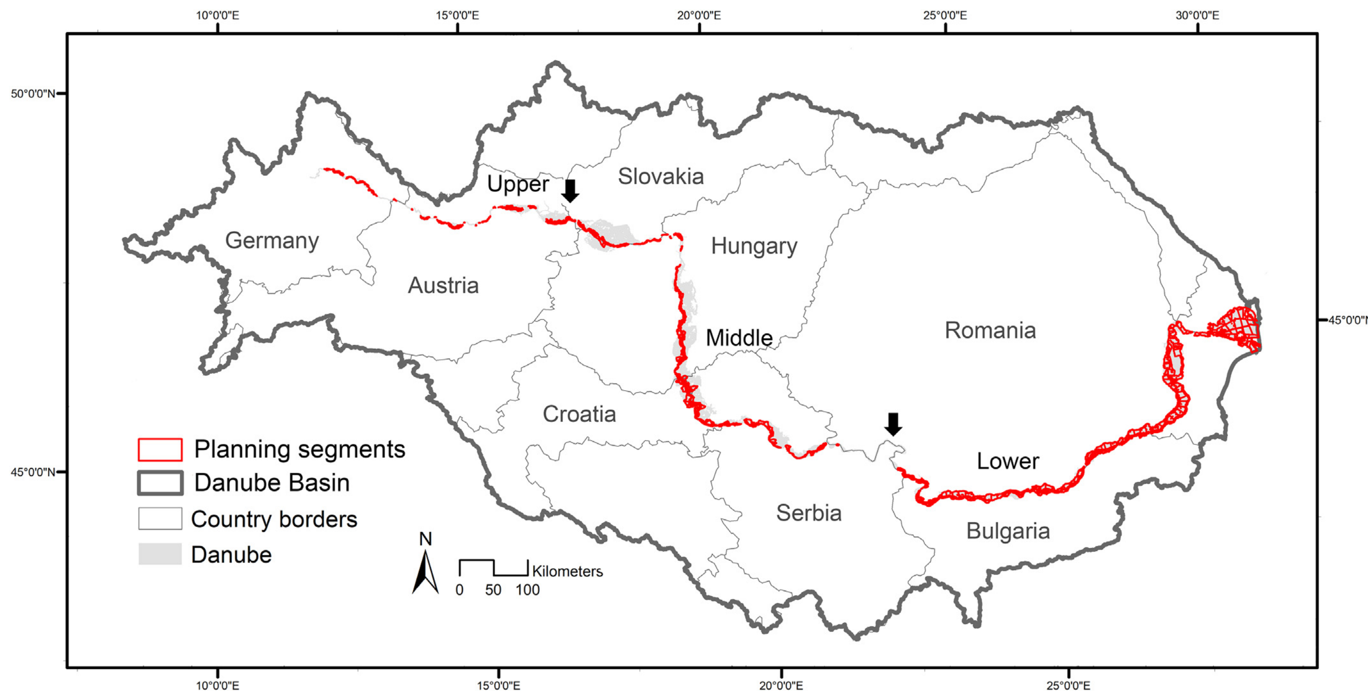

Fig. 1. Study area map showing the river-floodplain system, divided into segments based on the stretches from hydro-morphological assessment (Schwarz, 2014) along the navigable stretch of the Danube. Arrows mark borders between the three Danube Regions: Upper Danube: Germany and Austria, Middle Danube: Slovakia, Hungary, Croatia and Serbia; Lower Danube: Romania, Bulgaria and Ukraine. Gaps (grey) along the Danube show river sections where no floodplains occur due to natural causes (narrow valleys) or their complete loss from urbanization.

These floodplain losses have mainly been caused by the ongoing conversion of active floodplain and wetland areas into intensively used agricultural polders. The integrity of remaining floodplains is further threatened by hydrological disconnection due to river engineering works that provide flood control, navigation and hydropower generation (Hein et al., 2016, 2018; ICPDR, 2016).

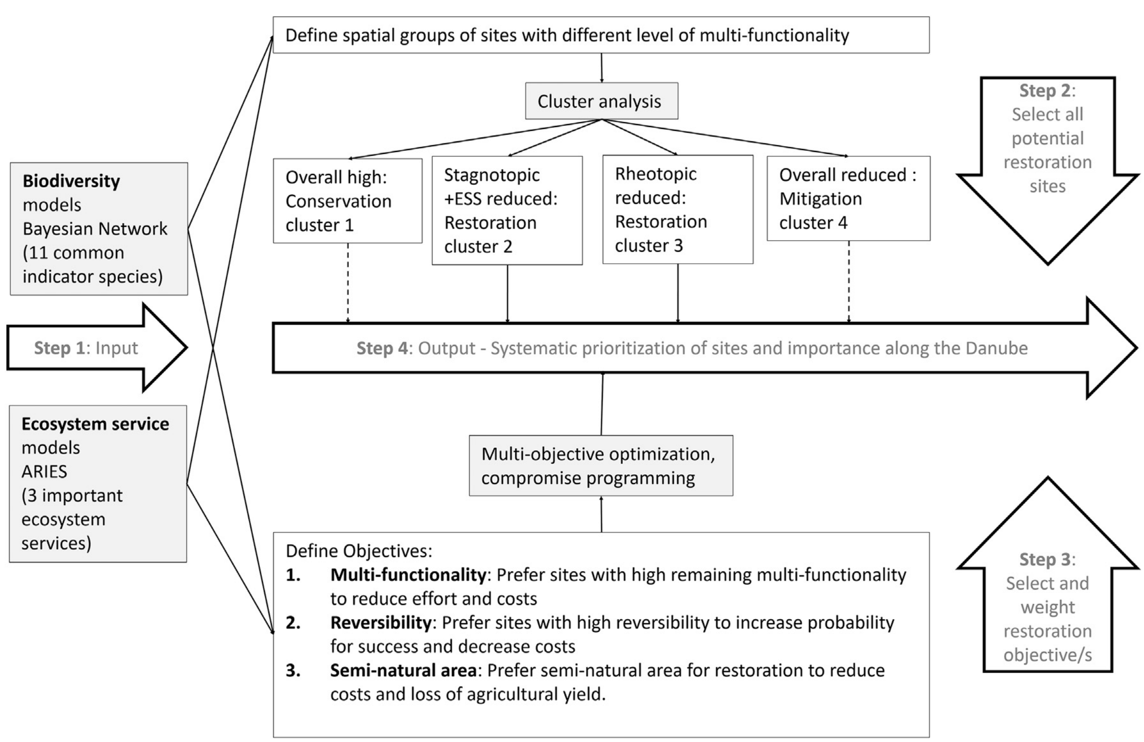

Fig. 2. Framework used for the prioritization of the river-floodplain system for conservation and restoration along the Danube. Work can be divided into four steps: Step 1: Modelling biodiversity and ecosystem service indicators as input for the optimization framework. Step 2: Clustering sites with different level of multi-functionality to select sites with conservation, restoration and reduced restoration potential (mitigation sites). Step 3: Defining and weighting objectives for restoration within scenarios and using compromise programming, to select sites with lowest distance to those objectives using a multi-objective optimization approach. Finally, in step 4, output from steps 2 and 3 is combined and results are compared along the Danube. Dashed arrows show potential additional analysis options.

2.2. Analysis framework

Our systematic prioritization approach can be divided into four steps (Fig. 2). In the first step, we generated initial input by modelling multiple indicator species to quantify biodiversity using Bayesian Networks and use the ARIES platform to quantify essential ecosystem services. In a second step, we systematically classified sites for conservation, restoration and those with a reduced restoration potential (mitigation sites) based on the remaining level of multi-functionality using cluster analysis. In a third step, we applied multi-objective optimization to support the identification of sites with the highest biodiversity and ecosystem service restoration potential for seven contrasting scenarios, based on the combinations of three main objectives relevant for restoration planning of large river-floodplain systems. These criteria include: (i) the actual level of *multi-functionality* to prioritize sites with high remaining value to reduce effort and costs, (ii) *reversibility*, expressed as the potential to successfully restore multi-functionality related to multiple drivers, and (iii) the availability of remaining *semi-natural area* versus agricultural land, which reduces restoration costs and losses of agricultural yield. In a final step, we combined multiple outputs from steps 2 and 3 to compare the importance of different conservation and restoration scenarios along the Danube and conducted a gap analysis.

2.3. Model input development (step 1)

2.3.1. Biodiversity models – Bayesian Networks

We used Bayesian network models to quantify biodiversity along the Danube. Models are based on open-access data quantifying drivers, pressures and biodiversity status in the system (Table 1). Land use was quantified using Copernicus land use/land cover data obtained from the European riparian zones dataset developed by the local component of Copernicus Land Monitoring Services (land.copernicus.eu, resolution of 20 m, 2011–2013, EEA, 2015b). Riparian zone extents were laterally delineated using the Potential Riparian Zones dataset (EEA, 2015b). For navigation, we included information on "critical locations" which are river stretches where the recommended fairway depth (depth of the channel that is required for navigation) of 2.5 m at Low Navigable Water Level (LNWL) was not achieved (Fairway and Danube, 2014; Fairway, 2016). We also incorporated information on navigation class according to the "Classification of European Inland Waterways" created by the European Conference of Ministers of Transport, which relates to the carriage of intermodal containers in convoys of barges (Economic Commission for Europe, 2012). Reservoir length (Table 1) of hydropower plants is also incorporated in the model. It was collected during the hydro-morphological assessment for the Joint Danube Survey 2 of the ICPDR (https://danubis.icpdr.org/). Further, to quantify hydro-morphological pressure, an assessment of hydro-morphological alterations is available for the navigable stretch of the Danube River. This was conducted in 2013 by integrating information on engineering structures and floodplains with adjacent land use, navigation, hydrological and morphological background data, using consistently collected field reports along the whole navigable stretch of the Danube River and following the European-wide guiding standard (CEN standard) supporting Water Framework Directive approaches (ICPDR, 2015; Schwarz, 2014). It consists of a semi-quantitative assessment based on 10 km river reaches, and includes ten assessment parameters of which six (Table 1) are included in our modelling approach. Finally, conservation status and population size of widely distributed protected species are included as biodiversity indicators. Natura 2000 sites information is collected from local experts and synthesized in a pan-European database by the European Environment Agency (EEA) (https://www.eea.europa.eu/data-and-maps/data/natura-9, database information from 2016 was used, Appendix, Fig. A.1). This European dataset is already widely used for conservation and management planning (e.g., Cortina and Boggia, 2014; Hermoso et al., 2018). We extracted information on the conservation status or population size of protected species collected for Habitats and Birds Directive for 121 sites along the navigable stretch of the Danube River. We included only widely distributed species with adequate representation in the database (represented in at least 60% of the sites situated along the Danube) to guarantee broad representativeness along the whole study area and statistical confidence. Large-scale studies provide wide evidence that common species are in general good indicators for biodiversity including the richness of rare species (Lennon et al., 2004; Mazaris et al., 2010; Pearman and Weber, 2007) and also ecosystem service delivery (Winfree et al., 2015). Additionally only species sensitive to hydro-morphological pressure variables (significant correlation, see Appendix, Table A.1) were selected for the modelling approach (Table 1).We also tested protected riparian and aquatic habitats data collected for Habitats and Birds Directive, but found no significant correlations with hydro-morphological pressure variables (Appendix, Table A.1). However, several of the included animal species are also indicative for naturalness of the terrestrial habitat and floodplain forests (Table 1). Overall, using this selection strategy, we can included eleven species from a variety of taxonomic groups (fish, amphibian, birds and mammals) and functional ranges (Table 1).

We split all geographical and associated tabular data and compiled them in ArcGIS 10.3 at the spatial scale of the hydro-morphological assessment (10 km river reaches see Schwarz, 2014, Fig. 1). We used these data for analysis of the relationships within and between multiple drivers and pressure ($N = 395$) and at the spatial scale of the Natura 2000 sites for the analysis of the relationships within and between pressure and biodiversity status variables (for N see Table 1).

We use Bayesian Networks for the analysis of biodiversity indicators, as they are highly suitable for the analysis of discrete data, they provide a visual depiction of the causal linkages between multiple environmental drivers, pressures and states, making it easy to interpret multiple interactions between variables included in the models (Death et al., 2015; Friedman et al., 1999; Milns et al., 2010; Mori and Saitoh, 2014). They explicitly account for uncertainty (Uusitalo, 2007) and can be used with small and incomplete datasets. We conducted Bayesian Network analyses using a completely data-driven approach within the R package "bnlearn" (Scutari, 2010). In a first step we analysed the causal relationships between multiple drivers and pressures (comprehensive driver-pressure dataset), creating a causal driver-pressure network. In a second step we linked the status indicators into this driver-pressure

Notes to Table 1:

[1] Vines et al., 2003.
[2] Gollmann et al., 1988.
[3] Ficetola and De Bernardi, 2004.
[4] Kolozsvary and Swihart, 1999.
[5] Schiemer and Waidbacher, 1998.
[6] Guti, 1996.
[7] Schiemer and Spindler, 1989.
[8] Kottelat and Freyhof, 2007.
[9] Prenda et al., 2001.
[10] Drozd et al., 2009.
[11] Oldham et al., 2000.
[12] Probst and Gaborik, 2011.
[13] Heneberg, 2013.

network based on the pressure-biodiversity status dataset and created driver-pressure-biodiversity status networks for each of the 11 conservation target species focusing on each network's predictive performance. Finally, we evaluated the predictive performance of all networks using cross validation and fit the final Bayesian Networks based on the available datasets.

The causal structure of the driver-pressure network was learned using a score-based structural learning algorithm. We selected this method as our data set is relatively small and constraint-based algorithms are known to require very large datasets to obtain adequate performance. We use a bootstrapping approach to estimate the importance of the possible links in the network and give a certainty value to

Table 1
Data description and classes/discretization for drivers (D), pressures (P) and biodiversity status (S) indicator variables used in Bayesian Network models.

Code	Description of indicator	Discretisation	Network (N - size of dataset)
Driver			
urban	Percentage of the potential floodplain area covered by urban structures	1/2/3/4: ≤1/1-3.8/3.8-10.4/>10.4 % coverage in the potential floodplain area	D-P and D-P-S
agriculture	Percentage of the potential floodplain area covered by agricultural land	1/2/3/4: <6.6/6.6-22.6/22.6-44.7/>44.7 % coverage in the potential floodplain area	D-P and D-P-S
navigation1	Navigation class according to the "Classification of European Inland Waterways"	2/3/4/5: navigation class VIa, VIb, VIc, VII	D-P and D-P-S
navigation2	Critical locations for inland navigation where the fairway depth of 2.5 m at Low Navigable Water Level was not achieved	0/1: river stretch contains critical locations or not	D-P and D-P-S
hydropower	River stretch is situated within the reservoir area upstream of a hydropower plant	0/1: river stretch is situated within reservoir area or not	D-P and D-P-S
Pressure			
bankstabilization	Extent of reach affected by artificial bank material (% of bank length)	1/2/3/4/5: high/good/moderate/poor/bad (see Schwarz, 2014)	D-P and D-P-S
planform	Planform of the River channel The planform describes the view of a river from above, showing for example the sidearms of a braided river.	2/3/4: good/moderate/poor or bad (see Schwarz, 2014)	D-P and D-P-S
erosiondeposition	Erosion/deposition character	1/3/5: high/moderate/bad (see Schwarz, 2014)	D-P and D-P-S
engineeringstructures	Impacts of artificial in-channel structures within the reach (impoundments, groynes)	1/3/5: high/moderate/bad (see Schwarz, 2014)	D-P and D-P-S
flooding	Degree of lateral connectivity of the river and the floodplain (Extent of floodplain not allowed to flood regularly, owing to engineering)	2/3/4/5: good/moderate/poor/bad (see Schwarz, 2014)	D-P and D-P-S
connectivity	Degree of lateral movement of the river channel	2/3/4/5: good/moderate/poor/bad (see Schwarz, 2014)	D-P and D-P-S
Biodiversity state			
Bombina	Conservation status of *Bombina sp.* (amphibian) Indicator for fish-free seasonal, pond like, sun-exposed waterbodies[1,2] and the availability of natural terrestrial habitats (woodland)[3,4]	1/2/3: excellent/good/average or reduced conservation status according to EU Habitats Directive	D-P-S (62)
Gym_bal	Conservation status of *Gymnocephalus baloni* (fish) Rheophilic species inhabiting the main stem and connected sidearms of large rivers[5], serving as an indicator for lateral connectivity as it migrates from main stems to river backwaters to spawn.[8]	1/2/3: excellent/good/average or reduced conservation status according to EU Habitats Directive	D-P-S (43)
Gym_sch	Conservation status of *Gymnocephalus schraetzer* (fish) Rheophilic species that serves as an indicator for the status of the main stem of large rivers[5,8]. It prefers sandy and muddy substrate[5]and spawns on gravel in inshore zones of the river[5]	1/2/3: excellent/good/average or reduced conservation status according to EU Habitats Directive	D-P-S (45)
Lutra	Conservation status of *Lutra lutra* (mammal) The species is a good indicator for overall natural habitat conditions including high natural bank vegetation, low human disturbance and surrounding natural forests.[9]	1/2/3: excellent/good/average or reduced conservation status according to EU Habitats Directive	D-P-S (53)
Misgurnus	Conservation status of *Misgurnus fossilis* (fish) Stagnophilic species that prefers stagnant sidearms with soft and muddy substrate and high macrophyte cover, spawning in dense flooded vegetation. The species is an indicator for the availability of natural stagnantbackwaters.[10]	1/2/3: excellent/good/average or reduced conservation status according to EU Habitats Directive	D-P-S (42)
Rhodeus	Conservation status of *Rhodeus amarus* (fish) Stagnophilic species[5] serving as an indicator for isolated to partially connected backwaters and their connectance[6,7]	1/2/3: excellent/good/average or reduced conservation status according to EU Habitats Directive	D-P-S (48)
Triturus	Conservation status of *Triturus dobrogicus* (amphibian) Indicator for temporary, macrophyte-rich, sun-exposed water bodies[11] and the availability of natural terrestrial habitats (woodland)[3,4]	1/2/3: excellent/good/average or reduced conservation status according to EU Habitats Directive	D-P-S (46)
Zin_str	Conservation status of *Zingel streber* (fish) Rheophilic species serving as an indicator for the status of the main stem of small to large rivers[5,8]. It prefers gravel substrate[5] and fast-flowing water[8], spawning in inshore zones of the river on gravel[5]	1/2/3: excellent/good/average or reduced conservation status according to EU Habitats Directive	D-P-S (41)
Zin_zin	Conservation status of *Zingel zingel* (fish) Rheophilic species inhabiting the main stem of large rivers[5,8], spawning on sand often in connected sidearms**5**It is an indicator for the status of the main stem of large rivers and availability of connected side-arms.	1/2/3: excellent/good/average or reduced conservation status according to EU Habitats Directive	D-P-S (46)
Haliaeetus	Population of *Haliaeetus albicilla* (bird) The species requires large open-water bodies for feeding near tall forest stands, mainly floodplain forest, which it uses for nesting. It is indicative of large undisturbed wetlands and floodplain forest as is it sensitive to disturbance.[12]	1/2/3: >3/1-3/<1 individuals per stretch	D-P-S (39)
Alcedo	Population of *Alcedo atthis* (bird) The species nests in vertical river banks, making it an indicator for active erosion and natural substrate along river banks[13]	1/2/3: >9/4-9/<4 individuals per stretch	D-P-S (32)

potential arcs and nodes using the approach of Friedman et al. (1999). Therefore, we used a BDe (Bayesian Dirichlet equivalent) score with a uniform prior distribution and equivalent sample size of five. This search procedure is used in hill-climbing search with random restarts. We conducted 1000 non-parametric bootstraps in the procedure using the "boot.strength" function from the package "bnlearn" for R (Scutari, 2010), which calculates the probability of each arc in the network based on its empirical frequency over a set of networks learned from bootstrap samples. Model averaging was used to build a driver-pressure network containing only the relevant arcs using the "averaged.network" function. Direction of arcs was restricted to go from drivers to pressures. Finally the procedure was repeated for all pressure and biodiversity status datasets for each species to determine most probable arcs between pressures and the respective species data.

The resulting structure of the driver-pressure network and pressure-biodiversity status networks were integrated into driver-pressure-biodiversity Bayesian networks for each species.

All driver-pressure-biodiversity status networks were validated with 10-fold cross-validation using driver-pressure-biodiversity data within the "bn.cv" function. Data were split into10 subsamples; for each subset a Bayesian Network is fitted on the other k - 1 subsets and posterior classification error is calculated for that subset (percent error is then computed, including all relevant nodes in the network). We ran cross-validation 50 times to get a representative value for the models' predictive performance. As final models, we retained the model structure with the best predictive performance for each species. Those were informed using the function "bn.fit" from the same R package. The network structure and conditional probability tables (CPTs, probabilities of the outcome for each possible combination of input values) related to drivers and pressures were thus informed by driver-pressure data, and CPTs related to species status variables were informed by pressure-biodiversity status data (see Pollino et al., 2007).

Final Bayesian Networks were used to estimate conditional probabilities (CP, probabilities predicted from the variables in the network) for each status class for all river segments. For the aggregation of the calculated probabilities into one status index (SI) per species, we used the following formula (compare Cortina and Boggia, 2014):

$$\mathrm{SI} = \mathrm{CP}(\text{"excellent conservation status"}) * 2. \\ +\mathrm{CP}(\text{"good conservation status"}) * 1$$

2.3.2. Ecosystem service modelling and aggregation

To represent a range of different ecosystem services, we included one of the most important provisioning, cultural and regulating ecosystem services for river-floodplain systems respectively, following the Common International Classification of Ecosystem Services (Haines-Young and Potschin, 2012): pollination, recreation, and flood regulation. Pollination is a further essential ecosystem service in the agricultural-dominated landscape, as it increases the yield and quality of 70% of globally important crops (Klein et al., 2007). Riparian areas and lake and river boundaries represent especially important nesting and foraging sites for many native pollinators given the abundance of floral resources they provide and their proximity to water bodies, making them important ovipositing sites (Resh and Cardé, 2009). Areas with low human influence, and specifically water bodies, exert a strong attraction for recreational purposes (Paracchini et al., 2014). Flood regulation is an important ecosystem service of floodplain systems, and direct links to the restoration of river and floodplain systems' flood retention capacity (Heintz et al., 2012).

The ARIES platform was used for assessing those three ecosystem services. ARIES is an open-source technology capable of selecting and running models to quantify and map all aspects of ecosystem service provision, including their biophysical generation, flow and extraction by sinks and beneficiaries (Villa et al., 2014).

The ARIES pollination model first calculates pollination supply, the suitability of the environment to support wild insect pollinators based on nesting suitability and floral availability (Zulian et al., 2014; Lonsdorf et al., 2009). The model also accounts for the positive effect of water bodies (streams and lakes) on the probability of pollinator presence based on inverse weighted distance, as well as the effect of ambient temperature and solar radiation on pollinator activity (Corbet et al., 1993). We estimated pollination demand based on the weighted sum of crop pollination dependencies (Klein et al., 2007), multiplied by their production for 55 crop types requiring insect pollination to increase their production (Monfreda et al., 2008).

The recreation model is inspired by the ESTIMAP model of nature-based outdoor recreation developed by Paracchini et al. (2014). Recreation supply is calculated as an additive function of naturalness based on land cover type and the Euclidean distance to nature-based factors of attractiveness (e.g., distance to protected areas, water bodies, or mountain peaks). Recreation demand takes into account the likelihood of taking a day trip to a certain location and the population defining the "catchment area" of that location.

The flood regulation model identifies areas providing greater flood regulation as those with higher flood hazard probability (based on topographic wetness index (Kirkby and Beven, 1979), mean annual precipitation, and mean temperature of the wettest season) and water retention by soils and vegetation, based on the Curve Number (CN) method (Chapman, 1985; Ferrer-Juliá, 2003). Demand for flood regulation is calculated using population density and flood hazard probability data.

A full description of all ecosystem service models and data sources can be found in this issue (Martínez-López et al., 2019a).

Finally, data for ecosystem services were normalized (from 0 to 1) and aggregated as the mean value across the potential area remaining for restoration for each river-floodplain segment using ArcGIS10.3.

2.4. Define clusters of multi-functionality (step 2)

We used cluster analysis to identify groups of river-floodplain reaches with homogenous sets of species (SI per species) and levels of ecosystem service provision (mean per segment). We identified and analysed clusters in the data using K-means cluster analysis (Raudsepp-Hearne et al., 2010), using Scree plots to determine an appropriate number of clusters. To stabilize the clusters, we set the number of iterations in the K-means procedure at 100 to ensure a global minimum of variance. Then, we mapped the clusters in ArcGIS10.3 (ESRI) to visualize their spatial pattern.

2.5. Restoration objectives and multi-objective optimization (step 3)

Next, we applied compromise programming, a multi-objective optimization approach (Malczewski, 1999), to identify the most relevant areas for biodiversity and ecosystem service restoration within different compromise scenarios related to three river-floodplain restoration objectives:

(1) Multi-functionality (e.g., Schindler et al., 2014, 2016): Natural floodplains provide habitat for various aquatic species and provide multiple ecosystem services. Restoration aims to re-establish these multiple functions. Sites with high remaining multi-functionality are priorities for restoration, as their protection will have lower effort and costs than areas requiring active restoration. We calculated multi-functionality by summing the aggregated species SI predicted and mean modelled ecosystem service provision per reach.

(2) Reversibility (e.g., Schiemer et al., 1999; Tockner et al., 1998): River-floodplain systems are impacted by a multitude of human activities that constrain their reversibility to natural conditions. This impact and interaction of multiple drivers affects the

potential to restore multi-functionality. Sites with high reversibility are priorities for restoration, as they are likely to have lower costs and greater probability of success than sites with low reversibility. We calculated reversibility by summing the aggregated species SI predicted based on drivers only.

(3) Semi-natural area (e.g., Benayas et al., 2009; Schindler et al., 2014): River-floodplain restoration is often restricted by the availability of natural and semi-natural areas that remain in the floodplain. Abandonment of agricultural polders for restoration and conversion into naturally vegetated land is associated with costs for purchase or future compensation to farmers and may decrease an area's agricultural yield. Semi-natural areas are priorities for restoration, in order to reduce costs and loss of agricultural yield. We calculated semi-natural area as the percentage of land in semi-natural conditions (excluding agricultural areas) from the total area that is directly adjacent to the river and therefore potentially available for restoration (excluding any type of urbanised area or infrastructure), using ArcGIS 10.3 (Fig. 2).

We used these three criteria within compromise programming methodology (Malczewski, 1999) to analyse the best compromise solution for spatial prioritization of restoration. The method is based on the distance from an ideal point (a theoretical optimal point, e.g., 100% multi-functionality or 100% semi-natural area), which is calculated as:

$$D_s = \left\{ \sum_{j=1}^{n} W_j \times \left[\frac{v_{ip,j} - v_{ns,j}}{v_{ip,j} - v_{nip,j}} \right]^m \right\}^{1/m}$$

where Ds is the distance from ideal point in scenario s; n is the number of criteria (j); $v_{ip,j}$ is the ideal value for the j_{th} criterion, $v_{ns,j}$ is the actual value of the j_{th} criterion in scenario s, $v_{nip,j}$ is the negative-ideal (worst possible) value for the j_{th} criterion and m is the metric which is used in the analysis. Metric parameter m can be quantified from 1 to ∞, ranging from a total compensatory to total non-compensatory approach, respectively. We used a metric value $m = 2$, which is equivalent to the Euclidean distance and represents a partial compensatory methodology.

We compared seven weighted compromise scenarios (Table 2), ranging from a scenario with river river-floodplain reaches only prioritized based on the availability of semi-natural areas to one with river-floodplain reaches prioritized based on the reversibility to natural conditions only, and analysing different compromises sequentially including all three criteria (multi-functionality, reversibility and semi-natural area).

2.6. Comparison of restoration scenarios and gap analysis (step 4)

To show the importance of the different compromise scenarios along the Danube, we summarized results for the Upper, Middle and Lower section of the Danube. We conducted a gap analysis to compare proposed clusters for conservation, restoration and mitigation with existing conservation sites. To do this, we overlaid polygons representing the boundaries of Natura 2000 sites with river segments identified for conservation, restoration, and mitigation in our analysis. We conducted this overlay in ArcGIS and calculated the percentage match of the existing and calculated areas.

3. Results

3.1. Model input development (step 1)

The architecture of the final driver-pressure Bayesian network (Fig. 3) shows multiple links between the different drivers and pressures. The impact of hydropower reservoirs (hydropower) has multiple links in the network. In reservoirs (variable hydropower), the waterway has less critical locations (variable navigation2) and a higher navigation class (variable navigation1). In reservoirs (variable hydropower) main stem and banks are altered by engineering structures (variables engineeringstructures and bankstabilization) and the planform of the river (variable planform) is significantly altered. Hydropower plants (hydropower) further strongly alter the erosion/deposition pattern (variable erosiondeposition) of the river. Close to urban areas and infrastructure (variable urban) the river is significantly impacted by bankstabilization (variable bankstabilization) measures. Engineering works in the main stem (variable engineeringstructures) and along the banks (variable bankstabilization) related to navigation (variable navigation1, 2) significantly alters the planform of the river (variable planform) as well as erosion/deposition pattern (variable erosiondeposition). Disconnection of floodplains (variable connectivity) is impacted by bankstabilization measures (variable bankstabilization) as well as flood regulation measures (variable flood) and is linked to all drivers in the model including agriculture in the riparian area (variable agriculture).

Looking at the other final Bayesian networks, including biodiversity status, it is evident that the architecture (Table 3, Appendix, Fig. A.2) and conditional probabilities (Appendix, Table A.2) vary across species indicators. Typical floodplain species (e.g., *Rhodeus amarus*, *Misgurnus fossilis*) showed stronger relationships to floodplain connectivity than typical river species (e.g., *Gymnocephalus schraetzer*, *Zingel streber*), which showed higher predictive performance in networks that included only variables related to the main stem of the river. As shown by the architecture of the different networks, changes in those variables that are directly or closely linked to the species node have the highest impact on the predicted probabilities per species. Conversely, nodes that are more distant have lower impact (Appendix, Table A.2).

Ten-fold cross validation (Table 3) of final driver-pressure-biodiversity status models shows good to moderate performance across species (Table 3), with comparable performance to similar studies (Death et al., 2015).

3.2. Define clusters of multi-functionality (step 2)

The cluster analysis identified four clusters with different levels of multi-functionality among reaches of the Danube River (Fig. 4). Cluster 1 identifies the most intact river-floodplain reaches, which shared high multi-functionality across species and ecosystem services. Therefore, this cluster can be defined as having the highest conservation potential. Flood regulation is the only ecosystem service with reduced provision in cluster one, as many reaches in this cluster are situated along the Lower Danube, where most of the floodplain area is used for agriculture, which have relatively low flood regulation capacity compared to forested riparian areas. Clusters 2 and 3 show bundles of river-floodplain reaches with either high remaining potential for only the rheotopic/river community, amphibians and recreation, or high remaining potential for the stagnotopic/floodplain community and all three ecosystem services, respectively (Fig. 4). These two clusters are therefore defined as having restoration potential of varying types. For cluster 2, this would entail restoration of stagnant water bodies and riparian habitats for stagnophilic species and ecosystem service supply, including abandonment of agricultural polders, while cluster 3would require restoration of the dynamic water bodies including reconnection of sidearms or removal of artificial bank material. Cluster 4 has reduced biodiversity potential across all species but high potential, with restoration, for increased flood regulation. We define this cluster as having potential for mitigation measures related to flood regulation. Most of the sites in this class have high hydromorphological constraints (e.g., river embankments, dykes or levees) due to navigation, hydropower and urbanization but remaining floodplain areas, often covered by floodplain forests, have high remaining flood regulation capacity or also capacity to maintain habitat for particular indicator species if considered for restoration.

3.3. Restoration objectives and multi-objective optimization (step 3)

The input variables related to the three objectives for the multi-objective optimization approach—multi-functionality, reversibility and semi-natural area—show clear patterns along the Danube. Areas with high remaining multi-functionality (Fig. 5a), having lowest distance to the ideal point, are mainly found along the Lower Danube followed by the Middle and Upper Danube. Near-natural area is found in large areas along the Upper and Middle Danube, but limited extents are found along the Lower Danube, and show a relatively low distance to the ideal point of 100% coverage with semi-natural area (Fig. 5b). Stretches with high reversibility are mainly found in the Lower Danube and a few sites in the Middle Danube (Fig. 5c). Accordingly, compromise programming results (Appendix, Fig. A.3) for the seven scenarios show a clear trade-off between the availability of semi-natural land for restoration and reversibility for restoration related to multiple drivers for the multi-functionality cluster described in step 4. The three criteria also show clear differences in the total distance to target. Coverage of semi-natural area ranges from 0 to 100% along the Danube, whereas distance to target related to multi-functionality and reversibility is never lower than 25%. This reflects the high level of alteration along the Danube, where even sites with the most natural conditions do not currently achieve full multi-functionality.

3.4. Comparison of restoration scenarios and gap analysis (step 4)

The seven compromise scenarios enable the systematic identification of the most promising areas for restoration, which can include the three criteria independently or in combination with different weightings (Table 2). Together with the cluster analysis results, segments of clusters 2 (rheotopic/river and recreation) and 3 (stagnotopic/floodplain species and multiple ecosystem services) with restoration potential are systematically prioritized (Appendix, Fig. A.3). As an example of the application of the approach, we compared results across regions (Fig. 6a). Along the Upper Danube, segments with restoration potential (clusters 2 and 3) are generally scarce, and the reversibility criterion further reduces the number of segments that are prioritized for restoration. Based on the semi-natural area criterion, many of the reaches with restoration potential along the Middle Danube have the lowest distance to the target, whereas based on reversibility alone potential reaches along the Lower Danube have lowest distance to target. Across the different compromise scenarios, the trend changes continuously by region, being most balanced across the Middle and Lower Danube for scenario 4. There are also numerous sites that are prioritized in the Middle and Lower Danube region that have relatively low distance to target across all scenarios.

Additionally we compared the compromise programming results across all scenarios for the two restoration clusters—clusters 2 and 3 (Fig. 6b). In the scenario that optimizes for semi-natural area only and the compromises 1 to 3, river segments of cluster 2 are scarcely represented. From compromise 4 to the scenario that optimizes for reversibility only, cluster 2 sites are represented more in greater balance with those selected in cluster 3.

Our gap analysis showed that already a very high proportion (about 80%) of the area in clusters 1 and 3 is already part of the Natura 2000 protected area network. Our high multi-functionality/conservation cluster and high multi-functionality/high restoration potential for stagnotopic species and ecosystem services cluster are already widely protected in Natura 2000 sites. Many of the river-floodplain systems identified in this cluster are part of well-known national parks like Nationalpark Donauauen in the Upper Danube, Kopački rit in the Middle Danube or Persina in the Lower Danube. For both clusters 2 and 4, about 50% of their area is protected under Natura 2000. River segments of these clusters have relatively high coverage of agricultural land, which in many cases is excluded from protected areas.

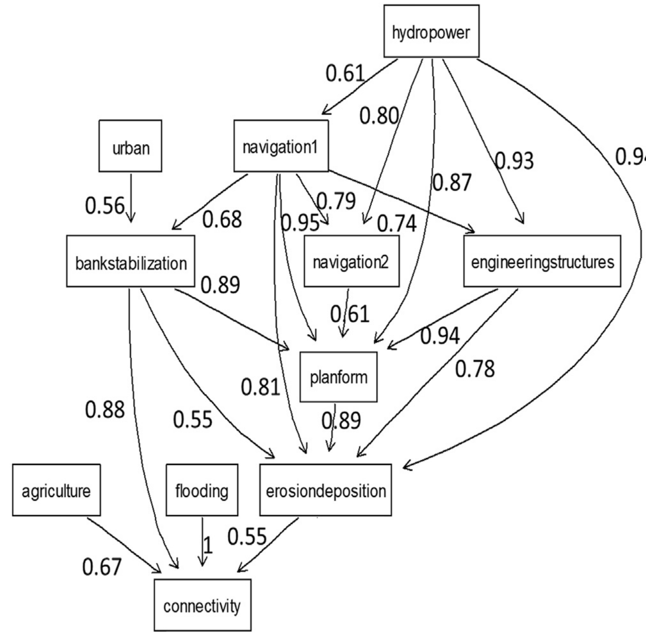

Fig. 3. Driver-Pressure Bayesian network, results from boosting the causal structure of the network. Numbers are the calculated probabilities of arcs. For description of codes, see Table 1.

Table 2
Weights for the compromise programming of the different scenarios.

Scenario	Multi-functionality	Semi-natural area	Reversibility
Seminatural	0	1	0
Compromise 1	0.5	0.5	0
Compromise 2	0.4	0.4	0.2
Compromise 3	0.33	0.33	0.33
Compromise 4	0.4	0.2	0.4
Compromise 5	0.5	0	0.5
Reversibility	0	0	1

4. Discussion

4.1. Strength of biodiversity models

Our approach of learning Bayesian networks for driver and pressure data to identify their structure successfully depicts multiple causal relationships in ways that generally agree with existing knowledge, demonstrating model sensitivity and validity as follows. For example, hydropower supports the navigability of the river, as in the deep and relatively wide reservoir reaches, no obstacles to navigation are present (Habersack et al., 2016). In these reservoirs, associated engineering structures significantly alter the system, substantially altering patterns of erosion and deposition as well as river planform (Graf, 2006; Habersack et al., 2016; Hein et al., 2016). Floodplain agriculture combined with related flood-protection measures (creation of agricultural polders) has led to a substantial reduction in floodplain areas hydrologically connected to the river (Hein et al., 2016; ICPDR, 2016).

Local expert judgment compiled within the database of the Natura 2000 network of protected areas proved to be a highly relevant source to predict habitat availability for multiple species across taxonomic and functional groups; this is critical in evaluating the multi-functionality of remaining river-floodplain systems. This matches the findings of other studies, as this dataset is already widely used for conservation and management planning (e.g., Cortina and Boggia, 2014; Hermoso et al., 2018). The results of our models matched basic knowledge on the habitat preferences of the selected species. These ranged from stagnophilic and rheophilic fish species (Schiemer and Waidbacher, 1998), to species dependent on active erosion like the European

Table 3
Structure and cross-validation results of the final selected Bayesian Networks for the conservation status of protected species (see also Appendix, Fig. A.2 for network structure).

Species code	Link to driver-pressure network	Included in network	Mean posterior classification error from 10-fold cross-validation
Alcedo	Erosion/deposition	All drivers and pressures	0.32 (±0.072)
Bombina	Erosion/deposition	All drivers and pressures	0.26 (±0.047)
Gym_bal	Erosion/deposition	All drivers and pressures	0.23 (±0.057)
Gym_sch	Erosion/deposition	Excluding agriculture, connectivity and flood	0.27 (±0.055)
Haliaeetus	Connectivity	All drivers and pressures	0.24 (±0.072)
Lutra	Erosion/deposition	All drivers and pressures	0.30 (±0.048)
Misgurnus	Connectivity	All drivers and pressures	0.25 (±0.056)
Rhodeus	Connectivity	All drivers and pressures	0.21 (±0.069)
Triturus	Erosion/deposition	All drivers and pressures	0.25 (±0.058)
Zin_str	Erosion/deposition	Excluding agriculture, connectivity and flood	0.21 (±0.075)
Zin_zin	Erosion/deposition	Excluding agriculture, connectivity and flood	0.29 (±0.057)

kingfisher (*Alcedo atthis*), which uses vertical river banks created by natural erosion (Heneberg, 2013) to amphibians, for whom active erosion increases the availability of small sun-exposed waterbodies preferred as spawning habitat (Tockner et al., 2003). We have also included species indicative for the status of riparian habitats like amphibians and the white-tailed eagle (*Haeliaeetus albicilla*, Table 1). However, not directly including riparian species as indicators may underestimate the biodiversity of the riparian habitats.

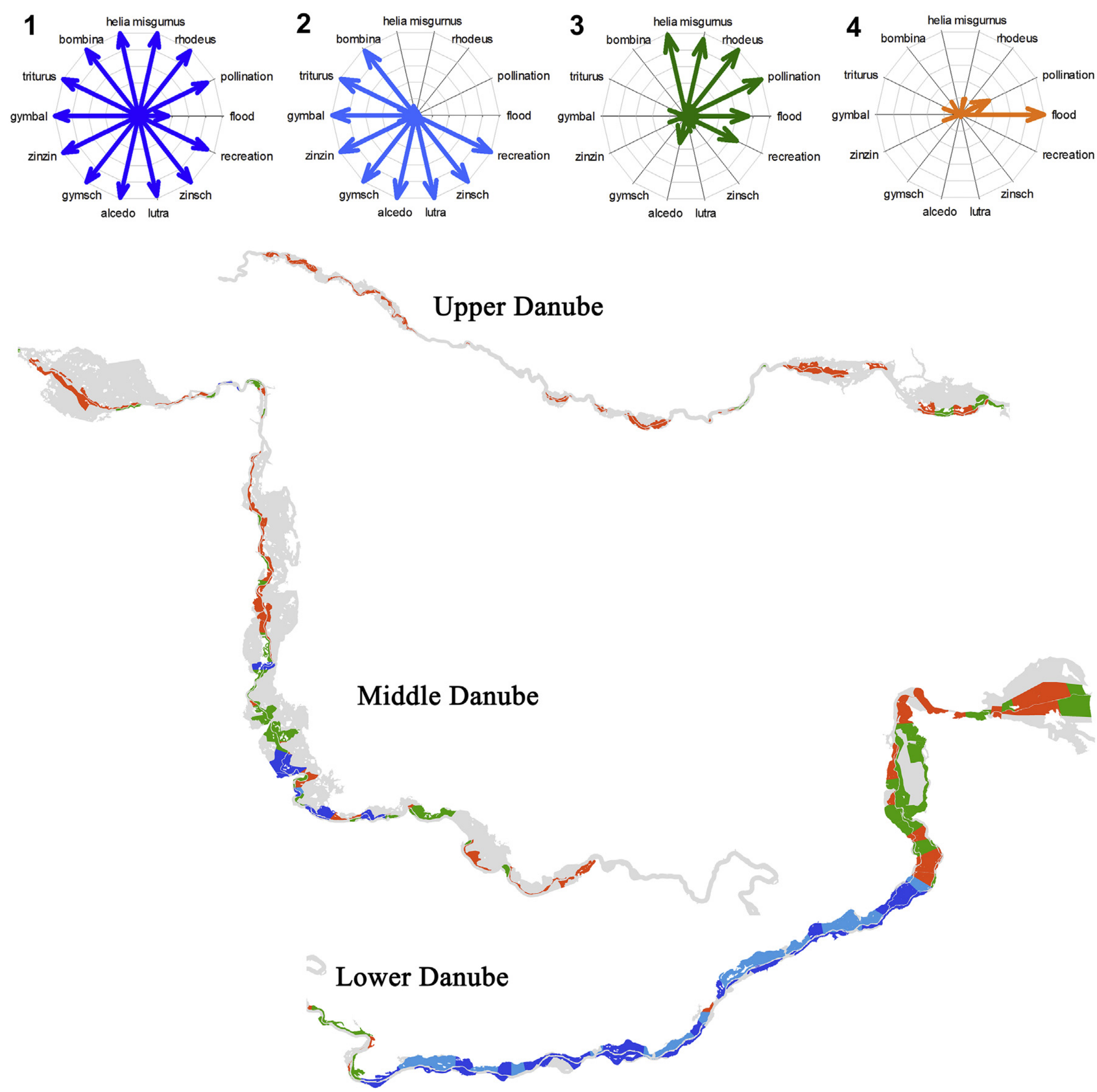

Fig. 4. Cluster analysis results, showing four relevant clusters related to species and ecosystem service values. Arrow lengths represent the relative value across the clusters, i.e., the longer the arrow, the higher the potential of species habitats and ecosystem services in the respective cluster. Colors of arrow plots correspond to the colors on the map. Dark blue/cluster 1: multi-functional cluster; light blue/cluster; light blue/cluster 2: rheophilic/river and recreation cluster; green/cluster 3: stagnophilic/floodplain species and multiple ecosystem service cluster; orange/cluster 4: reduced multi-functionality with remaining high flood regulation potential cluster. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Our approach, based on multiple aquatic species with contrasting habitat requirements and selected important ecosystem services, enables the identification of river reaches that show a high degree of multi-functionality. The recorded high overlap between areas important for biodiversity and ecosystem service is consistent with other studies (Egoh et al., 2011; Maes et al., 2012) pointing to the close relationship between biodiversity and ecosystem services, which is often greater in natural systems (Chan et al., 2011; Schneiders et al., 2012). However, others have found less spatial overlap between biodiversity and ecosystem services (Egoh et al., 2014), pointing to the importance of approaches that analyse for their congruence like our clustering approach (Bai et al., 2011).

Sites with high restoration potential were effectively selected, and were grouped into two clusters. One has deficits mainly for the rheotopic community, and requires restoration of natural dynamics through reconnection of sidearms or removal of artificial bank material. The other shows deficits for the stagnotopic community and ecosystem services and requires restoration of stagnant water bodies and riparian habitats, including abandonment of agricultural polders. This cluster aligned with the findings of Schindler et al. (2014), who identified that the abandonment of agricultural area could lead to high-level restoration of ecosystem services. By contrast, floodplain reconnection has high potential for biodiversity restoration (Mueller et al., 2017; Paillex et al., 2009, 2015; Reckendorfer et al., 2006; Rumm et al., 2018; Straatsma et al., 2017), its effect on ecosystem services can expected to be positive but lower (Schindler et al., 2014).

Lastly one cluster bundled sites with reduced biodiversity potential across all species but high potential, with restoration, for increased flood regulation. We thus define this cluster as having potential for mitigation measures related to flood regulation. But there is also capacity to maintain habitat for particular indicator species. Even heavily degraded floodplain system can have high value or restoration potential for a specific, mostly stagnotopic, community (Funk et al., 2009; Schiemer et al., 1999). It would also be possible to prioritize segments for mitigation measures by focusing on this cluster using the same three criteria (i.e., multi-functionality, reversibility and semi-natural area).

4.2. Multi-objective optimization

The two main causes of deterioration of the hydro-morphological conditions of river-floodplain systems, and therefore main targets for restoration, are the loss of floodplain area caused by agricultural polders and hydrological disconnection of remaining floodplains due to river engineering works. These issues are directly addressed by our approach via the semi-natural area and the reversibility criterion, respectively. Therefore, our prioritization method selects river reaches where floodplain restoration can minimize loss of agricultural land and those where hydrological connectivity between river and floodplain could be restored with the least effort and risk of failure.

For our approach, compromise programming is more advantageous than spatial conservation planning tools like Marxan, which are widely used for conservation planning (Reyers et al., 2012; Vallecillo et al.,

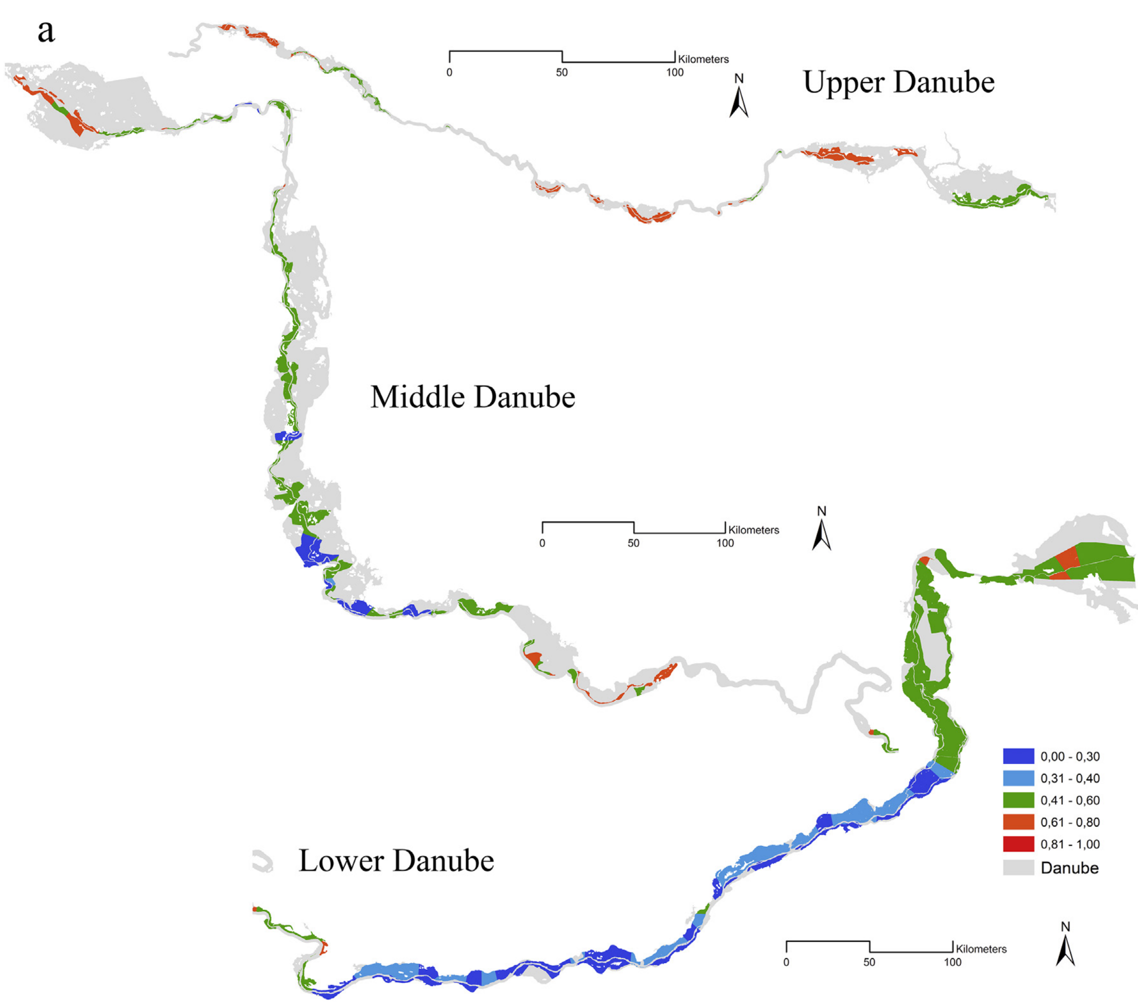

Fig. 5. Input variables for the multi-objective optimization approach using compromise programming. Values are expressed as distance from ideal point ranging from blue (relative close to ideal conditions, with high priority for conservation and restoration) to red (highest distance to ideal conditions, with low priority for restoration). (a) Multi-functionality, (b) Reversibility, (c) Semi-natural area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

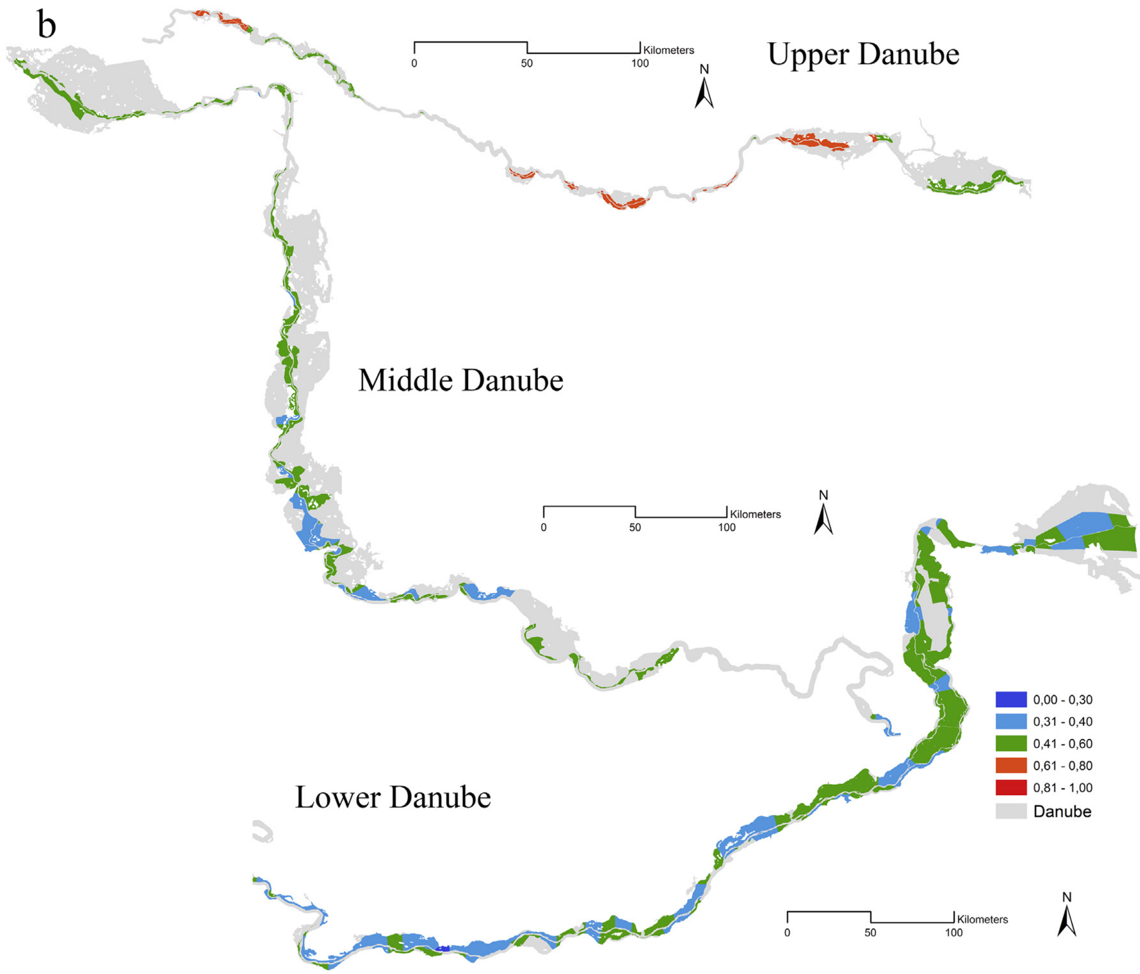

Fig. 5 (*continued*).

2018; Domisch et al., submitted, this issue). Compromise programming is a multi-objective optimization tool (e.g. Sacchelli et al., 2013), which enables the systematic optimization of different restoration strategies, which are not considered in Marxan (Dujardin and Chadès, 2018). Additionally, when the focus is on selecting for multi-functional sites, a hotspot method, i.e., using summed and merged indices, might be favoured since sites selected by Marxan are not necessarily those that contain high levels of both multiple biodiversity components and ecosystem services (Schröter and Remme, 2016). Hotspot approaches comparable to ours have already been used for diverse purposes including planning of green infrastructure networks (Liquete et al., 2015) and site prioritization for ecological restoration (Comín et al., 2018).

4.3. Relevance for the Danube River floodplains

Our gap analysis showed that most of the sites we are prioritizing for conservation are already part of Natura 2000 sites (80% of the area). Sites with a high multi-functionality related to the stagnotopic community and ecosystem services are already widely part of Natura 2000 sites, indicating the effectiveness of Natura 2000's site selection along the Danube. Sites with a high coverage of agricultural area and high multi-functionality related to the rheophilic community are less protected (50% of the area) under the Habitats and Birds Directive. However, these sites are important for restoration, and their nomination for Natura 2000 status and subsequent restoration planning should be considered in order to preserve the Danube's full suite of biodiversity and ecosystem services.

In relation to restoration plans included in the Danube River Basin Management Plan (ICPDR, 2016), some high-priority sites that we identified have high priorities across the different scenarios and are already designated as sites with high restoration potential (e.g., "Incinta Bistret Nedeia Jiu" or "Dabulen Potelu Corabia" in Romania). We also identified sites where restoration is already planned and ongoing ("Donau-Auen National Park" in Austria https://www.danubegis.org/), and others in areas where no sites are yet designated, e.g., along the Hungarian Danube.

4.4. Analysis framework

Our approach supports the systematic prioritization of conservation and restoration of ecosystem services and biodiversity along one of Europe's largest rivers—the Danube—based on a framework including modelling, cluster analysis, and multi-objective optimization. By prioritizing sites with greater probability of restoration success at lower cost across the entire Danube River ecosystem, our approach may foster transboundary coordination and cooperation as it is independent from administrative and political boundaries and thus offers potential for better cost-effectiveness in achieving large scale conservation and ecosystem service targets (Bladt et al., 2009; Egoh et al., 2014).

By considering the multi-functionality of river-floodplain systems plus the cumulative impacts of multiple important human activities including agriculture, navigation and hydropower, the approach also has potential to foster conservation and restoration planning across multiple policies. This includes measures to be proposed under the Water Framework Directive for European rivers to reach prescribed "good

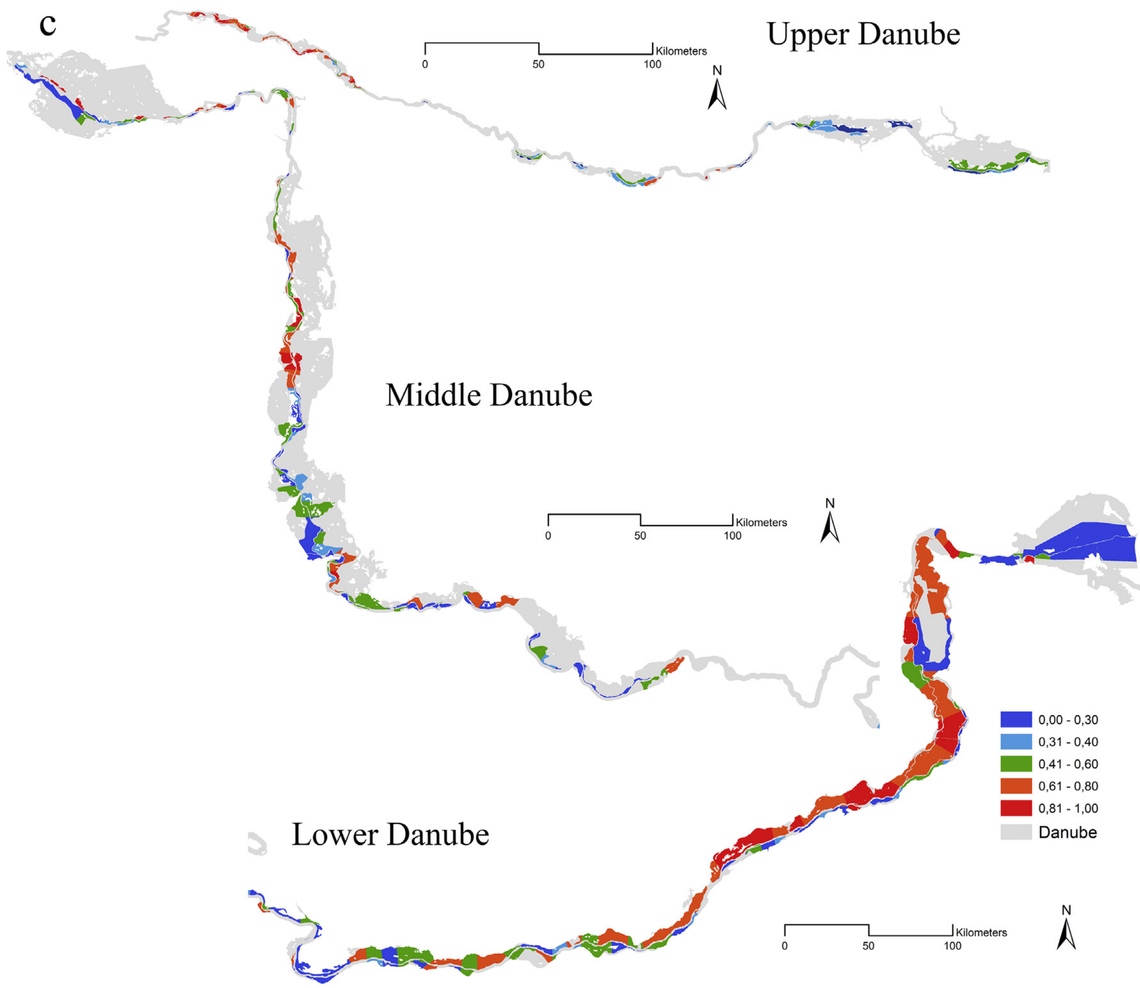

Fig. 5 (*continued*).

ecological status." A prioritization approach is also necessary for the Natura 2000 network along the Danube River (Hermoso et al., 2018). In this sense, restoration prioritization can guide the selection of sites for restoration project funding e.g., under the EU LIFE+ programme (http://ec.europa.eu/environment/life/funding/lifeplus.htm), and thus also support the implementation of the EU Biodiversity Strategy (Cortina and Boggia, 2014; Hermoso et al., 2018). Local restoration of lateral connectivity in river-floodplain systems is a pre-requisite for attaining effective environmental flows (e-flow) at catchment scale (another Water Framework Directive goal, EC, 2015), through hydrological restoration and restoration of sediment supply and transport (Hayes et al., 2018, Opperman et al., 2010). Direct accounting for catchment-scale impacts on hydrology and erosion and deposition related to sediment transport was not possible within our approach because of lack of sufficient knowledge and availability of indicators (Habersack et al., 2016).Generally, however, floodplains restored to an ecologically dynamic state are more resilient to external perturbation (Palmer et al., 2005).

Furthermore, enhancing ecosystem services has become a top priority in environmental policy in Europe that is connected to flood regulation (EU Flood Risk Directive), the EU Green Infrastructure Strategy, and the EU Biodiversity Strategy, which aim to maintain and enhance ecosystems and their services by establishing green infrastructure and restoring at least 15% of degraded ecosystems (Schindler et al., 2014).

Based on varying socio-economic or political conditions for the different scenarios, our results can guide restoration proposals for different regions, but can also guide country-level or even water body-level (as defined under Water Framework Directive) prioritization within the Danube watershed, as it is possible to combine different compromise scenarios spatially within this very flexible approach. Our approach also makes it possible to weight criteria differently across space, depending on political or socio-economic zoning (Malczewski, 1999).

5. Conclusions

Our approach of coupling predictive models with spatial prioritization is a promising tool with high potential to support catchment-scale management decisions. As the method is very flexible and the criteria we use (multi-functionality, reversibility and availability of semi-natural land for restoration) are broadly applicable, we believe that our approach is transferable to other river-floodplain systems with comparable management challenges. To make the approach operational, participatory processes involving decision makers across the catchment, member state and local levels would be a further important step (Martínez-López et al., 2019b; Schwarz, 2010). Although open-access data and expert judgment proved to give sufficient information within our approach, detailed field data would be highly relevant for the validation of our results. Finally, as the loss of aquatic habitat from disconnection of river-floodplain systems is a continuing process (Habersack et al., 2016), rapid decision tools that build upon best-available data and information are required in management planning. Such approaches would ideally follow a precautionary approach, where a lack of full scientific certainty is not viewed as a reason for postponing decisions (De Santo, 2017), as no action is clearly leading to a

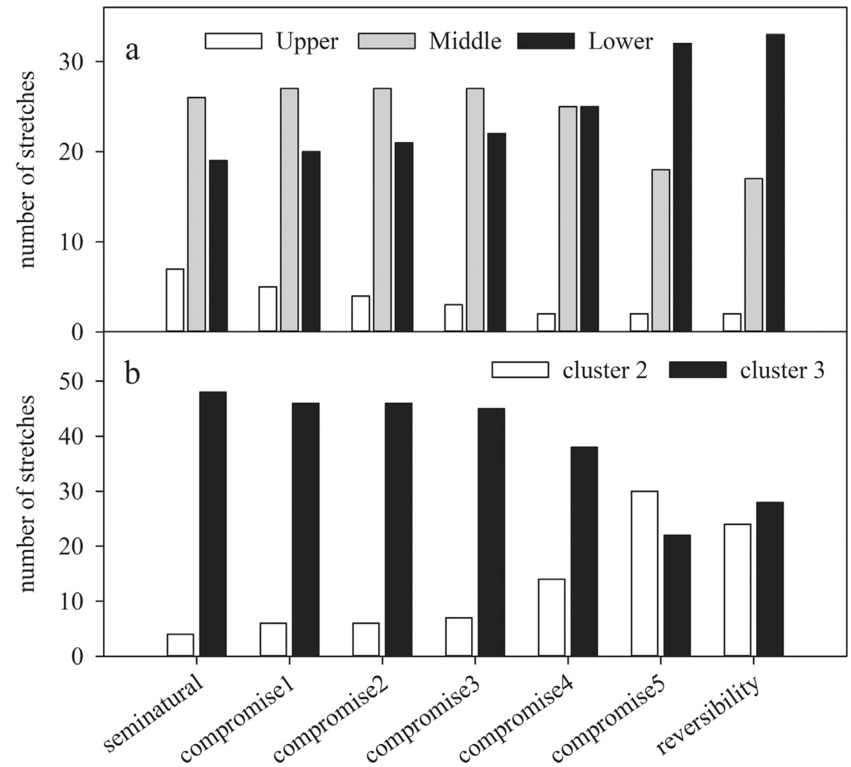

Fig. 6. Example for the prioritization of river-floodplain segments for restoration, comparing (a) Upper, Middle and Lower regions of the Danube and (b) for the two restoration clusters, clusters 2 and 3 (see Fig. 4). For this example the 15%restoration target (target 2) of the EU Biodiversity Strategy to 2020 was applied. The most promising 15% of segments with restoration potential (clusters 2 and 3) are counted per scenario, as calculated using compromise programming.

progressive deterioration of aquatic habitats, biodiversity, ecosystem services and functions of the system.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.10.322.

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