SUPPLEMENTARY INFORMATION

Hydropower regulation reshapes littoral invertebrate communities: functional traits reveal impacts beyond richness and abundance

Aquatic Sciences

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Table of Contents

Supplementary Methods

Lake characteristics

General environmental characteristics and water chemistry were obtained for the study lakes from the openly accessible knowledge database for water management in Norway, Vann-Nett (https://vann-nett.no), operated by the Norwegian Environment Agency. Information on registered anthropogenic impacts was also obtained from this resource.

Table S1 Overview of lake chemistry and depth for the Norwegian study lakes. Data from Vann-Nett (https://vann-nett.no, accessed 05.02.2025). Coordinates mark sampling sites in this study

Lake name	Waterbody ID	Depth	Calcium type	Humic type	Turbidity	Decimal latitude	Decimal longitude
Barsetvatnet	134-662-L	Shallow	Lime-deficient	Clear	Clear	63.79780140	9.82804950
Roksetvatnet	132-37133-L	Shallow	Lime-deficient	Humic	Clear	63.65402420	10.06643140
Jonsvatnet	123-910-L	Deep	Lime-deficient	Clear	Clear	63.34479090	10.55001740
Gjøljavatnet	134-659-L	Deep	Lime-deficient	Clear	Clear	63.78926090	10.02517340
Storvatnet	132-950-1-L	Shallow	Lime-deficient	Humic	Clear	63.62117760	10.23337590
Stor-Drakstsjøen	123-897-L	Shallow	Lime-deficient	Clear	Clear	63.28646110	10.80247130

Notes: Waterbody ID correspond to the management system Vannmiljø by The Norwegian Environment Agency. For depth, shallow is defined as 3-15 m and deep as > 15 m. For calcium type, lime deficient is defined as Ca = 1 - 4 mg/l, Alk = 0.05-0.2 mekv/l. For humic type, clear is defined as < 30 mg Pt/L, TOC 2 - 5 mg/L and humic as 30-90 mg Pt/L, TOC 5-15 mg/L. For turbidity, clear is defined as STS < 10 mg/L (inorganic part at least 80%).

Table S2 Fish species registered in each lake. Data source: GBIF (https://gbif.org, accessed 25.03.2026)

Lake name	Brown trout *Salmo trutta*	Arctic charr *Salvelinus alpinus*	Northern pike *Esox lucius*	Three-spined stickleback *Gasterosteus aculeatus*	European eel *Anguilla anguilla*	Burbot *Lota lota*
Barsetvatnet	X*					
Roksetvatnet	X					
Jonsvatnet	X	X	X	X	X**	X***
Gjøljavatnet	X	X				
Storvatnet	X	X	X	X	X**	
Stor-Drakstsjøen	X	X	X	X		

Notes:

*For Barsetvatnet, no fish are registered in online databases, but fish were observed on-site during fieldwork. Brown trout has been registered within the watershed, in nearby connected rivers and smaller lakes.

** Very old registrations, no recent observations.
*** Registered in 1993 by the Norwegian Institute for Nature Research (NINA) but has not been observed during more recent fish surveys done by the NTNU University Museum in 2020. The population is likely either small or has disappeared.

Hydropower

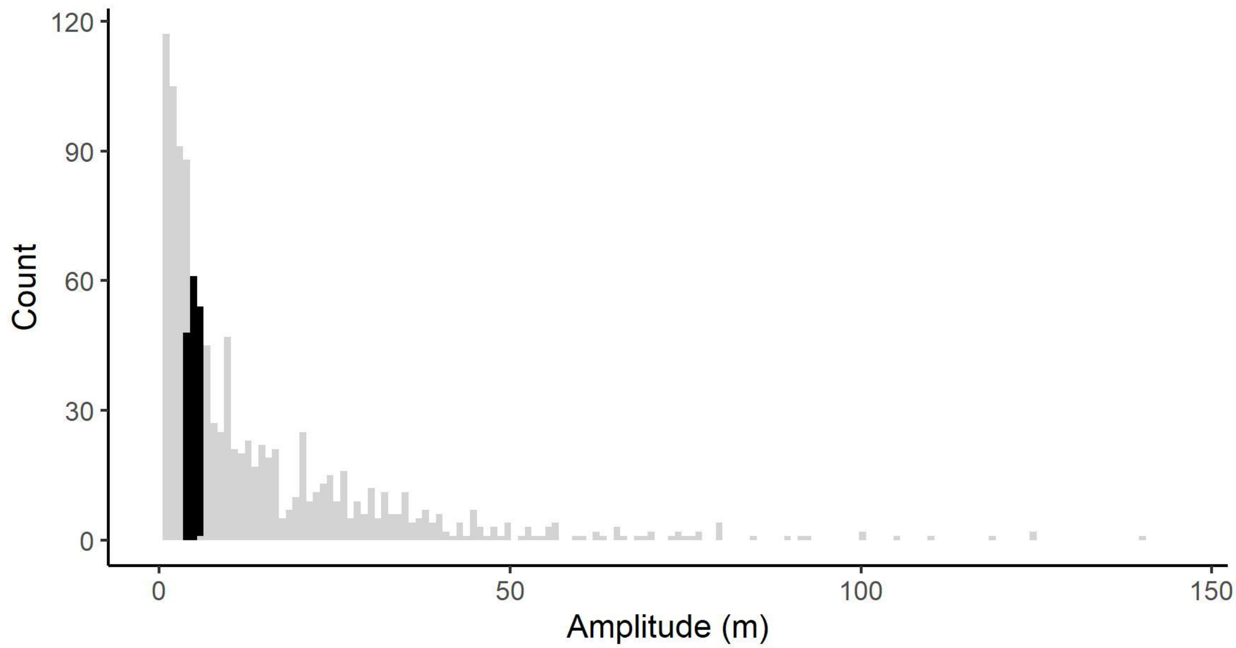

Fig. S1 Distribution of regulation amplitudes for hydropower reservoirs in Norway. Only reservoirs which are in operation (as of 2022) and where data on max + min regulation height was available are included (nr. reservoirs plotted = 1114). Data downloaded from NVE (https://nedlasting.nve.no/gis/). Marked in black are reservoirs with amplitude 4-6 meters, which constitute 14.5 % of those plotted. Highest registered regulation amplitude is 140 meters, representing lake Vatnedalsvatn

Water level data

Recorded water levels from control lakes show that these lakes experienced small water level fluctuations, with variations during the sampling period of < 0.5 m for all sites (Supplementary Information (SI), Fig. S2).The measurements were made by placing a pole in the lakeshore substrate at around 0.5-1 meters depth, measuring water level relative to the pole at the same spot, and finally using a satellite-device to measure the absolute height above sea level for the pole. Measurements could then be converted to meters above sea level.

Historical water level measurements could be obtained for two of the regulated lakes, but not for Storvatnet (SI, Fig. S3).

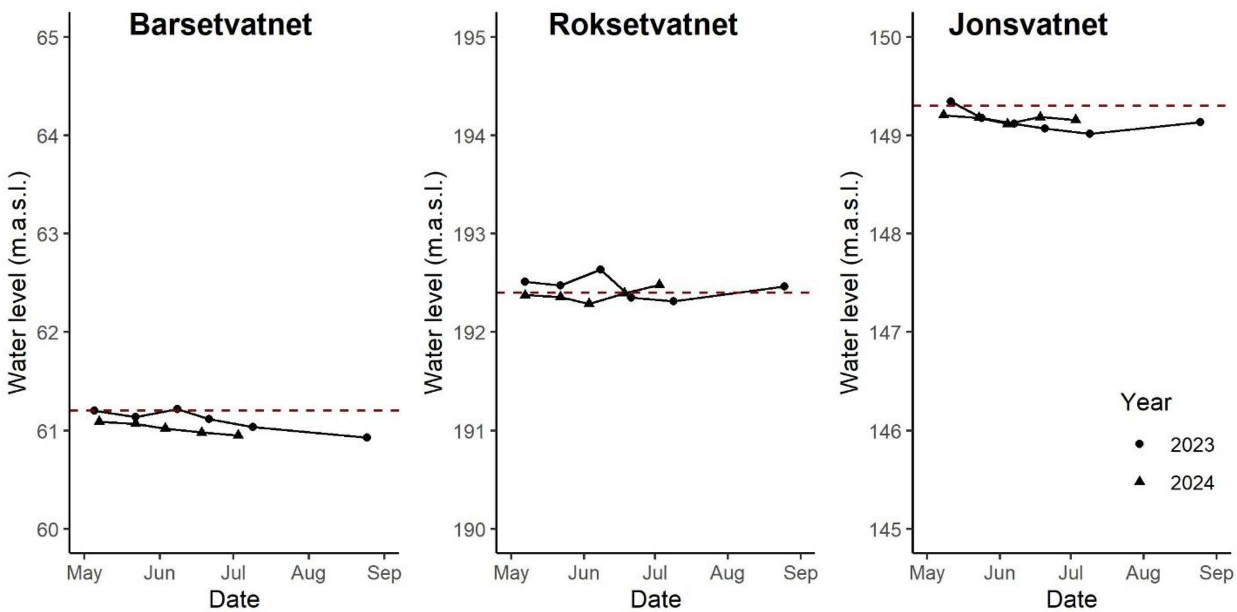

Fig. S2 Water level fluctuations in the control lakes measured throughout the study period. Red dotted line marks the estimated water level based on interpolations (EUREF89 UTM-33) provided by The Norwegian Mapping Authority (https://norgeskart.no)

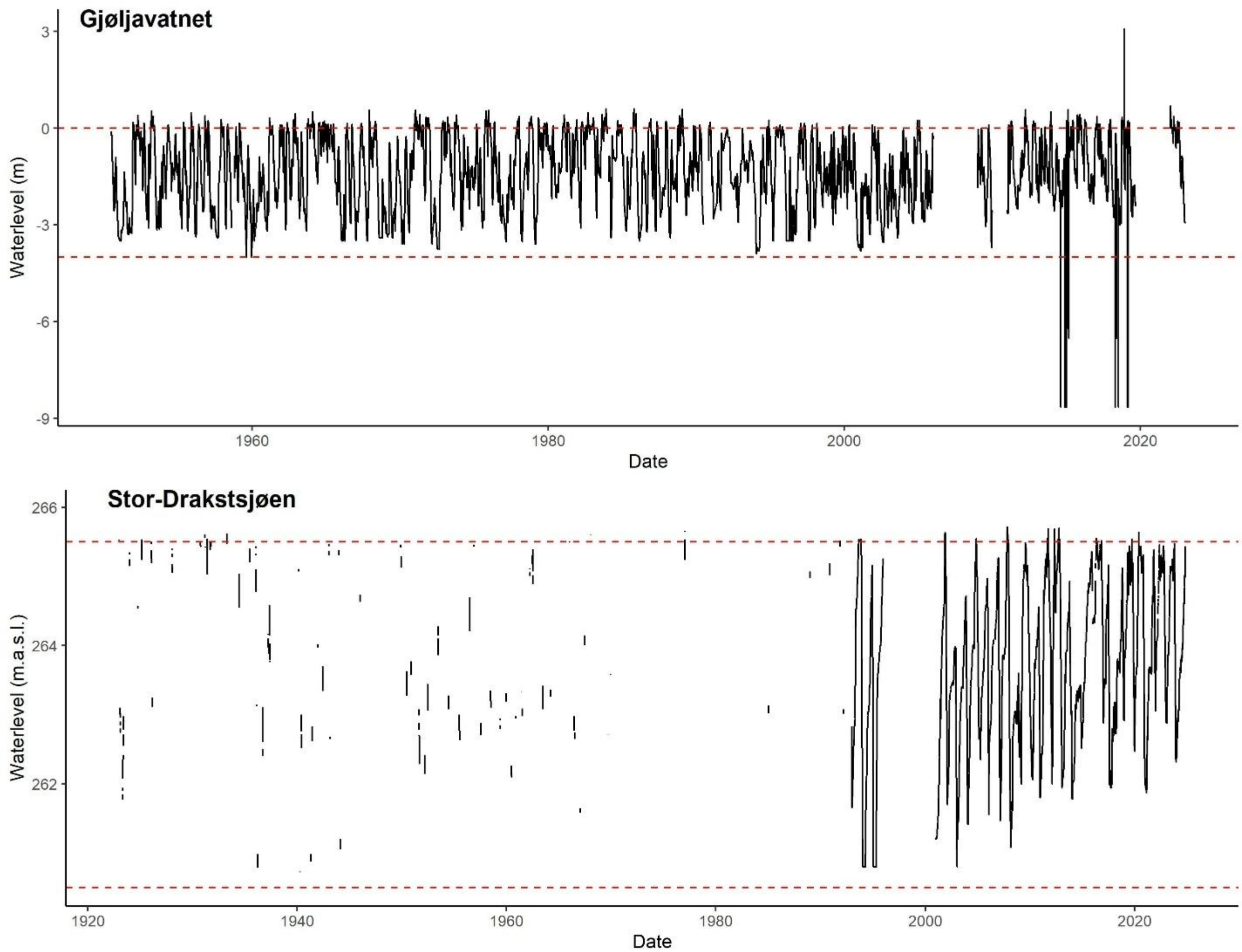

Fig. S3 Historical water level fluctuation data from lakes A) Gjøljavatnet (years 1950-2022) and B) Stor-Drakstsjøen (years 1923-2024) obtained from the hydrological database Sildre (https://sildre.nve.no/). Data is plotted on the scale originally provided. Horizontal dotted lines represent concession-set upper and lower limits for water levels. Large outliers are expected to be caused by logger failure, but this has not been confirmed

Temperature data

Water temperature measurements showed that all lakes experienced similar temperature variation, including a cold spring in 2023 (SI, Fig. S4). Temperature-loggers (HOBO pendant light/temp UA-002-64) were placed in each lake from after ice-melt until the end of each sampling period. Two loggers were used per lake: one logger was placed from shore (0.4-1 m depth) and the other was placed in open waters using a buoy and anchor (1.5m depth). Overall, shore-zone and open water loggers recorded similar temperature changes. For lake Stor-Drakstsjøen, challenges at the sampling site resulted in a shorter period logged from shore in 2023 and in 2024.

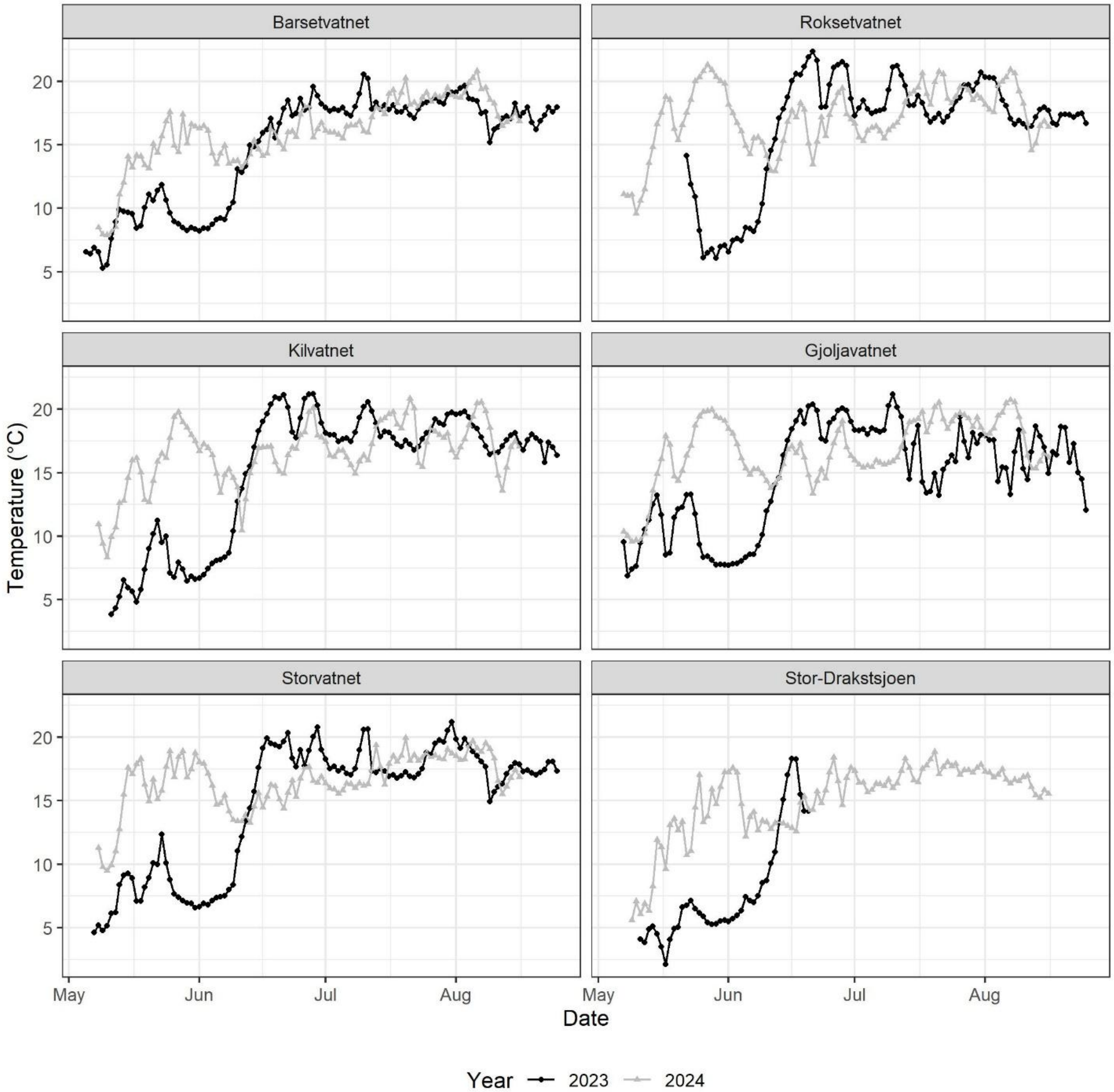

Fig. S4 Daily average water temperatures measured during the study period in each lake. Data represent measurements from shore-zone loggers (depth ≈ 0.5 meters) except for Stor-Drakstsjøen 2024 where data is from the open water logger (depth ≈ 1.5 meters)

Supplementary Results

Species abundance and richness

Table S3 Species list for Ephemeroptera, Plecoptera and Trichoptera, reporting abundance of each species in the dataset. Bar = Barsetvatnet, Jon = Jonsvatnet, Rok = Roksetvatnet, Gjø = Gjøljavatnet, St-D = Stor-Drakstsjøen, Sto = Storvatnet

Scientific name	Bar	Jon	Rok	Gjø	St-D	Sto
Agrypnia obsoleta (Hagen, 1864)	1	2	0	0	0	0
Ameletus inopinatus Eaton, 1887	0	0	1	0	0	0
Annitella obscurata (McLachlan, 1876)	4	0	0	0	0	0
Apatania stigmatella (Zetterstedt, 1840)	5	0	0	22	1	0
Arthroplea congener Bengtsson, 1908	0	54	1	0	0	0
Athripsodes aterrimus (Stephens, 1836)	0	0	0	9	0	1
Athripsodes cinereus (Curtis, 1834)	3	0	0	10	0	12
Caenis horaria (Linnaeus, 1758)	102	142	3	224	0	12
Centroptilum luteolum Müller, 1776	0	0	0	2	0	4
Cloeon dipterum (Linnaeus, 1761)	0	4	0	0	0	0
Cyrnus flavidus McLachlan, 1864	15	2	2	1	0	0
Cyrnus trimaculatus (Curtis, 1834)	81	28	35	4	0	0
Ephemera vulgata Linnaeus, 1758	23	4	0	12	0	0
Glyphotaelius pellucidus (Retzius, 1783)	0	1	0	0	0	0
Halesus digitatus (von Paula Schrank, 1781)	0	1	0	0	0	0
Halesus radiatus (Curtis, 1834)	3	0	0	0	0	0
Heptagenia dalecarlica Bengtsson, 1912	0	0	0	0	0	1
Heptagenia fuscogrisea (Retzius, 1783)	29	1	10	1	28	5
Heptagenia sulphurea (Müller, 1776)	0	0	0	0	0	3
Holocentropus dubius (Rambur, 1842)	8	0	0	0	0	0
Holocentropus picicornis (Stephens, 1836)	0	1	1	0	0	0
Lepidostoma hirtum (Fabricius, 1775)	3	2	0	6	0	0
Leptophlebia marginata (Linnaeus, 1767)	22	25	3	13	19	11
Leptophlebia vespertina (Linnaeus, 1758)	370	198	262	176	20	0
Leuctra fusca (Linnaeus, 1758)	155	0	1	26	1	0
Limnephilus coenosus Curtis, 1834	0	0	0	1	0	0
Limnephilus rhombicus (Linnaeus, 1758)	1	2	0	0	0	0
Limnephilus stigma Curtis, 1834	0	1	0	0	0	0
Limnephilus vittatus (Fabricius, 1798)	1	0	0	15	0	1
Metretopus borealis (Eaton, 1871)	65	0	0	17	0	22
Molanna angustata Curtis, 1834	0	1	0	2	0	0
Mystacides azureus (Linnaeus, 1761)	11	11	4	28	0	0
Nemoura avicularis Morton, 1894	1	0	0	0	0	0
Nemoura cinerea (Retzius, 1783)	1	0	0	0	0	0
Oecetis lacustris (Pictet, 1834)	0	0	0	2	0	0
Oecetis ochracea (Curtis, 1825)	0	0	0	1	0	0

Polycentropus flavomaculatus (Pictet, 1834)	95	8	3	6	0	0
Polycentropus irroratus Curtis, 1835	3	1	0	0	0	0
Procloeon bifidum (Bengtsson, 1912)	0	0	7	0	0	0
Sericostoma personatum (Kirby & Spence, 1826)	2	0	0	0	0	0
Silo pallipes (Fabricius, 1781)	0	0	0	7	0	0
Siphlonurus alternatus (Say, 1824)	0	0	5	5	0	0
Siphlonurus lacustris Eaton, 1870	2	11	18	0	0	3
Tinodes waeneri (Linnaeus, 1758)	0	0	7	0	0	0
Triaenodes bicolor (Curtis, 1834)	0	2	2	0	0	0

Table S4 Model comparison of candidate models testing for the effect of regulation status and year on EPT species abundance (negative binomial) or species richness (poisson)

Model	K	AICc	ΔAICc	AICc weight (w_i)
Species abundance				
~ status	4	549.7	0.00	0.430
~ 1	3	550.9	1.19	0.237
~ status + year	5	551.5	1.78	0.177
~ year	4	552.6	2.83	0.104
~ status*year	6	553.9	4.20	0.053
Species richness				
~ status	3	292.8	0.00	0.385
~ 1	2	293.2	0.43	0.310
~ status + year	4	294.8	1.99	0.142
~ year	3	295.1	2.34	0.119
~ status*year	5	297.1	4.35	0.044

Note: Models are ranked by increasing AICc value, which were obtained from mixed-effect models fitted with maximum likelihood (ML). Locality was included as a random factor in all models.

Table S5 Parameter estimates for fixed effects (β) from the highest ranked models (ΔAICc < 2) predicting EPT species abundance or richness using regulation status and year as predictor variables

Model	Parameter	Estimate	*SE*	95 % CI	
Species abundance					
~ status					
	intercept	4.04	0.44	3.02	5.07
	status (regulated)	-1.35	0.63	-2.82	0.09
~ 1					
	intercept	3.36	0.42	2.39	4.33
~ status + year					
	intercept	4.11	0.46	3.07	5.17
	status (regulated)	-1.36	0.64	-2.85	0.11
	year (2024)	-0.19	0.24	-0.65	0.29
Species richness					
~ status					
	intercept	1.93	0.27	1.30	2.55
	status (regulated)	-0.69	0.38	-1.60	0.19
~ 1					
	intercept	1.58	0.24	1.02	2.12
~ status + year					
	intercept	1.95	0.27	1.32	2.58
	status (regulated)	-0.69	0.38	-1.60	0.19
	year (2024)	-0.06	0.11	-0.28	0.16

Note: All parameter values are given on the $\log_e$ scale. Locality was included as a random factor in all models.

Random effects plots

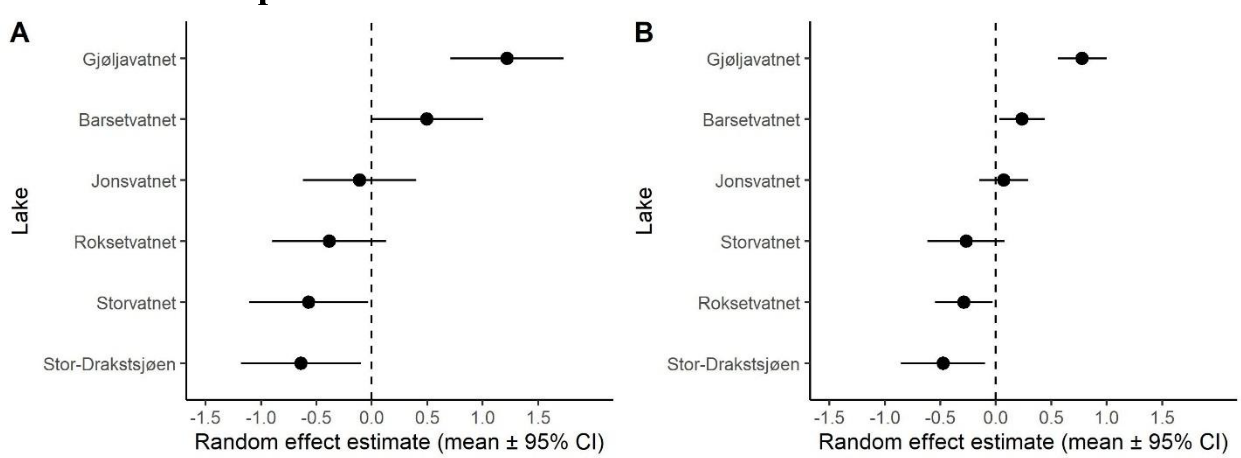

Fig. S5 Random effects (locality intercepts) caterpillar plot for the highest ranked mixed models for A) species abundance and B) species richness. Shows the deviance from the mean population abundance/richness for each locality, together with confidence intervals

Functional traits

Table S6 Ratios of abundance (control/regulated) for each trait level, extracted from generalized linear mixed effects models. Values greater than 1 indicate higher abundance in control lakes

Trait level	Ratio (control/regulated)	p	95 % CI	
Model: Locomotion and surface relation				
full water swimmer	2.15	0.331	0.46	10.10
burrower	3.03	0.197	0.56	16.20
crawler	3.46	0.099	0.79	15.10
temporarily attached	39.41	**<.0001**	**7.61**	**204.00**
Model: Armour				
mineral	0.22	0.077	0.04	1.18
mixed	2.93	0.214	0.54	15.89
sclerotized	3.92	0.080	0.85	18.04
vegetation	6.47	**0.042**	**1.07**	**39.13**
silk	60.14	**<.0001**	**10.98**	**329.45**

Note: Confidence intervals were calculated from estimated marginal means and are based on asymptotic (Wald) approximations, back-transformed to the response scale. Sampling event nested within locality was included as a random factor in both models.

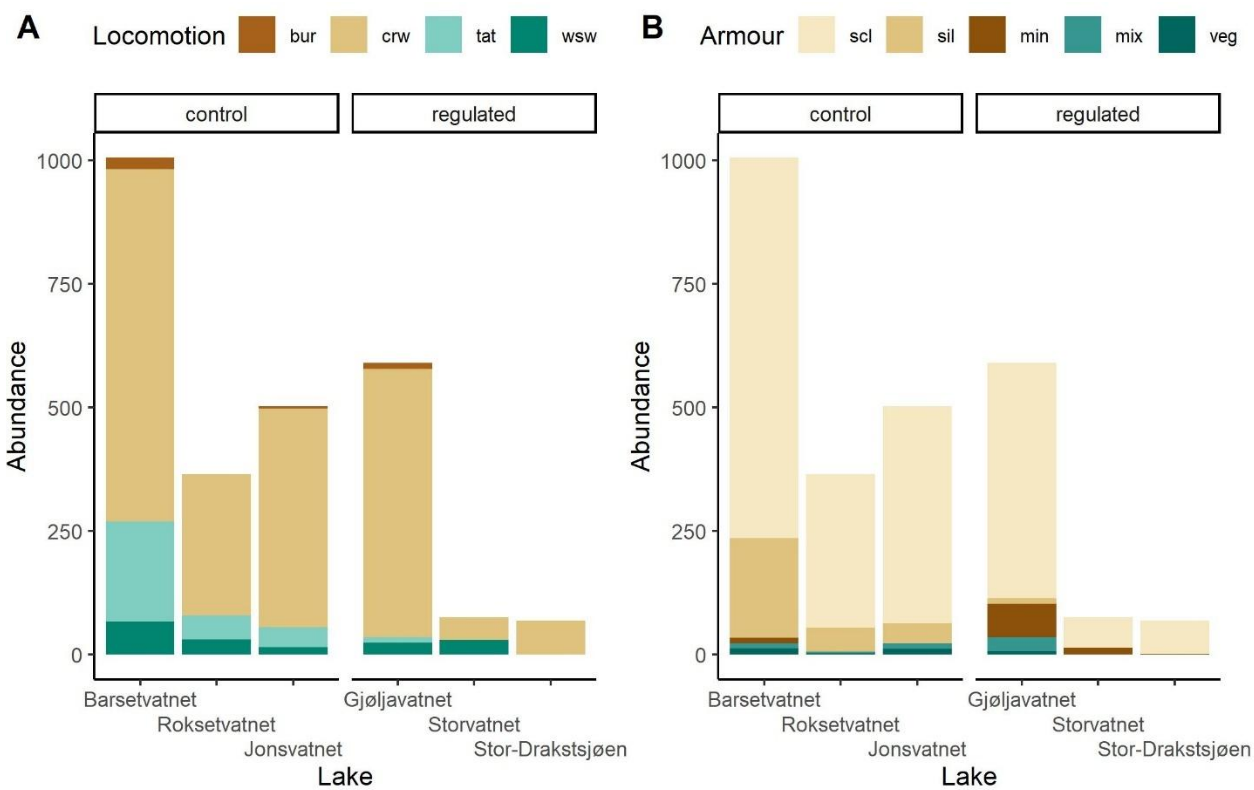

Fig. S6 Abundance of EPT individuals in each trait category for the traits A) *Locomotion and substrate relation* (bur = burrower, crw = crawler, tat = temporarily attached, wsw = full water swimmer) and B) *armour* (scl = sclerotized, sil = silk, min = mineral, mix = mixed, veg = vegetation). Number of samples per lake = 10

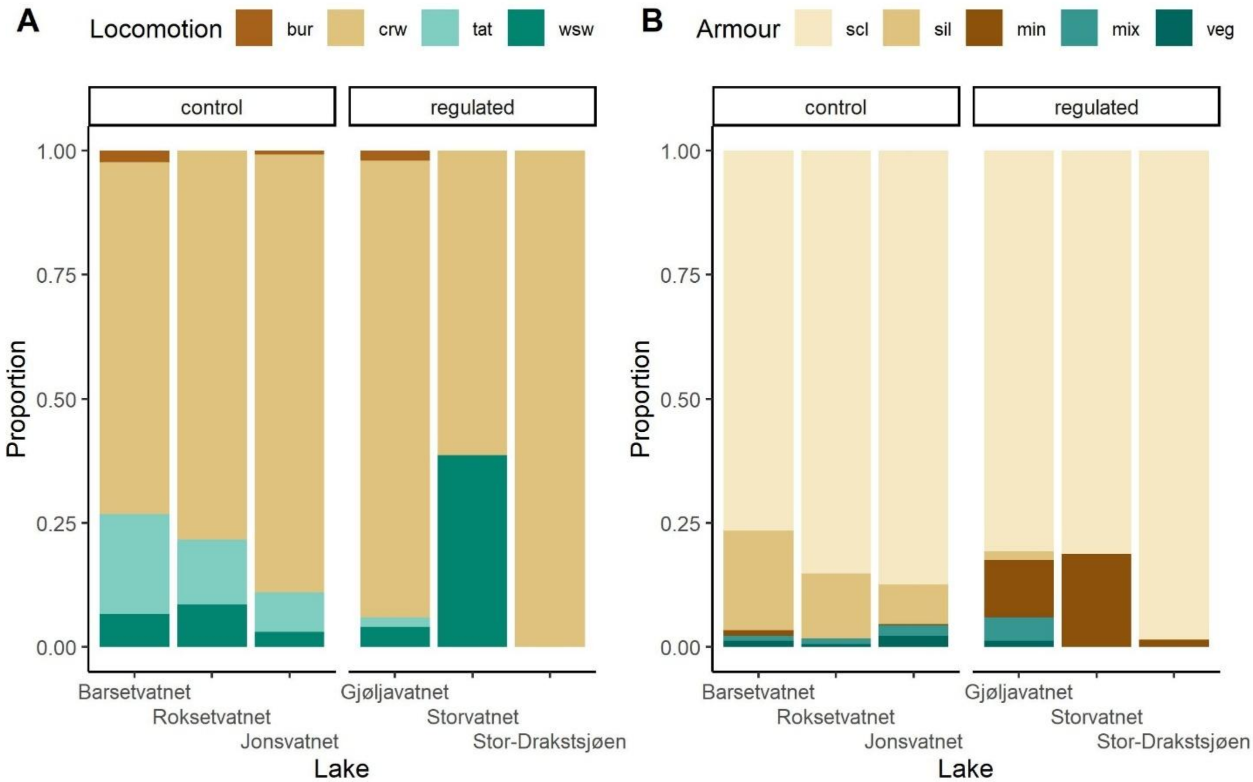

Fig. S7 Proportion of EPT individuals in each trait category for the traits A) *Locomotion and substrate relation* (bur = burrower, crw = crawler, tat = temporarily attached, wsw = full water swimmer) and B) *armour* (scl = sclerotized, sil = silk, min = mineral, mix = mixed, veg = vegetation). Number of samples per lake = 10