

Changing conditions and consequences of weather extremes on nutrient dynamics in a shallow eutrophic lake observed during a three-year monitoring study - Supplementary information



Figure S1. Map of Lake Seeburg showing the sampling locations (arrows) at the main inflow (Aue creek), the western part of the lake (bathing pier) and the eastern part near the outflow. The shaded area represents the Seeanger wetland upstream of the main tributary (Aue creek).

Table S1: Standards used for IC analyses of cations and anions

		1 [mg/L]	2 [mg/L]	3 [mg/L]	4 [mg/L]	5 [mg/L]	6 [mg/L]	7 [mg/L]	8 [mg/L]	9 [mg/L]	10 [mg/L]
standards for anions	NO₃	100	80	60	40	20	20	10	5	2	1
	Cl	100	80	60	40	20	20	10	5	2	1
	SO₄	100	80	60	40	20	20	10	5	2	1
	F	5	4	3	2	1	2	1	0,5	0,2	0,1
	PO₄	5	4	3	2	1	2	1	0,5	0,2	0,1
	Br	5	4	3	2	1	2	1	0,5	0,2	0,1
standards for cations	Ca	200	100	80	40	20	10	5	2	1	
	Mg	100	50	40	20	10	5	2	1	0,5	
	Na	200	100	80	40	20	10	5	2	1	
	K	100	20	15	10	5	2	1	0,5	0,2	
	Li	-	-	-	-	-	2	1	0,5	0,2	
	Sr	-	-	-	-	-	2	1	0,5	0,2	
	Ba	-	-	-	-	-	2	1	0,5	0,2	

Table S2: Compilation of the data obtained at the sampling positions in 2017

Date	Location	Temperature °C	pH	Oxygen mg L ⁻¹	Alkalinity meq L ⁻¹	SRP mg L ⁻¹	Nitrite mg L ⁻¹	Nitrate mg L ⁻¹	Ammonium mg L ⁻¹	Calcium mg L ⁻¹	Chloride mg L ⁻¹
January '17	inflow	2.4	8.3		4.64	0.172	0.008	19.440	0.066	134.6	46.7
	Lake Seeburg outflow										
February '17	inflow	3.8	7.9		4.56	0.172	0.008	21.469	0.277	139.0	29.4
	Lake Seeburg outflow		8.0		3.8		0.007	4.687	0.035	112.3	32.5
March '17	inflow	9.5	8.2		4.36	0.166	0.090	18.736	0.042	128.0	32.0
	Lake Seeburg	9.3	8.5		3.14	0.163	0.050	1.278	0.033	95.4	31.9
	outflow	9.3	8.6		3.24	0.171	0.050	1.654	0.035	96.8	31.8
April '17	inflow	6.0	8.3	14.57	4.02	0.136	0.022	17.909	0.374	120.6	28.7
	Lake Seeburg	9.8	8.2	11.70	3.22	0.062	0.015	2.581	0.131	98.3	31.7
	outflow	9.8	8.2	12.11	3.32	0.046	0.015	2.009	0.068	100.3	31.5
May '17	inflow	15.1	7.9	8.06	3.8	0.262	0.253	14.760	0.307	110.1	25.5
	Lake Seeburg	19.0	8.3	9.14	3.14	0.031	0.003	1.654	0.144	96.3	31.9
	outflow	19.1	8.2	8.77	3.34	0.035	0.004	1.819	0.166	95.8	32.2
June '17	inflow	17.3	8.1	7.60	3.76	0.344	0.365	13.212	0.127	126.8	21.7
	Lake Seeburg	22.5	8.4	9.16	2.86	0.351	0.013	0.708	0.091	91.2	31.2
	outflow	22.7	8.4	9.48	2.74	0.266	0.028	0.750			31.1
July '17	inflow	16.5	8.0	8.17	4.32	0.306		15.988	0.006	125.2	28.0
	Lake Seeburg	22.1	8.6	12.33	3.46	0.330		1.204	0.008	90.6	31.7
	outflow	22.9	8.6	12.62	3.3	0.346		1.205	0.008	91.2	31.6
August '17	inflow	19.5	7.3	0.22	4.44	1.355		1.215	0.708	107.2	23.1
	Lake Seeburg	22.1	8.7	10.45	2.88	0.262		1.224	0.634	73.3	26.5
	outflow	23.0	8.7	12.34	2.84	0.249		1.221	0.584	73.9	26.5
September '17	inflow	16.0	7.7	7.61	4.06	0.230		14.591	0.140	119.9	28.8
	Lake Seeburg	19.4	8.4	8.13	3.12	0.780		1.032	0.322	78.2	26.2
	outflow	19.8	8.5	9.46	2.96	0.654		1.178	0.418	77.6	26.3
October '17	inflow	12.8	7.5	7.47	3.72	0.239	0.050	8.323	0.120	104.4	24.8
	Lake Seeburg	15.5	8.3	7.54	2.84	0.183	0.010	0.896	0.102	81.3	26.5
	outflow	15.5	8.1	7.3	2.92	0.161	0.020	1.004	0.183	81.3	26.4
November '17	inflow	8.4	7.7	7.05	4.48	0.128		15.902	0.206	129.5	29.0
	Lake Seeburg	8.6	7.7	6.74	3.16	0.096		2.339	0.283	90.5	27.1
	outflow	8.7	7.6	6.41	3.1	0.084		2.209	0.205	90.8	27.1
December '17	inflow	3.4	7.7	11.26	4.8	0.018		15.824	0.247	121.3	34.2
	Lake Seeburg	2.5	8.0	12.28	3.58	0.008		4.234	0.165	99.0	28.1
	outflow	2.6	7.9	12.51	3.46	0.007		3.659	0.163	98.2	27.4

Table S2 (continued): Compilation of the data obtained at the sampling positions in 2018

Date	Location	Temperature °C	pH	Oxygen mg L ⁻¹	Alkalinity meq L ⁻¹	SRP mg L ⁻¹	Nitrite mg L ⁻¹	Nitrate mg L ⁻¹	Ammonium mg L ⁻¹	Calcium mg L ⁻¹	Chloride mg L ⁻¹
January '18	inflow	3.8	7.7	11	4.48	0.220	0.069	17.163	0.177	122.0	28.3
	Lake Seeburg	3.2	7.9	12.2	3.72	0.105	0.040	5.618	0.101	102.2	26.7
	outflow	3.2	7.9	13.5	3.76	0.103	0.040	5.105	0.140	102.2	26.7
February '18	inflow	3.1	7.2	12.16	3.98	0.135	0.041	19.673	0.062	132.3	32.2
	Lake Seeburg	2.5	8.1	12.95	4.06	0.055	0.074	6.493	0.012	111.8	29.3
	outflow	2.6	8.0	12.89	3.90	0.056	0.039	6.692	0.013	112.1	29.5
March '18	inflow	7.7	7.7	10.08	4.06	0.124	0.093	21.551	0.096	109.8	39.4
	Lake Seeburg	6.4	7.9	12.08	3.90	0.015	0.026	8.244	0.042	102.9	35.0
	outflow	5.8	8.2	12.05	3.92	0.007	0.026	6.975	0.044	102.5	35.2
April '18	inflow	13.3	8.4	14.1	4.20	0.149	0.157	15.754	0.052	114.9	32.1
	Lake Seeburg	12.7	8.2	10.97	4.04	0.017	0.052	5.318	0.052	108.9	31.5
	outflow	13.9	8.2	11.07	3.98	0.036	0.058	5.463	0.063	107.9	31.9
May '18	inflow	15.6	8.0	8.13	4.30	0.241	0.482	17.785	0.207	123.6	31.1
	Lake Seeburg	18.5	8.4	12.2	3.94	0.017	0.079	2.010	0.055	99.5	33.8
	outflow	18.7	8.4	13.17	3.82	0.011	0.062	1.608	0.071	105.2	33.4
June '18	inflow	17.8	8.3	9.19	4.00	0.267	0.255	17.139	0.038	120.6	28.0
	Lake Seeburg	25.6	8.6	11.66	3.38	0.042	0.008	0.025	0.020	93.0	32.5
	outflow	26.0	8.6	11.83	3.28	0.052	0.008	0.029	0.015	90.7	32.6
July '18	inflow	14.5	8.2	8.81	3.66	0.214	0.112	17.765	0.054	112.7	28.0
	Lake Seeburg	22.2	8.8	14.15	2.78	0.045	0.007	0.024	0.022	75.0	32.9
	outflow	20.9	8.7	12.51	2.74	0.024	0.016	0.028	0.022	79.0	32.9
August '18	inflow	18.9	8.1	7.61	3.96	0.306	0.078	18.640	0.020	118.8	27.6
	Lake Seeburg	25.9	8.8	11.4	1.74	0.206	0.014	0.043	0.021	54.6	33.7
	outflow	25.2	8.8	11.7	1.40	0.099	0.012	0.047	0.028	46.6	34.0
September '18	inflow	14.3	8.1	8.38	3.88	0.199	0.044	19.504	0.023	127.4	27.0
	Lake Seeburg	19.2	9.3	12.69	2.64	0.618	0.031	0.062	0.017	71.6	34.3
	outflow	18.4	9.0	7.75	2.70	0.667	0.012	0.037	0.017	70.1	34.4
October '18	inflow	9.8	8.2	10.06	3.94	0.150	0.089	19.366	0.033	127.1	27.0
	Lake Seeburg	13.7	9.0	10.5	3.08	0.681	0.033	0.342	0.029	76.3	33.8
	outflow	13.3	8.7	8.4	3.06	0.687	0.038	0.314	0.023	68.8	33.9
November '18	inflow	9.7	8.1	9.06	4.20	0.156	0.098	19.657	0.014	126.1	26.9
	Lake Seeburg	9.0	8.0	6.3	3.10	0.408	0.038	0.696	0.319	84.6	32.9
	outflow	9.3	7.9	4.53	3.22	0.414	0.050	0.711	0.356	86.3	32.9
December '18	inflow	5.3	8.0	10.58	3.30	0.333	0.056	14.812	0.026	111.7	30.6
	Lake Seeburg	5.1	8.5	11.6	3.22	0.341	0.047	2.274	0.329	90.0	31.5
	outflow	4.9	8.5	12.01	3.20	0.323	0.064	2.523	0.251	91.8	32.1

Table S2 (continued): Compilation of the data obtained at the sampling positions in 2019

Date	Location	Temperature °C	pH	Oxygen mg L ⁻¹	Alkalinity meq L ⁻¹	SRP mg L ⁻¹	Nitrite mg L ⁻¹	Nitrate mg L ⁻¹	Ammonium mg L ⁻¹	Calcium mg L ⁻¹	Chloride mg L ⁻¹
January '19	inflow	6.0	8.1	10.42	4.02	0.224	0.059	20.357	0.039	134.2	38.4
	Lake Seeburg	4.2	8.5	12.33	3.42	0.210	0.039	5.410	0.141	97.1	31.3
	outflow	4.2	8.8	12.95	3.38	0.208	0.041	4.894	0.108	98.6	32.7
February '19	inflow	4.2	7.7	11.87	3.64	0.174	0.046	21.396	0.017	119.6	42.5
	Lake Seeburg	3.7	8.1	12.71	3.08	0.073	0.023	4.078	0.015	101.4	33.5
	outflow	3.8	8.2	13.87	3.20	0.057	0.022	6.271	0.012	101.9	34.8
March '19	inflow	8.6	7.6	11.53	3.96	0.156	0.068	16.471	0.071	118.7	29.6
	Lake Seeburg	7.3	8.5	12.55	3.22	0.015	0.032	4.312	0.022	102.6	33.6
	outflow	7.7	8.5	12.58	3.14	0.025	0.030	4.427	0.032	103.4	33.9
April '19	inflow	8.8	8.2	13.43	4.18	0.132	0.055	15.887	0.023	115.1	30.1
	Lake Seeburg	10.4	8.4	11.67	3.26	0.020	0.028	2.059	0.031	99.9	32.4
	outflow	11.0	8.4	12.38	3.20	0.017	0.028	2.031	0.050	98.1	33.5
May '19	inflow	9.8	8.3	11.58	3.72	0.175	0.063	15.666	0.027	113.9	28.3
	Lake Seeburg	13.7	8.4	9.93	2.84	0.043	0.026	0.897	0.016	101.0	32.6
	outflow	13.8	8.5	11.91	3.10	0.025	0.025	0.777	0.035	100.0	32.7
June '19	inflow	18.3	8.0	6.42	3.26	0.340	0.381	9.339	0.249	93.7	22.0
	Lake Seeburg	25.6	8.9	9.64	3.08	0.034	0.004	0.041	0.038	97.7	30.8
	outflow	25.3	8.8	8.96	2.98	0.039	0.007	0.060	0.058	98.2	30.9
July '19	inflow	17.0	7.8	6.36	4.12	0.499	0.422	8.253	0.101	116.0	21.0
	Lake Seeburg	24.7	8.3	8.07	3.62	0.191	0.013	0.004	0.023	95.7	23.6
	outflow	23.1	8.2	7.32	3.54	0.181	0.009	0.000	0.025	95.1	23.1
August '19	inflow	18.1	7.9	6.54	3.80	0.415	0.080	12.048	0.042	122.7	26.4
	Lake Seeburg	24.0	8.5	6.85	3.52	0.427	0.015	0.073	0.115	97.7	30.7
	outflow	24.9	8.6	7.39	3.42	0.329	0.014	0.000	0.024	96.7	30.9
September '19	inflow	18.6	8.0	7.06	4.04	0.307	0.025	13.567	0.031	123.4	26.1
	Lake Seeburg	24.4	8.9	11.4	3.56	0.354	0.017	0.000	0.027	97.6	31.3
	outflow	23.6	8.7	8.72	3.62	0.373	0.020	0.001	0.031	98.8	31.1
October '19	inflow	13.1	8.1	8.28	4.20	0.242	0.025	12.815	0.030	119.6	24.6
	Lake Seeburg	15.5	8.9	11.25	2.82	0.130	0.027	0.006	0.022	79.3	30.7
	outflow	15.5	9.0	12.26	2.82	0.084	0.025	0.003	0.034	76.9	30.8
November '19	inflow	10.3	7.9	9.41	4.32	0.204	0.060	14.517	0.029	126.0	25.9
	Lake Seeburg	9.9	8.7	10.30	2.90	0.145	0.016	0.108	0.015	81.2	29.9
	outflow	10.4	8.7	10.56	2.80	0.137	0.017	0.063	0.017	80.3	30.1
December '19	inflow	6.5	7.9	10.54	4.50	0.163	0.059	8.585	0.056	128.0	21.8
	Lake Seeburg	4.5	8.3	11.60	3.28	0.251	0.029	0.004	0.220	85.0	24.6
	outflow	4.4	8.2	11.38	3.10	0.250	0.034	0.000	0.209	86.2	24.0

Table S3: Lake inflow between April 2018 and December 2019

Date	Waterflow L s ⁻¹
April '18	225
May '18	157
June '18	136
July '18	115
August '18	99
September '18	95
October '18	84
November '18	97
December '18	195
January '19	223
February '19	315
March '19	148
April '19	124
May '19	117
June '19	146
July '19	98
August '19	87
September '19	72
October '19	117
November '19	92
December '19	116

Table S4: Soluble reactive phosphate (SRP) concentrations in the pore water of the lake sediment in 2018.

Date	SRP mg L ⁻¹
January '18	1.677
February '18	0.614
March '18	0.003
April '18	0.359
May '18	12.303
June '18	3.441
July '18	3.232
August '18	7.767
September '18	34.369
October '18	0.579
November '18	1.468
December '18	0.398

Table S5: Quality classification for nutrients according to the "Bund/Länder-Arbeitsgemeinschaft Wasser" (LAWA), (abbreviated from <https://www.nlwkn.niedersachsen.de/download/92683>, last accessed 12.05.2021, according to Grage et al., 2014)

Nutrient [mg/L]	Quality class						
	I	I-II	II	II-III	III	III-IV	IV
NO ₃ ⁻ -N	≤ 1	≤ 1.5	≤ 2.5	≤ 5	≤ 10	≤ 20	> 20
NO ₂ ⁻ -N	≤ 0.01	≤ 0.05	≤ 0.1	≤ 0.2	≤ 0.4	≤ 0.8	> 0.8
NH ₄ ⁺ -N	≤ 0.04	≤ 0.1	≤ 0.3	≤ 0.6	≤ 1.2	≤ 2.4	> 2.4
PO ₄ ³⁻	≤ 0.05	≤ 0.08	≤ 0.15	≤ 0.3	≤ 0.6	≤ 1.2	> 1.2
PO ₄ ³⁻ -P	≤ 0.02	≤ 0.04	≤ 0.1	≤ 0.2	≤ 0.4	≤ 0.8	> 0.8

Nitrate:

- inflow: III-IV
- lake: II (mean), III (max)

Ammonium:

- inflow: II (mean 2017), I-II (mean 2018/2019), III (max)
- lake: II (mean 2017), I-II (mean 2018/2019)

Nitrite:

- inflow: II-III (mean), III (max 2017), III-IV (max 2018/2019)
- lake: I-II

Soluble reactive phosphate (SRP)

- inflow: II-III (mean), IV (max 2017), III (max 2018/2019)
- lake: II-III (mean), III-IV (max 2017/2018), III (max 2019)

Table S6: Calculations of soluble reactive phosphate (SRP) in- and outputs and dissolutions from the sediment:

	Water volume in- and outflow [L/s]	SRP conc. (inflow) [mg/L]	SRP conc. (outflow) [mg/L]	Inflow [kg/day]	Outflow [kg/day]	Difference [kg/day]	Redissolution from sediment [g/m ² day] ²⁾	Redissolution from sediment [kg/day] ²⁾
July 2017 ¹⁾	550	1.355	0.249	64.3	11.8	52.6		
January 2018		0.220	0.103				0.0032	2.85
February 2018		0.135	0.056				0.0011	0.98
March 2018		0.124	0.007				-0.000016	-0.014
April 2018	225	0.149	0.036	2.9	0.7	2.2	0.00068	0.61
May 2018	157	0.241	0.011	3.3	0.1	3.1	0.025	22.25
June 2018	136	0.267	0.052	3.1	0.6	2.5	0.007	6.23
July 2018	115	0.214	0.024	2.1	0.2	1.9	0.0065	5.785
August 2018	99	0.306	0.099	2.6	0.8	1.8	0.0155	13.8
September 2018	95	0.199	0.667	1.6	5.5	-3.8	0.069	61.4
October 2018	84	0.15	0.687	1.1	5.0	-3.9	-0.0002	-0.178
November 2018	97	0.156	0.414	1.3	3.5	-2.2	0.002	1.78
December 2018	195	0.333	0.323	5.6	5.4	0.2	0.0003	0.267
January 2019	223	0.224	0.208	4.3	4.0	0.3		
February 201	315	0.174	0.057	4.7	1.6	3.2		
March 2019	148	0.156	0.025	2.0	0.3	1.7		
April 2019	124	0.132	0.017	1.4	0.2	1.2		
May 2019	117	0.175	0.025	1.8	0.3	1.5		
June 2019	146	0.34	0.039	4.3	0.5	3.8		
July 2019	98	0.499	0.181	4.2	1.5	2.7		
August 2019	87	0.415	0.329	3.1	2.5	0.6		
September 2019	72	0.307	0.373	1.9	2.3	-0.4		
October 2019	117	0.242	0.084	2.4	0.8	1.6		
November 2019	92	0.204	0.137	1.6	1.1	0.5		
December 2019	116	0.163	0.250	1.6	2.5	-0.9		

¹⁾ The maximum flow through a weir (550 L/s) downstream of the Seeanger wetland was consistently reached during the heavy rain event.

²⁾ For calculation see table 7.

Table S7: Calculation of the amount of soluble reactive phosphate (SRP) released from the sediment into the pore water during the cyanobacterial bloom in 2018. Calculation according to Scholtysik et al., 2020.

$J_P = \frac{\varphi}{\theta^2} * D_P * \frac{\Delta C_P}{\Delta z}$
$\phi = \frac{\frac{\omega}{\rho(\text{water})}}{\frac{\omega}{\rho(\text{water})} + \frac{1 - \omega}{\rho(\text{sediment})}} = \frac{\frac{0.7}{1}}{\frac{0.7}{1} + \frac{1 - 0.7}{2.43}} = 0.85$
$\rho(\text{sediment}) = \frac{1}{\frac{LOI}{\rho(\text{org})} + \frac{1 - LOI}{\rho(\text{min})}} = \frac{1}{\frac{0.10}{1.4} + \frac{1 - 0.1}{2.65}} \text{ g cm}^{-3} = 2.43 \text{ g cm}^{-3}$
$\theta = \sqrt{1 - \ln \Phi^2} = \sqrt{1 - \ln(0.84)^2} = 0.98$
$J_P = \frac{\varphi}{\theta^2} * D_P * \frac{\Delta C_P}{\Delta z} = \frac{0.84}{0.98^2} * 4.7 * 10^{-5} * \frac{34.4 - 0.69}{0.02} \text{ g m}^{-2} \text{ day}^{-1} = 0.069 \text{ g m}^{-2} \text{ day}^{-1} = 61.4 \text{ kg day}^{-1} \text{ in the hole lake}$

where:

- J_P is the diffusion rate of P ($\text{g m}^{-2} \text{ day}^{-1}$)
- φ is the porosity
- ρ is the density [g cm^{-3}]
- θ is the tortuosity
- D_P is the molar diffusion coefficient of Phosphate in the sediment ($5.5 * 10^{-6} \text{ cm}^2 \text{ s}^{-1}$ or $4.7 * 10^{-5} \text{ m}^2 \text{ s}^{-1}$)*

* according to Bourdreau, BP. (1997). Diagenetic models and their implementation. Vol. 410. Springer, Berlin.