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Supplement of

Long-term temperature, oxygen and water clarity trends in Swiss lakes

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S1 Details about resolution, instruments and their accuracy

Lake	Time and space resolution			Instrument specifications									
	Period	Time frequency	Depth resolution	Period	Temperature			Conductivity			Oxygen		
					instrument	type	accuracy	instrument	type	accuracy	instrument	type	accuracy
Lake Baldegg and Sempach	until 1982	sparse	discrete	until Nov 2006	Meereselektronik	sonde	0.01 °C	unknown	lab	unknown	Winkler	lab	2 - 6 % **
	1982-2014	monthly	discrete	Dec 2006 - Dec 2007	Hydrolab MS5	sonde	0.1 °C	Hydrolab MS5	sonde	1 uS/cm	Winkler	lab	2 - 6 % **
	since 2015	8/year	discrete	Jan 2008 - Mar 2023	Hydrolab MS5	sonde	0.1 °C	Hydrolab MS5	sonde	1 uS/cm	Hydrolab MS5	sonde	0.2 mg/L
				since Apr 2023	In-situ Aquatroll	sonde	0.1 °C	In-situ Aquatroll	sonde	2 uS/cm	In-situ Aquatroll	sonde	0.1 mg/L
Lake Biel, Thun and Brienz				until 1993	unknown			unknown			unknown		
	until 1994	sparse	discrete	1994 - Mar 2021	Seabird	sonde	0.005 °C	Seabird	sonde	1 uS/cm	Seabird	sonde	0.14 mg/L
	since 1995	monthly	continuous	since Apr 2021	RBR Maestro	sonde	0.002 °C	RBR Maestro	sonde	3 uS/cm	RBR Maestro	sonde	5%
Lake Murten	1986 - 1998	sparse	discrete	until 2001	thermometer	field	unknown	unknown			unknown		
	since 1999	monthly	continuous	2001 - Mar 2021	Seabird	sonde	0.005 °C	Seabird	sonde	1 uS/cm	Seabird	sonde	0.14 mg/L
				since Apr 2021	RBR Maestro	sonde	0.002 °C	RBR Maestro	sonde	3 uS/cm	RBR Maestro	sonde	5%
Lake Neuchatel	1957 - 1998	sparse	discrete	until 2001	thermometer	field	unknown	unknown			unknown		
	since 1999	monthly	continuous	2001 - Mar 2021	Seabird	sonde	0.005 °C	Seabird	sonde	1 uS/cm	Seabird	sonde	0.14 mg/L
				since Apr 2021	RBR Maestro	sonde	0.002 °C	RBR Maestro	sonde	3 uS/cm	RBR Maestro	sonde	5%
Lake Geneva	until 1969	sparse	discrete	until Mar 1991	inverse thermometer	field	0.02 °C *	unknown			unknown		
	since 1970	ca. 18/year	continuous	since Mar 1991	diverse sondes	sonde	diverse	diverse sondes	sonde	diverse	diverse sondes	sonde	diverse
Greifensee and Lake Pfaffikon				until Dec 1999	unknown			unknown			unknown		
	until 1955	sparse	discrete	Jan 2000 - Aug 2013	YSI 6600	sonde	0.15 °C	YSI 6600	sonde	0.5 % + 1 uS/cm	YSI 6600	sonde	2 % / 0.2 mg/L
	since 1956	monthly	discrete	Sept 2013 - Oct 2016	EXO1	sonde	0.01 °C	EXO1	sonde	0.5 % / 1 uS/cm	EXO1	sonde	1 % / 0.1 mg/L
				since Nov 2016	EXO2	sonde	0.2 °C	EXO2	sonde	1% / 2 uS/cm	EXO2	sonde	1 % / 0.1 mg/L
Lake Hallwil	until 1985	sparse	discrete	1969 - 1997	HPT (Züllig)	sonde	0.1 °C	HPT (Züllig)	sonde	1 uS/cm	HPT (Züllig)	sonde	0.1 mg/L
	since 1985	monthly	discrete	1997 - 2016	YSI 6000	sonde	0.15 °C	YSI 6000	sonde	0.5 % / 1 uS/cm	YSI 6000	sonde	0.2 mg/L
				since 2016	Exo 2	sonde	0.2 °C	Exo 2	sonde	1 % / 2 uS/cm	Exo 2	sonde	1 % / 0.1 mg/L
Lake Joux	1984 - 2023	monthly	discrete	1984 - 2007	unknown			unknown			unknown		
				2008 - 2011	YSI ProODO	sonde	0.3 °C	unknown			YSI ProODO	sonde	2 %/0.2 mg/L
				2012 - 2022	YSI ProODO	sonde	0.3 °C	Mettler T7	lab	2%	YSI ProODO	sonde	2 %/0.2 mg/L
				2022 - 2023	YSI ProODO	sonde	0.3 °C	HQ440d Hach-Lang	lab	3%	YSI ProODO	sonde	2 %/0.2 mg/L
Lake Maggiore	since 1988	monthly	discrete	until 2015	inverse thermometer	field	0.02 °C *	conductometry	lab	1 uS/cm	Winkler	lab	2 - 6 % **
				since 2015	Idronaut OS7 CTD304	sonde	0.005 °C	conductometry	lab	1 uS/cm	Winkler	lab	2 - 6 % **
Walensee	monthly to 2001; 4/year after		discrete	until Jan 2001	various	field	0.1 °C	conductometry	lab	6 uS/cm	Winkler	lab	2 - 6 % **
Upper Lake Zurich	monthly to 2005; 6/year after		discrete	Feb 2001 - Jul 2008	FLP-10	sonde	0.1 °C	FLP-10	sonde	1 uS/cm	FLP-10	sonde	0.2 mg/L
Lower Lake Zurich	monthly		discrete	since Aug 2008	DS5, HL4, EXO3	sonde	0.1 - 0.2 °C	DS5, HL4, EXO3	sonde	1 % or 2 uS/cm	DS5, HL4, EXO3	sonde	0.1 - 0.2 mg/L
Lake Zug				until 1961	inverse thermometer	field	0.02 °C *	unknown			Winkler	lab	2 - 6 % **
				1961 - 1970	Oxytester	sonde	unknown	unknown			Winkler	lab	2 - 6 % **
	until 1975	sparse	discrete	1970 - 1993	inverse thermometer	field	0.02 °C *	Metrohm probe	lab	unknown	Winkler	lab	2 - 6 % **
	since 1976	monthly	discrete		and HPT (Züllig)	sonde	unknown						
	since 1993	monthly	continuous	1993 - 2020	Seabird SBE19	sonde	0.01 °C	Seabird SBE19	sonde	1 uS/cm	Seabird SBE19	sonde	2%
				since 2020	Exo3	sonde	0.01 °C	Exo3	sonde	0.5 % / 1 uS/cm	Exo3	sonde	0.1 mg/L
Upper Lake Constance	since 1963	monthly	discrete	until 2017	unknown			unknown			unknown		unknown
				since 2017	Hydrobios CT-Set	sonde	0.005 °C	Hydrobios CT-Set	sonde	10 uS/cm	Winkler	lab	2 - 6 % **
Lower Lake Constance	since 1974	monthly	discrete	until 2017	unknown			unknown			unknown		
				since 2017	Exo2	sonde	?	Exo2	sonde	1 % / 2 uS/cm	Exo2	sonde	1 % / 0.1 mg/L
Upper and Lower Lake Lugano	since 1987	12 - 24/year	continuous	1987 - 1996	Idronaut 501	sonde	0.01 °C	Idronaut 501	sonde	20 uS/cm	Idronaut 501	sonde	0.1 mg/L
				since 1997	Idronaut 316	sonde	0.002 °C	Idronaut 316	sonde	3 uS/cm	Idronaut 316	sonde	0.1 mg/L

*Table S1: Measurement methods for temperature, electrical conductivity and oxygen concentration for 21 lakes and lake basins. The information was provided by the cantonal environmental offices and international lake commissions. *typical accuracy according to American Meteorological Society (2025), **typical accuracy according to DIN EN 25813:1993-01.*

S2 Additional calibration information for monitoring data

<u>Lake Baldegg and Lake Sempach</u>

Information from Canton Lucerne: Monthly calibration of sonde.

<u>Lake Biel, Lake Thun, Lake Brienz, Lake Murten and Lake Neuchâtel 1999 - 2023</u>

Information from Canton Bern: As an accredited laboratory, all measurements and instruments are subject to strict quality control procedures. Data collected by the Seabird and RBR Maestro instruments are regularly compared with in situ measurements taken using a different sensor (e.g., WTW Multi 3630). Additionally, oxygen concentrations are routinely verified using the Winkler titration method (ISO 5813:1983).
If any measured values—particularly oxygen—fall outside the acceptable range of deviation, they are corrected accordingly.
No digital records of quality control procedures exist prior to 2008. From 2008 onward, instruments have been regularly quality controlled. When quality standards were not met, the affected sensors were calibrated, serviced, or replaced.
Quality control was conducted as follows:

- **Seabird**: From September 2008 to September 2021, checks were performed in January, May, June, and September each year.
- **RBR Maestro**: Checks were performed in:
    - May and September 2021
    - January, May, and September 2022
    - January and May 2023

<u>Lake Murten 1986 – 2001</u>

Temperature data below 5 m shows many measurement artifacts (e.g. increasing temperature towards bottom) and is not in agreement with the CTD-monitoring from 1999 – 2023 in the overlapping period (1999 – 2001). Also, oxygen measurements at the bottom were shown to be suspicious (Müller and Schmid, 2009). Therefore, all measurements below 5 m are disregarded between 1986 and 1999.

<u>Lake Hallwil</u>

Information from Canton Aargau about calibration of the Exo2 sonde:

pH: monthly

O2: 4 times a year

Temperature, depth, turbidity: every few years, in case of instrument revision

Chlorophyll, phycocyanin: comparison of trends with measurements from photometric measurements from bulk samples.

Sonde comparison between different offices and cantons 2013, 2022, 2025

<u>Walensee and Upper and Lower Lake Zurich</u>

Information from Wasserversorgung Zürich (WVZ) about calibration of sensors:

The temperature sensor is checked twice a year in a water bath using a calibration thermometer. If the deviation is 0.2°C, the sensor is sent to the manufacturer for recalibration. The temperature sensor can only be calibrated by the manufacturer.

The oxygen sensor is calibrated before each profile measurement by determining the 100% value in moist air. Calibration (100% O_2 saturation) including a control sample with zero oxygen in the laboratory is done four times a year. If the tolerable range is exceeded, a new calibration is performed and, if necessary, the sensor cap is replaced.

The conductivity sensor is calibrated twice a year in the laboratory (1-point calibration, 5 mM KCl at 25°C).

S3 Sonde comparison between different cantonal offices

Several cantons regularly compare their monitoring sondes in dedicated comparison experiments. Here, the comparison for temperature, conductivity and oxygen is shown for 2013 (in Lake Constance; organized by Canton Bern and ISF Langenargen), 2019 (in Lake Biel; organized by Canton Bern) and 2022 (in Lake Hallwil; organized by Canton Aargau). The data from 2013 (Figure S3.1) shows a fair agreement between the sondes for temperature (one sonde showing a bias of around 1 °C) and conductivity, and a good agreement for oxygen concentrations (all sondes within ± 0.5 mg/L).

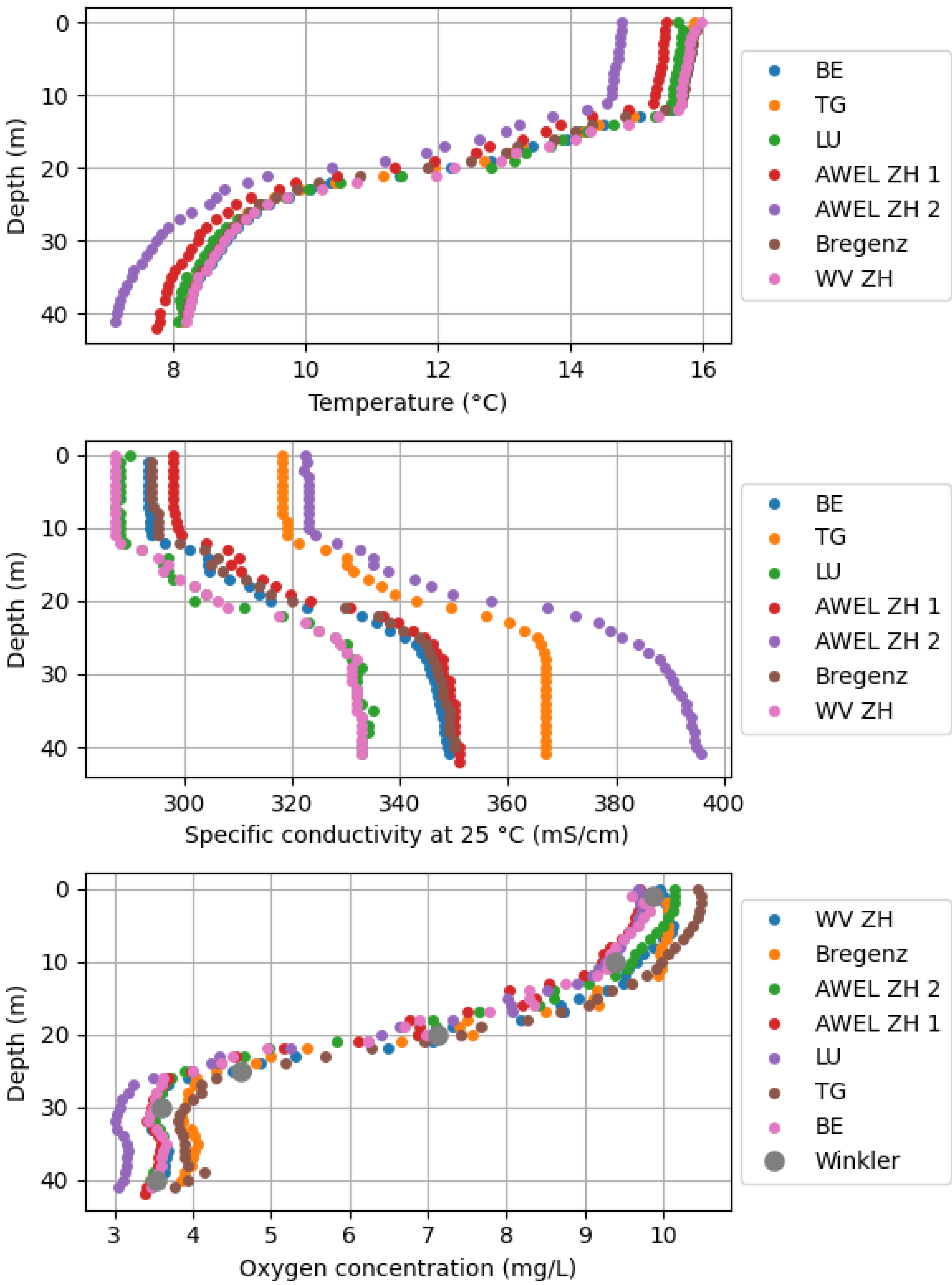

Figure S1: Comparison of temperature, specific conductivity, and oxygen concentration measured by the monitoring sondes of various cantonal environment agencies (Canton Bern, Canton Thurgau, Canton Lucerne, AWEL Zurich (2 sondes), Bregenz and WV Zurich) in 2013 in Lake Constance.

The data from 2019 (Figure S3.2) shows very good agreement for temperature, conductivity and oxygen concentration. The Seabird instrument (SBE) of Canton Zug overestimates temperature by a few tenth of a degree, though.

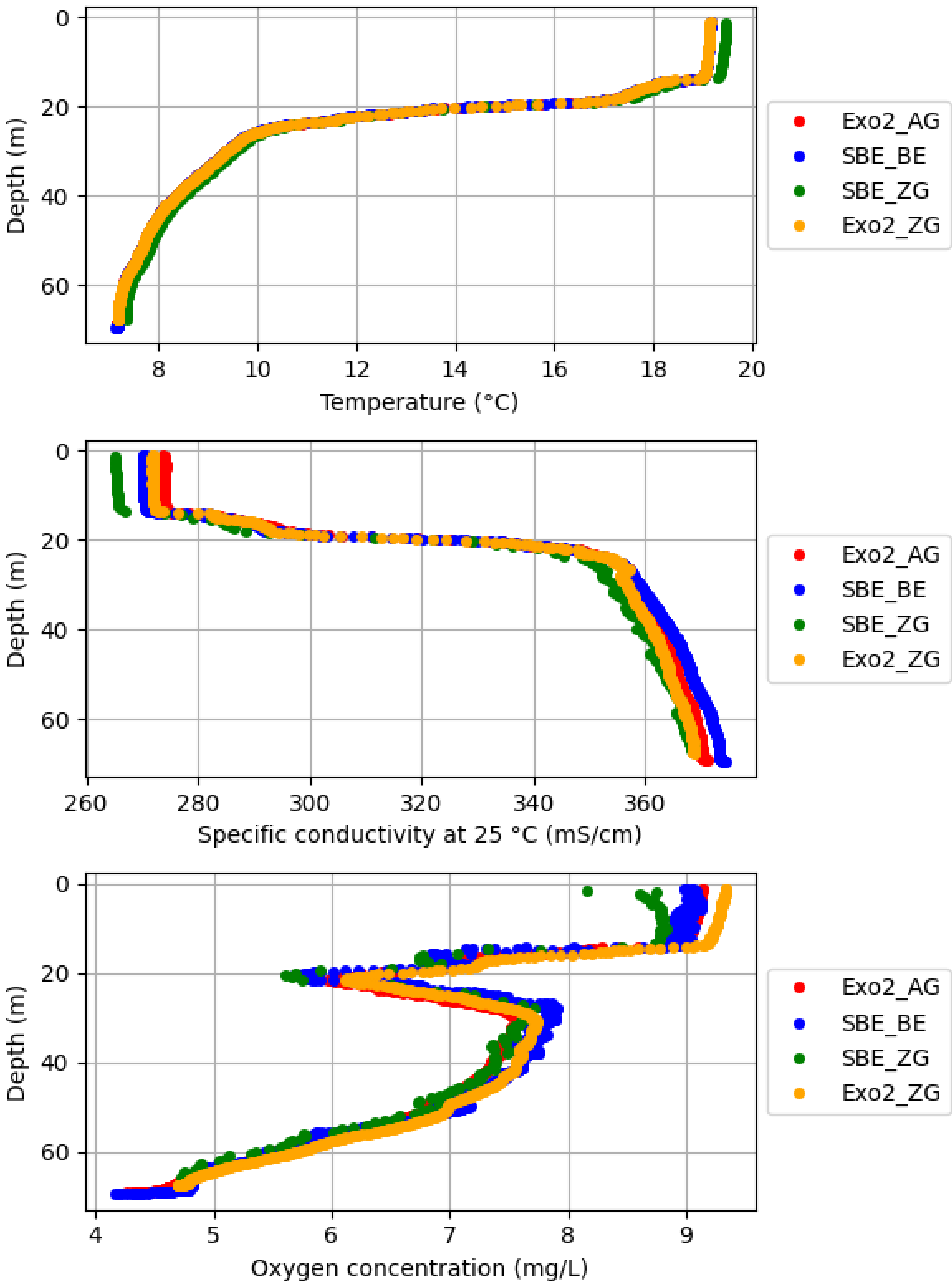

Figure S2: Comparison of temperature, specific conductivity, and oxygen concentration measured by the monitoring sondes of the environmental agencies of Cantons Aargau, Bern and Zug (2 sondes) in 2019 in Lake Biel.

The data from 2022 (Figure S3.3) shows a very good agreement for temperature and a good agreement for conductivity (one sonde has a positive bias) and oxygen concentration, where the main differences occur when concentration changes rapidly with depth. The latter issue is most probably related to different response times of the oxygen sensors.

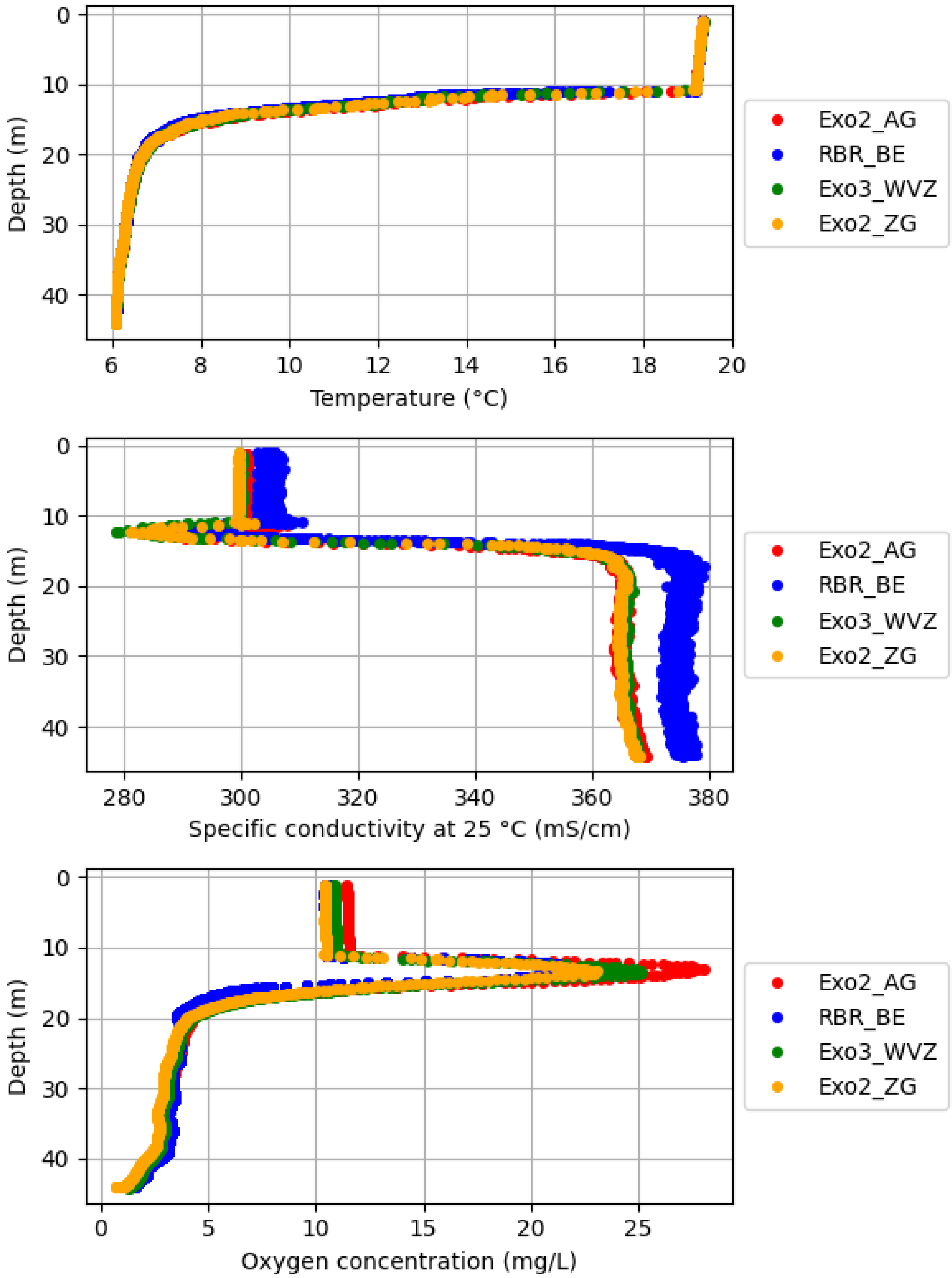

Figure S3: Comparison of temperature, specific conductivity, and oxygen concentration measured by the monitoring sondes of the environmental agencies of Cantons Aargau, Bern, Zug and WV Zurich in 2022 in Lake Hallwil.

S4 Chen & Millero (1986) density formula

$$\rho = 1000(0.9998395 + 6.7914 * 10^{-5}T - 9.0894 * 10^{-6}T^2 + 1.0171 * 10^{-7}T^3 - 1.2846 * 10^{-9}T^4 + 1.1592 * 10^{-11}T^5 - 5.0125 * 10^{-14}T^6 + (8.181 * 10^{-4} - 3.85 * 10^{-6} * T + 4.96 * 10^{-8}T^2)S)$$

S5 Additional summary plots

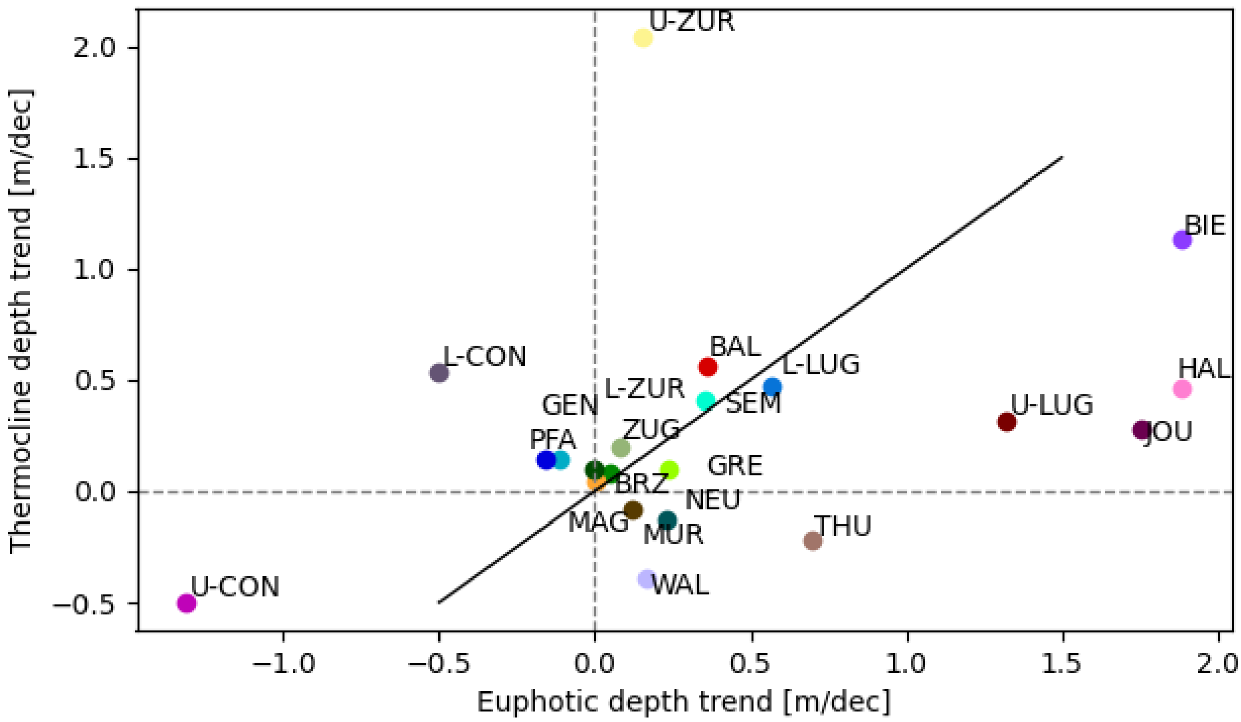

*Figure S4: Trend of euphotic depth (calculated as 2.5 * Secchi depth) vs. trend of thermocline depth since 1980*

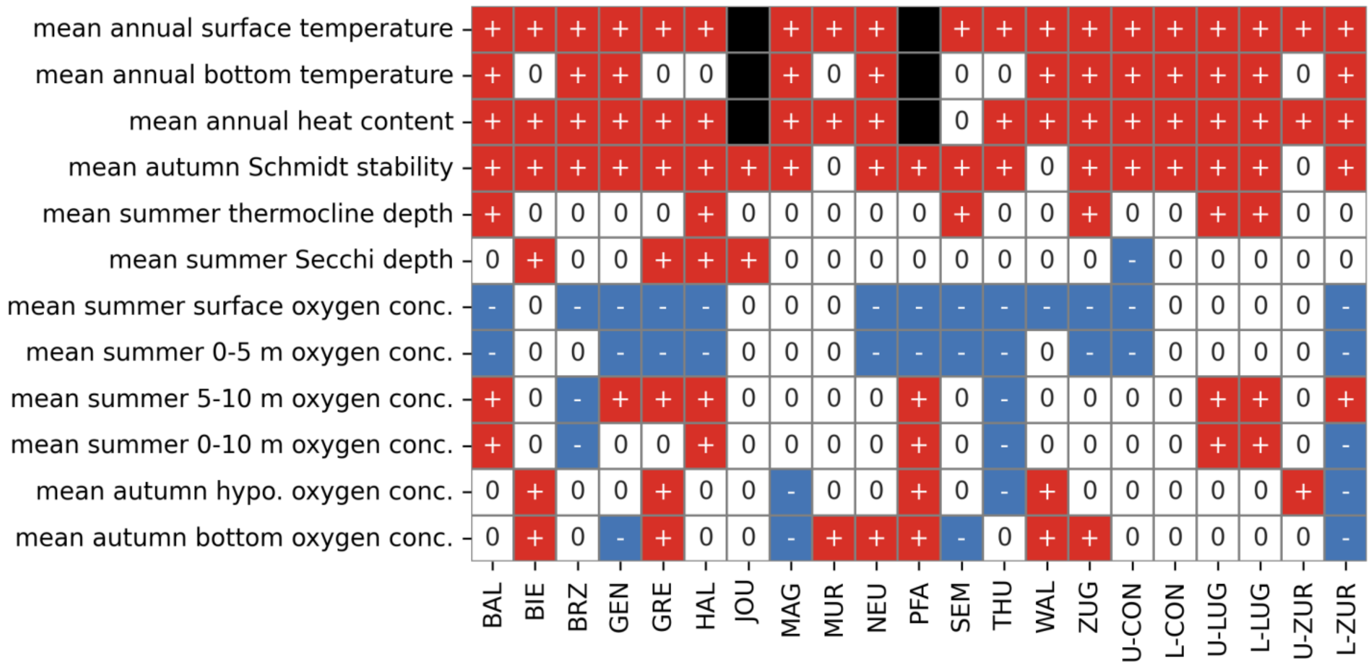

Figure S5: Significance of linear trends of several variables for all lakes. The trends are calculated between 1980 and 2023 with Theil Sen slopes. A slope is considered significantly positive ("+") if the whole 95 % uncertainty envelope is positive and significantly negative ("-") if the whole 95 % uncertainty envelope is negative. Non-significant trends are shown with a "0" and black means that there was not enough data to compute a trend.

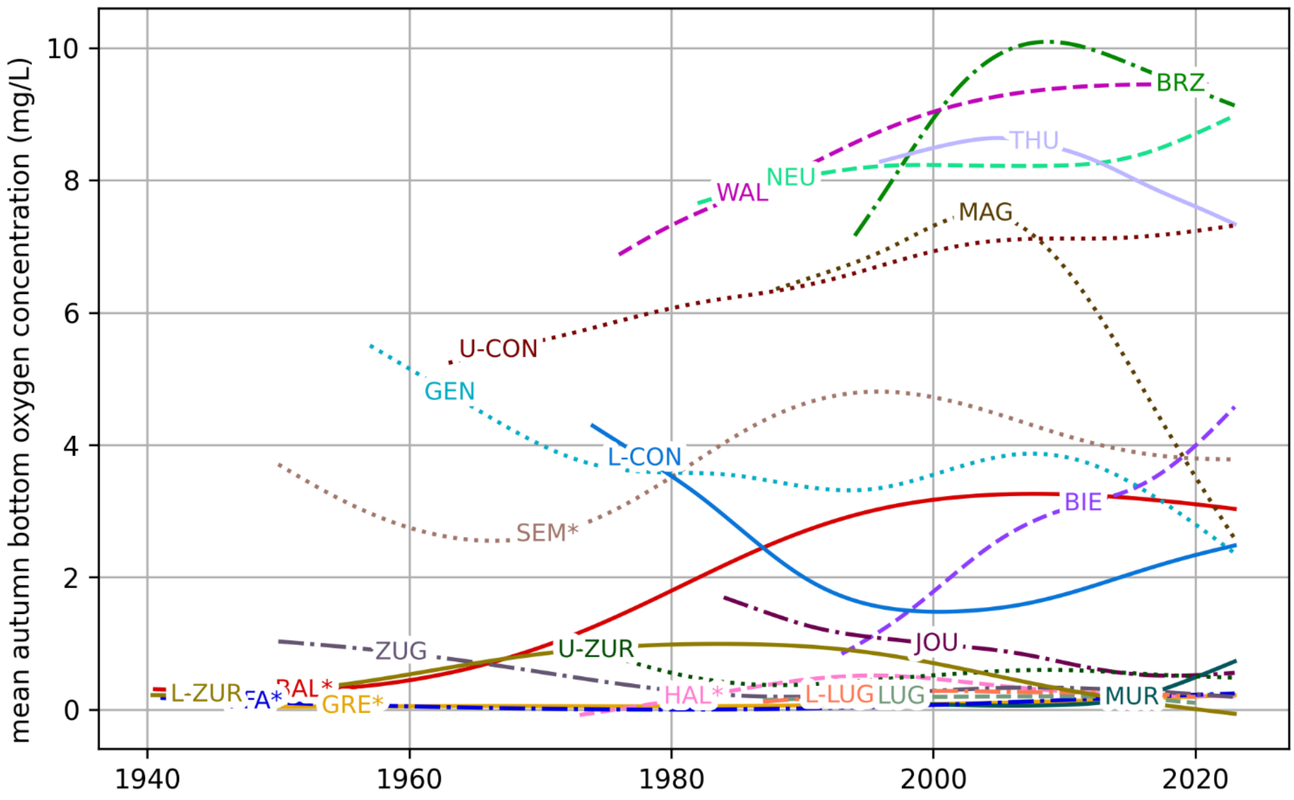

Figure S6: Mean autumn bottom oxygen concentration of 21 Swiss lakes and lake basins calculated using GAM regression. The lake codes are explained in Figure 1 in the main paper. Lakes with asterisk are or were artificially aerated: BAL since 1982, SEM since 1984, HAL since 1986, GRE since 2009 (only a small aeration system) and PFA between 1992 and 2010.

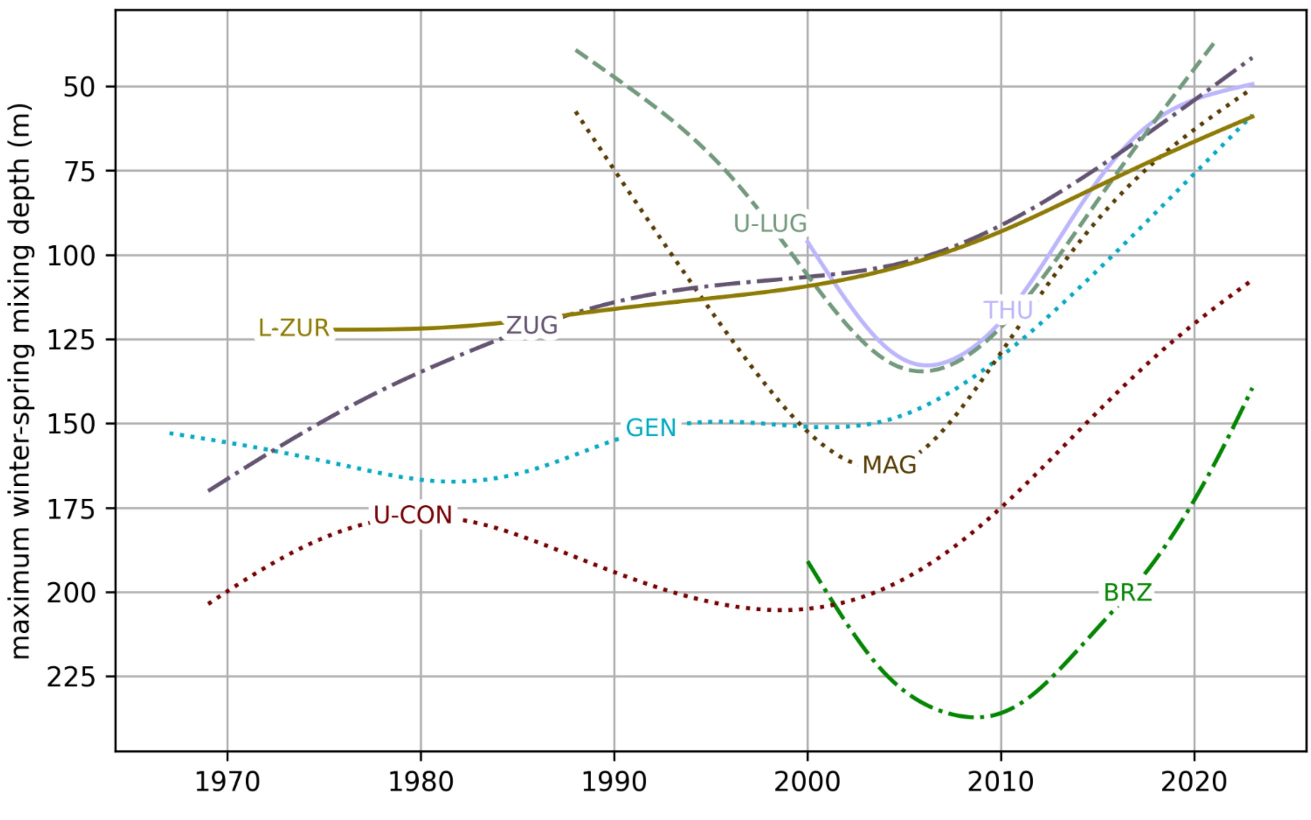

Figure S7: Maximum winter-spring mixing depth of 8 oligomictic Swiss lakes and lake basins calculated using GAM regression. Maximum winter-spring mixing depth is defined as the maximum depth at which density is still within a fixed threshold (0.005 kg/m³) compared to the surface. The surface is defined at 5 m depth such that re-stratification at the surface is neglected. The lake codes are explained in Figure 1 in the main paper.

S6 Detailed results for all lakes and lake basins

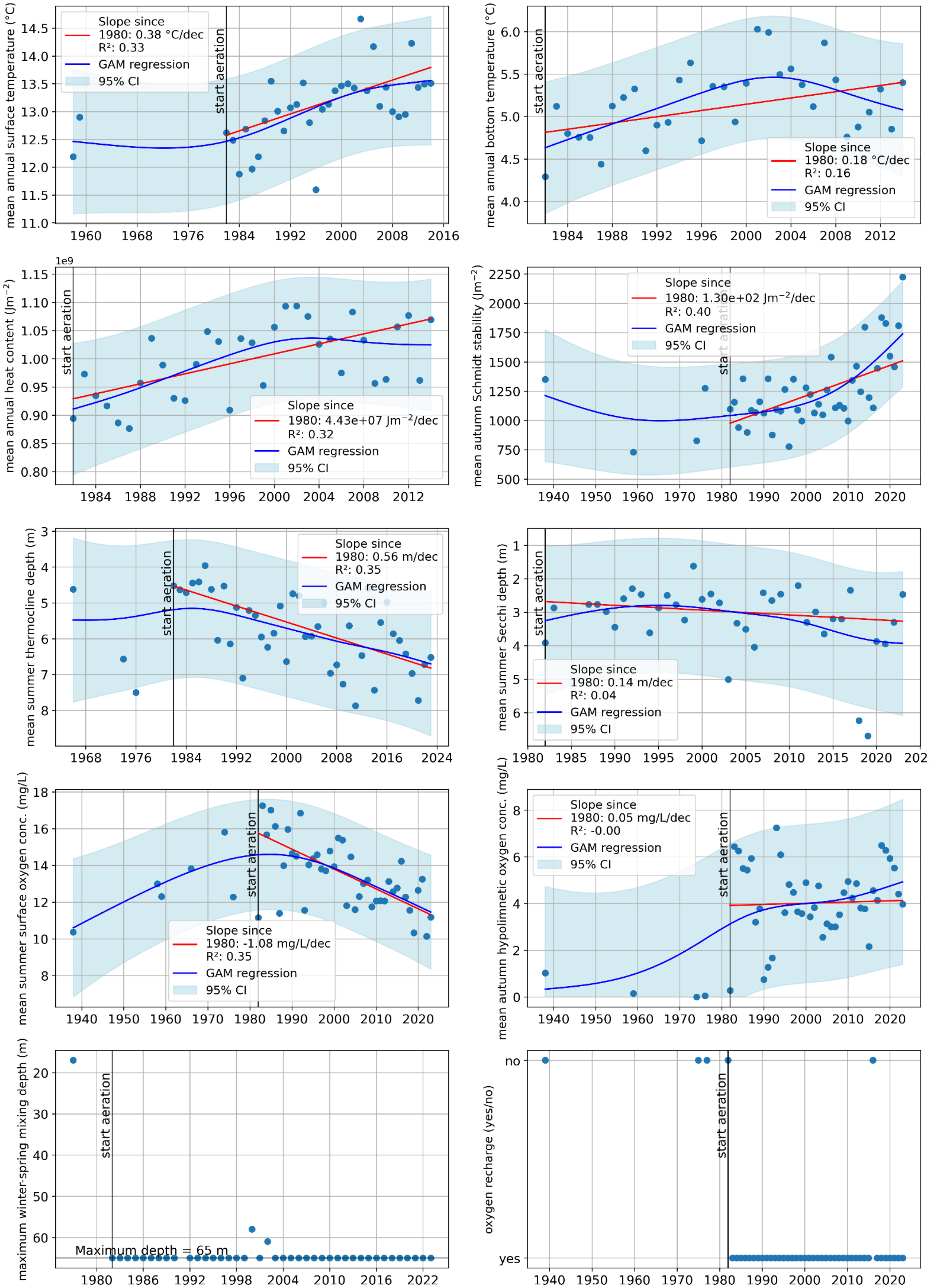

Figure S8: Detailed results of Lake Baldegg. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

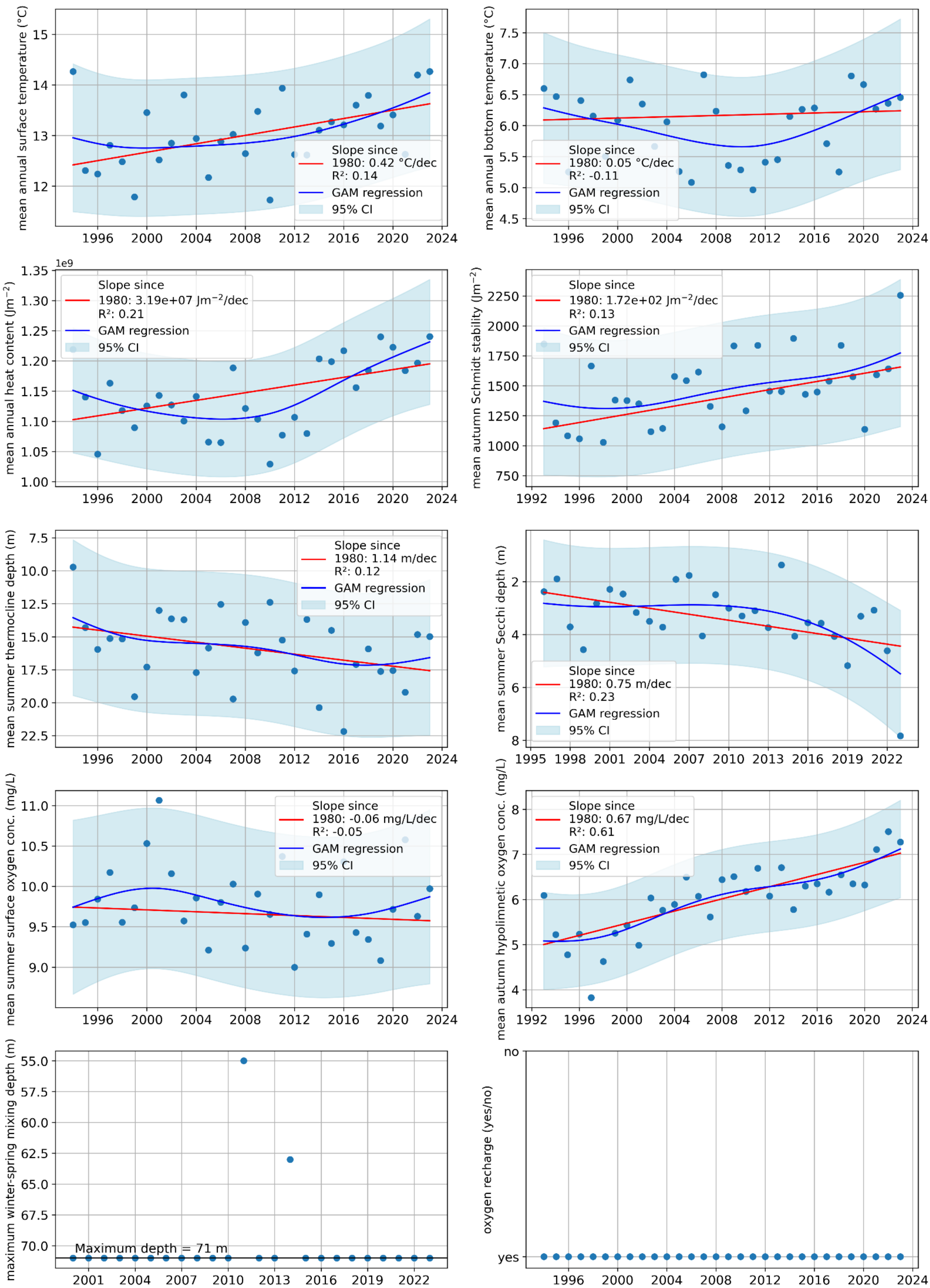

Figure S9: Detailed results of Lake Biel. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

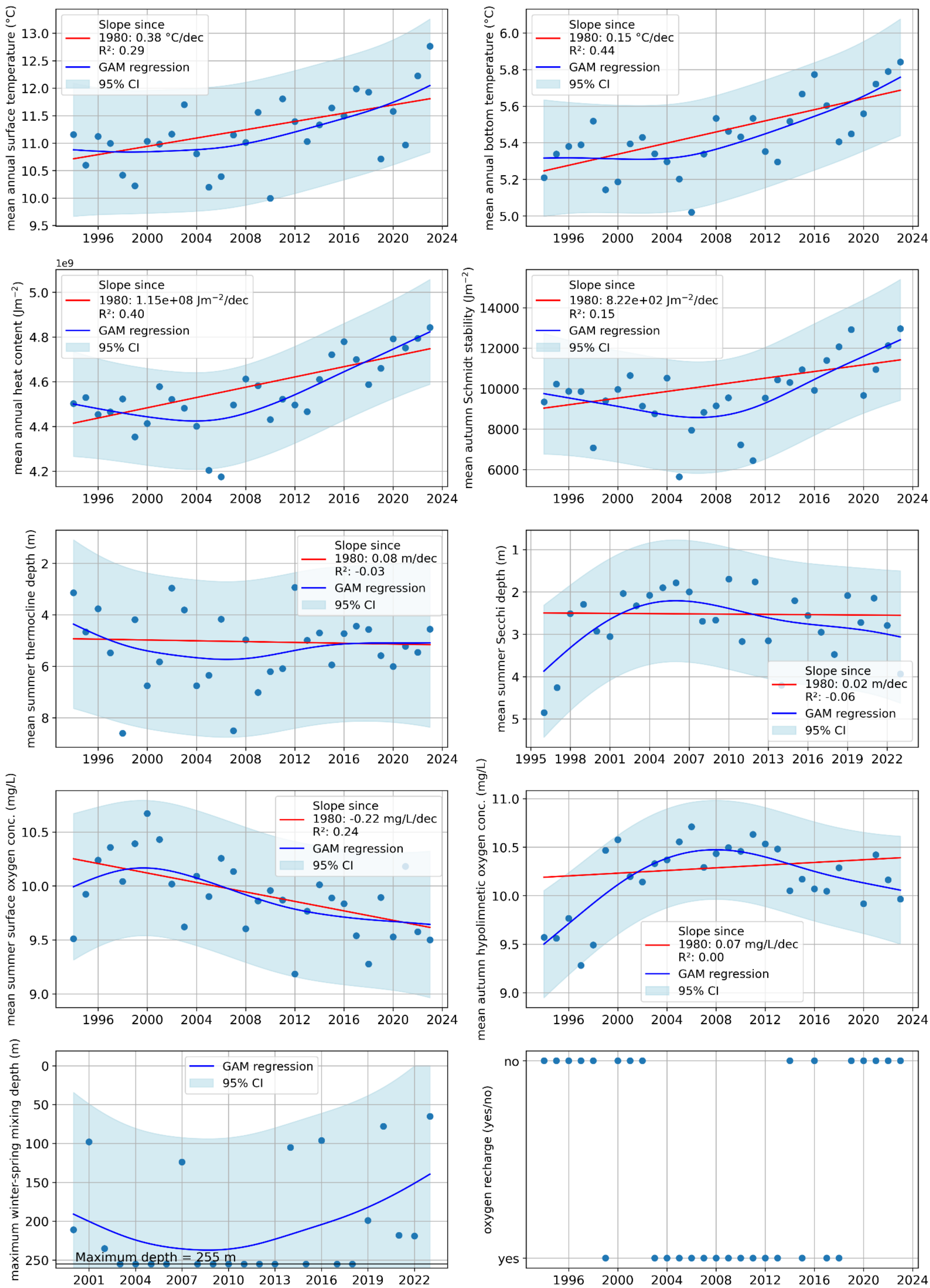

Figure S10: Detailed results of Lake Brienz. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

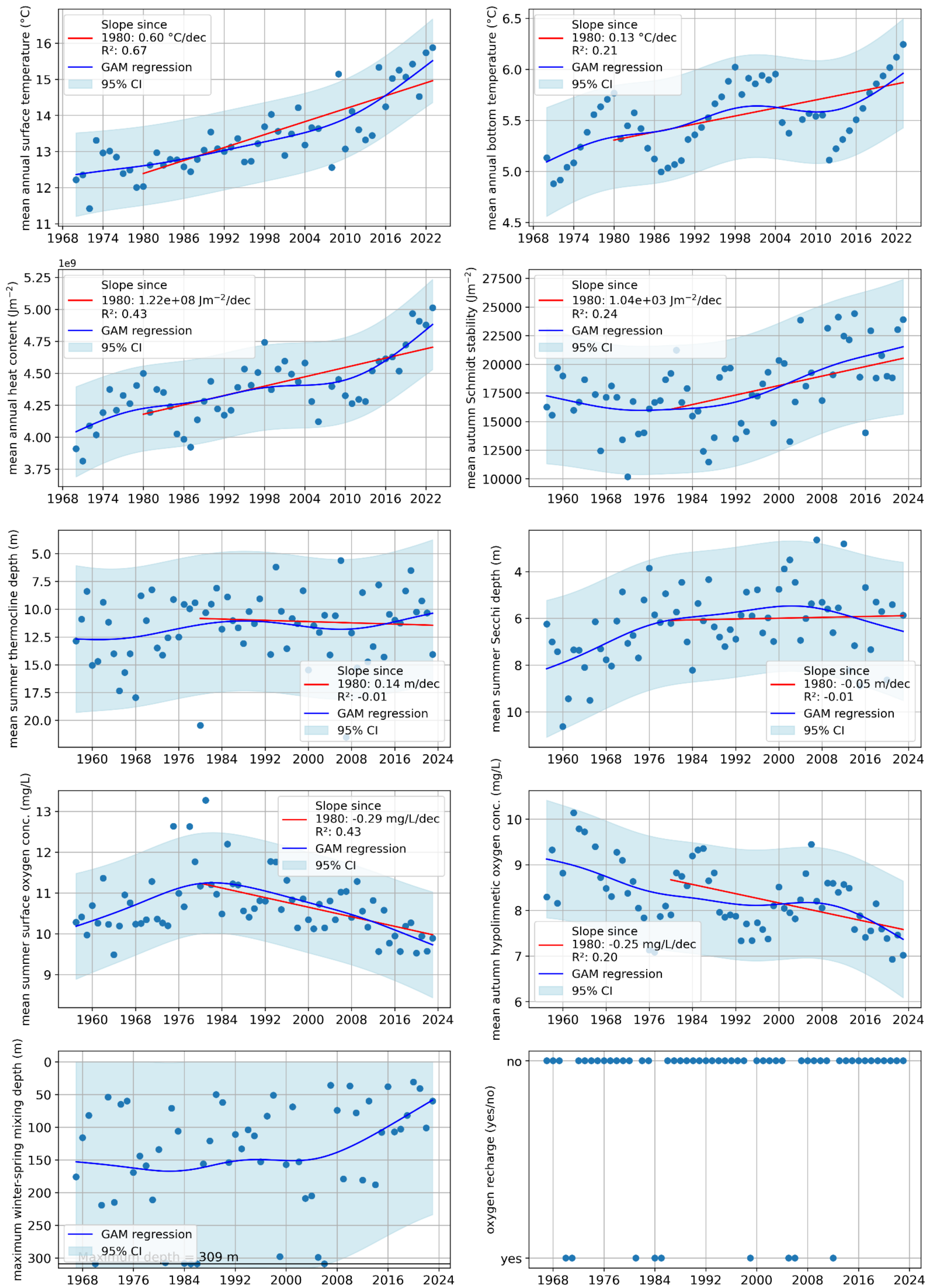

Figure S11: Detailed results of Lake Geneva. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

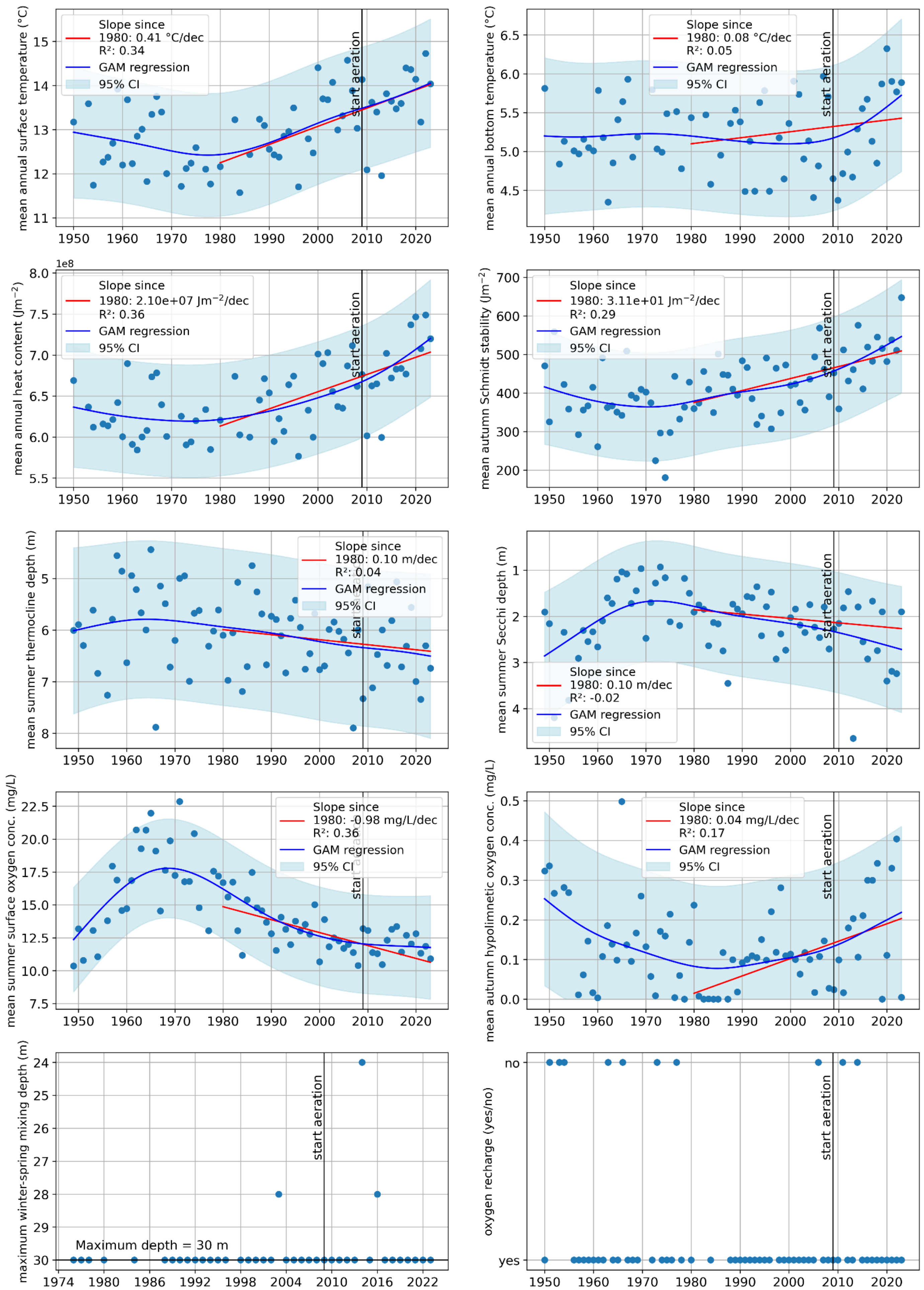

Figure S12: Detailed results of Greifensee. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue. The aeration system in Greifensee is not comparable to systems in other lakes and only influences a small part of the lake.

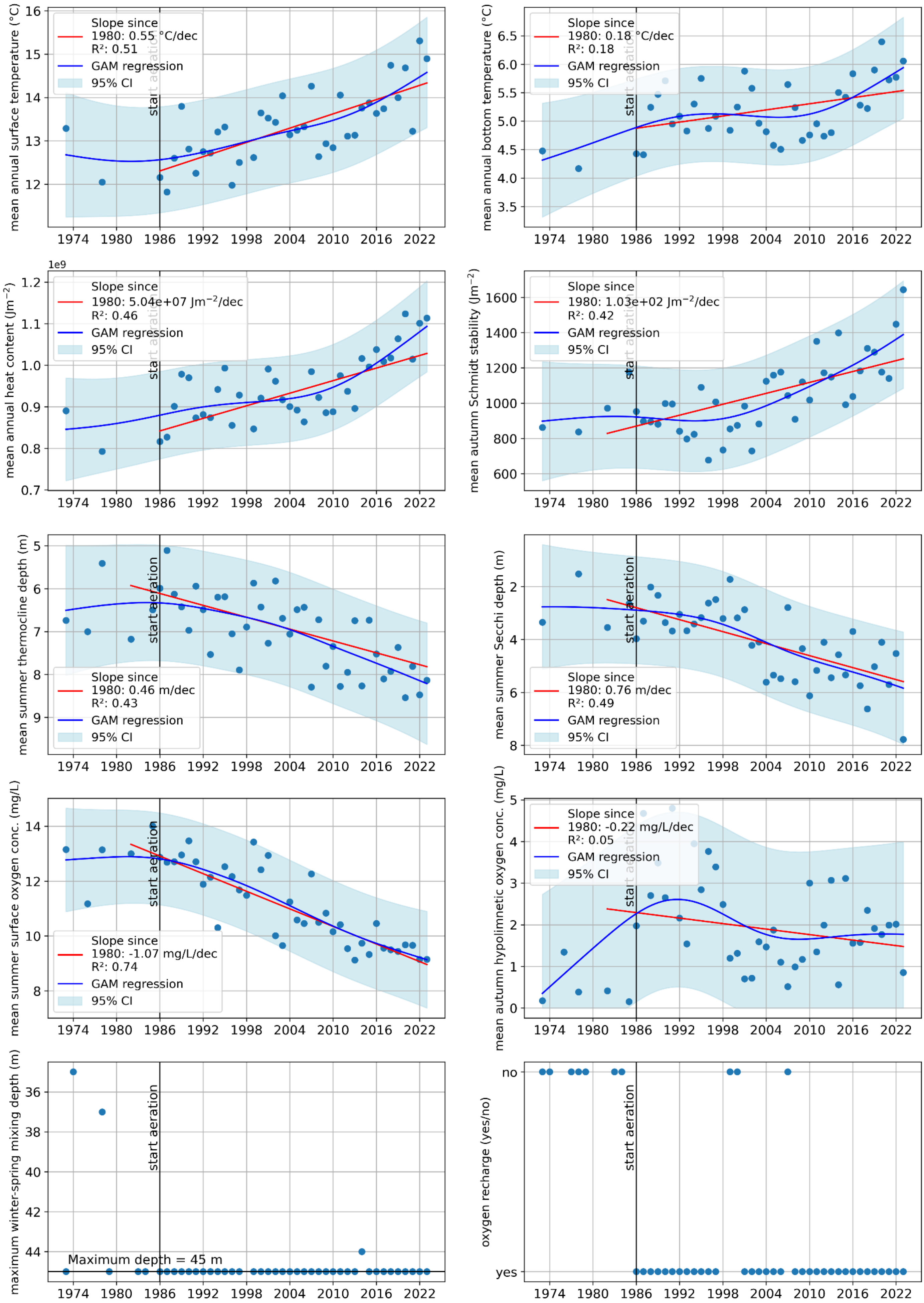

Figure S13: Detailed results of Lake Hallwil. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

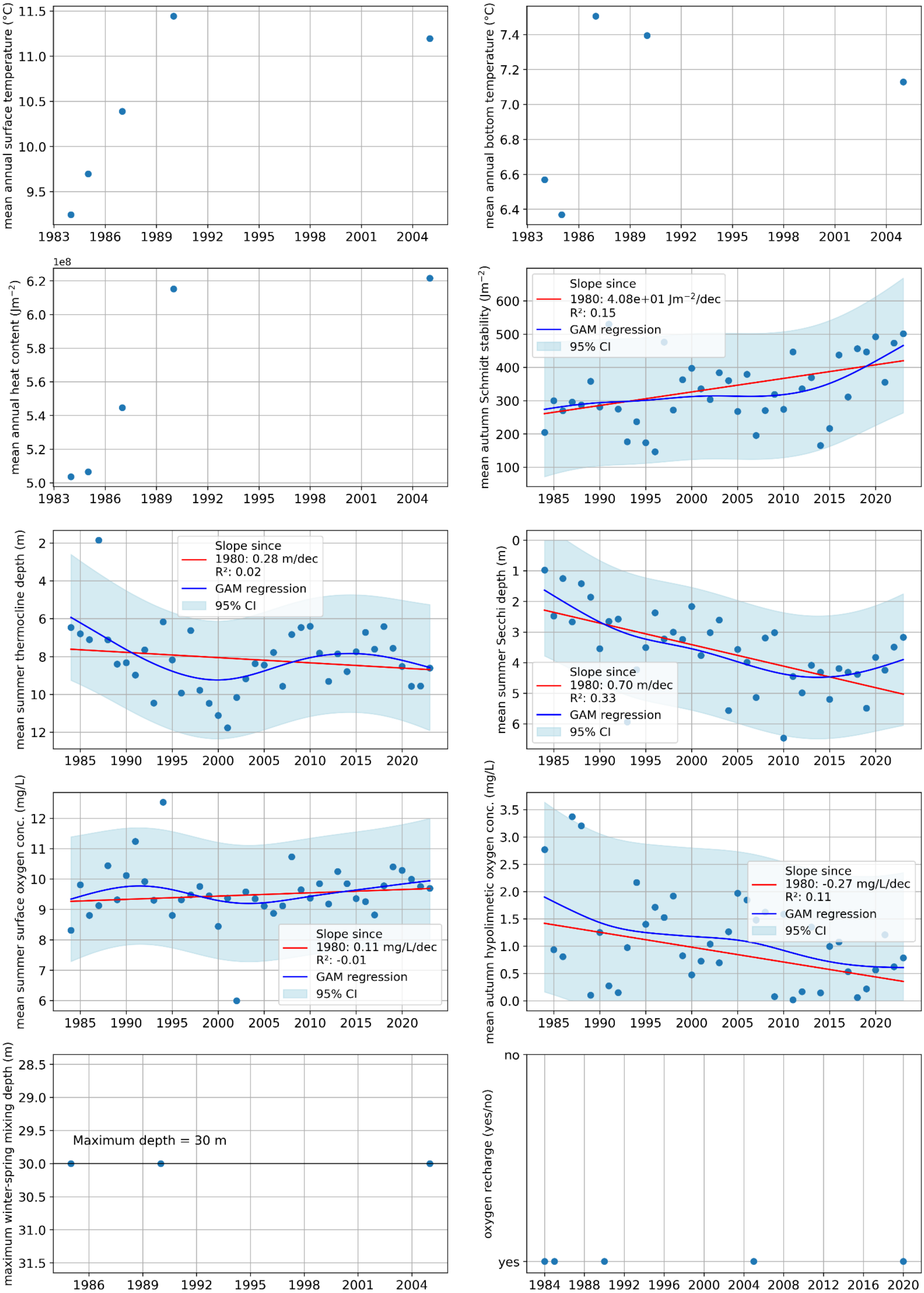

Figure S14: Detailed results of Lac de Joux. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

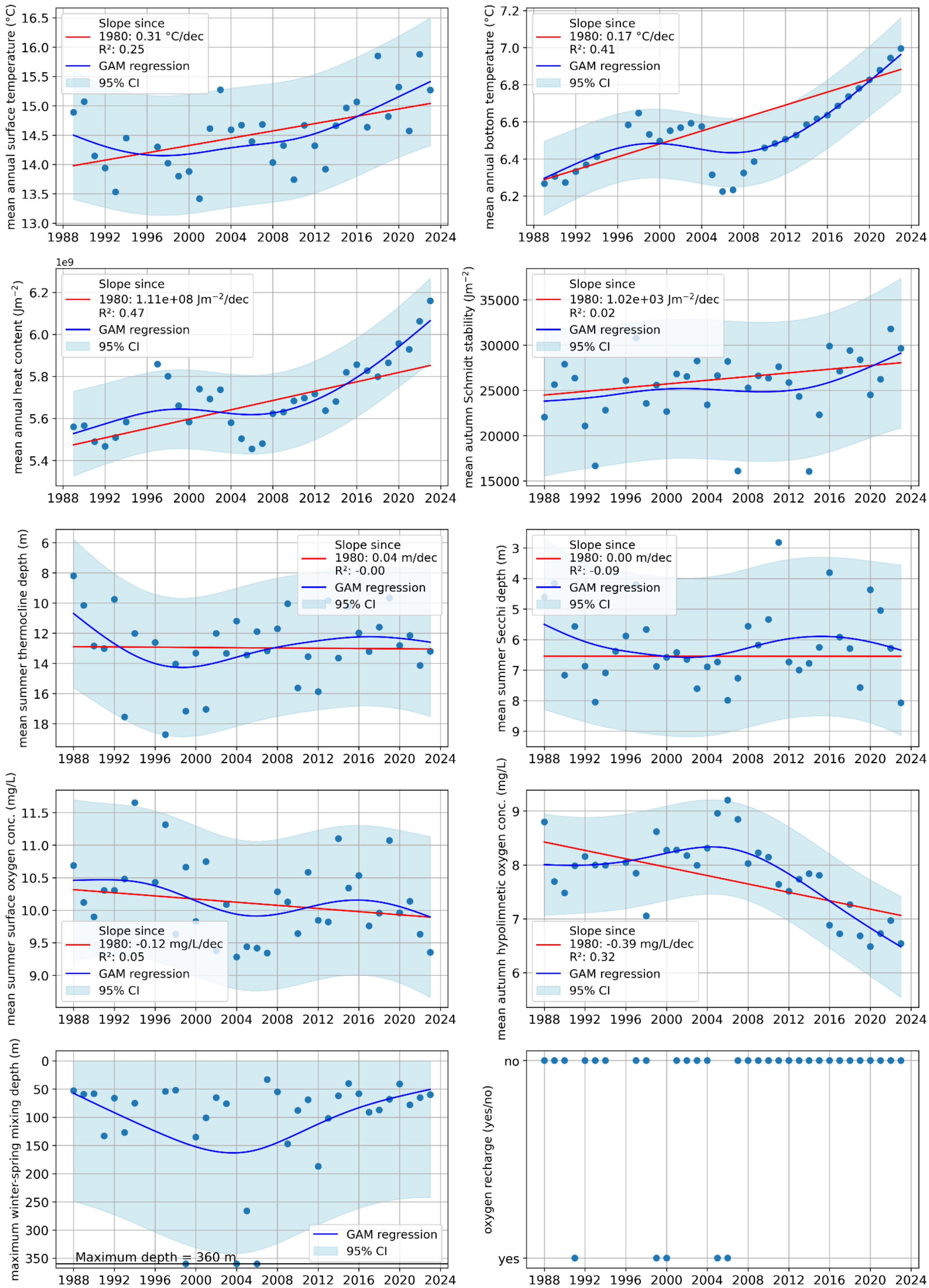

Figure S15: Detailed results of Lake Maggiore. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

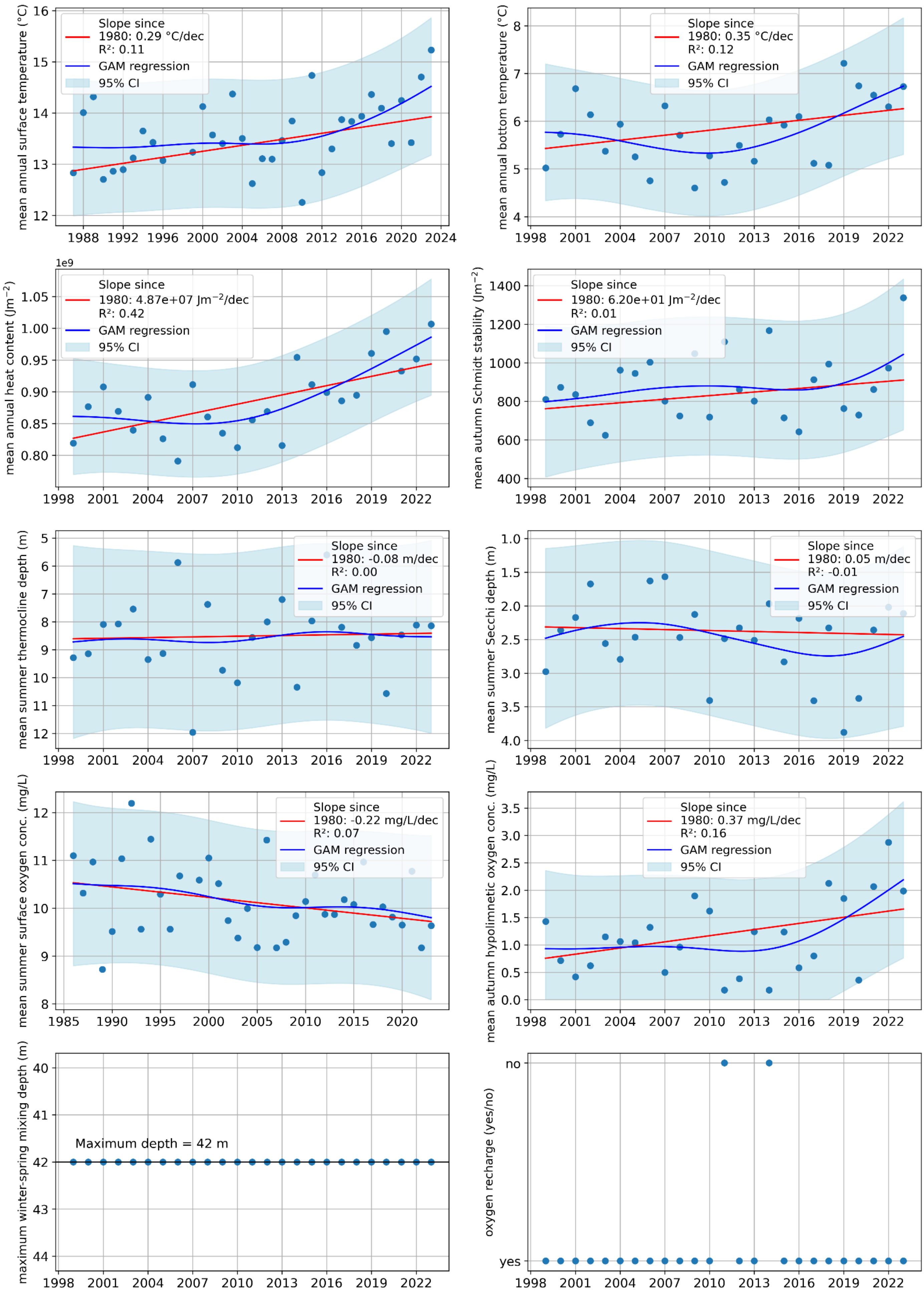

Figure S16: Detailed results of Lake Murten. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

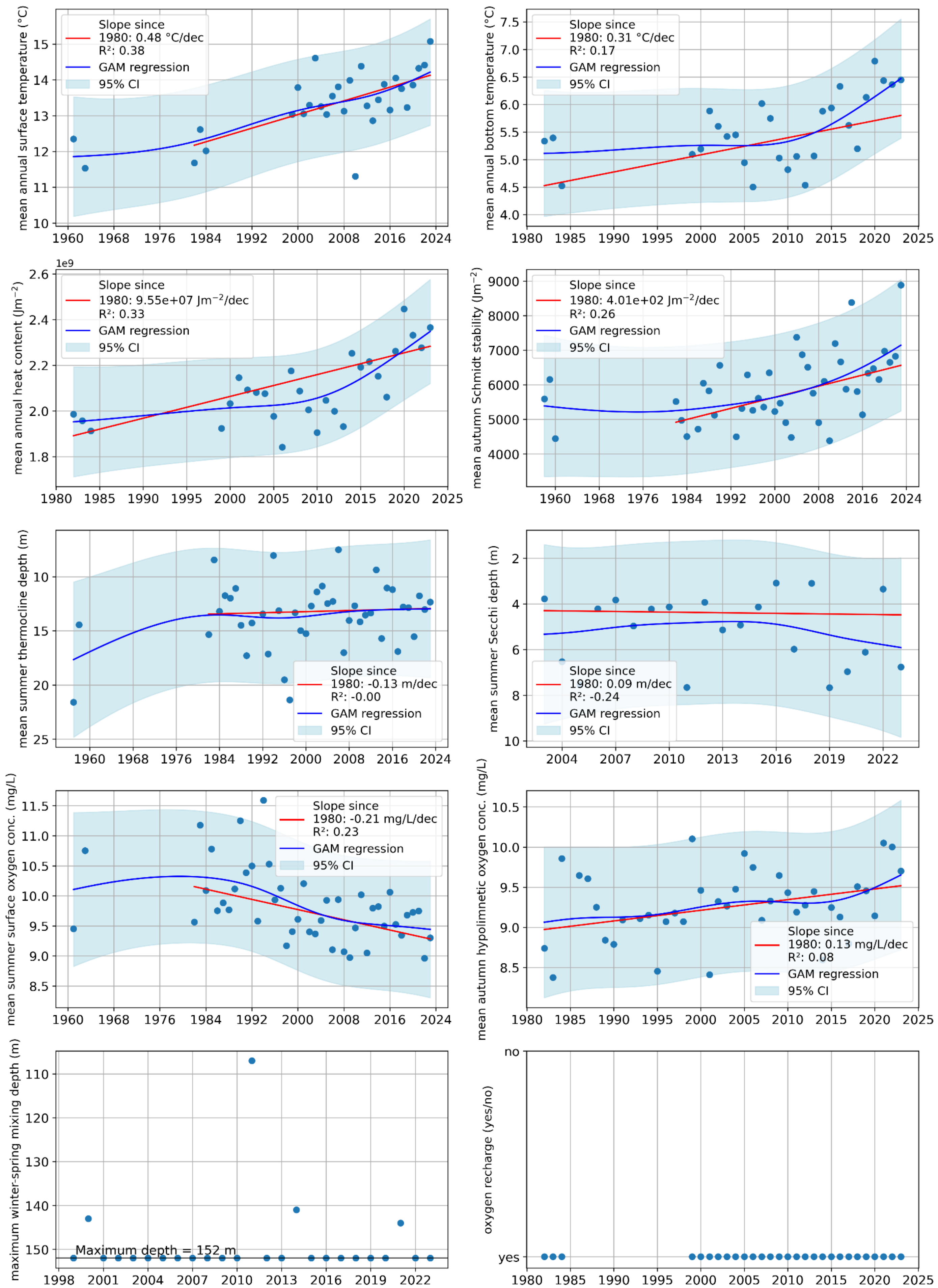

Figure S17: Detailed results of Lake Neuchâtel. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

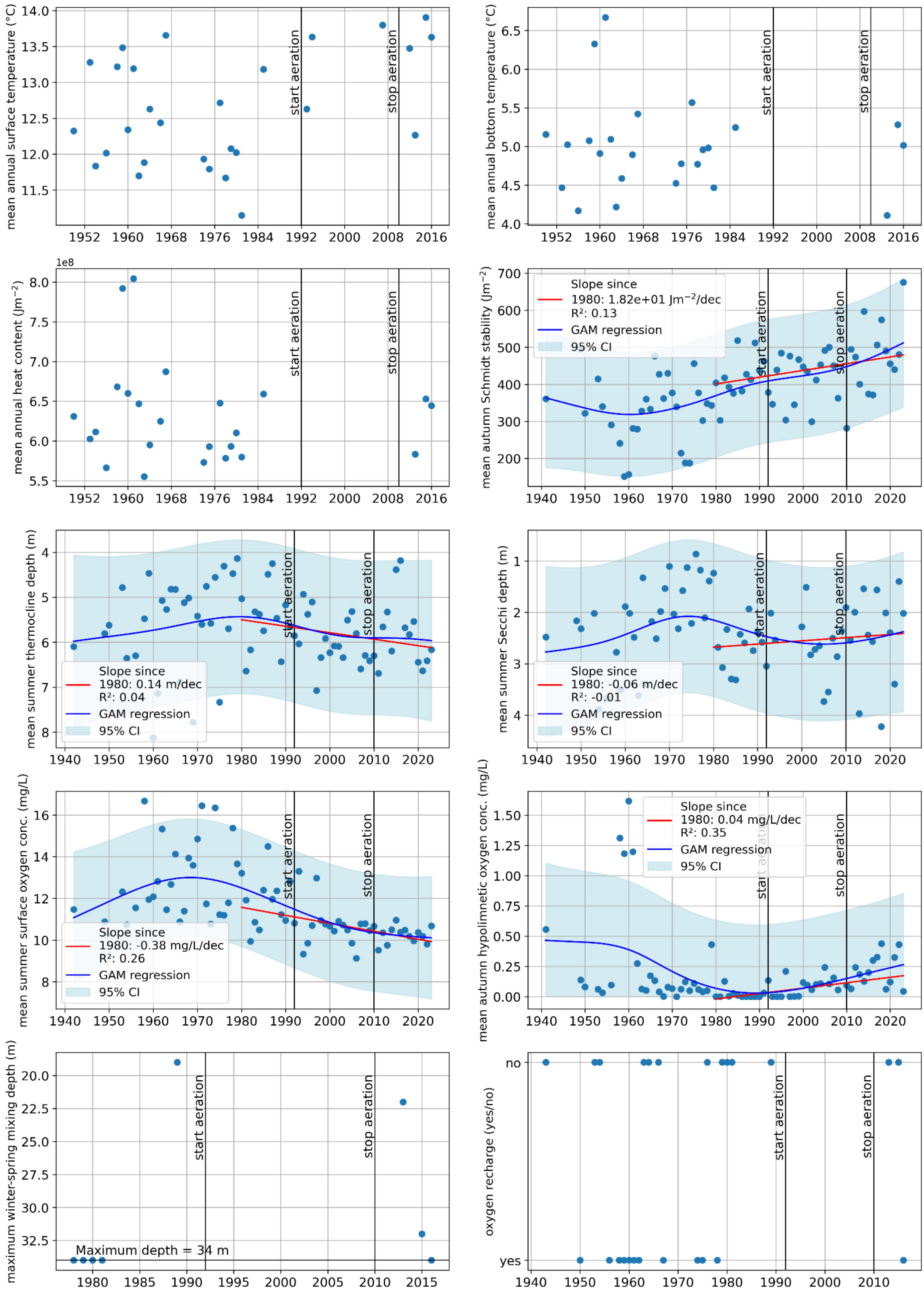

Figure S18: Detailed results of Lake Pfäffikon. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

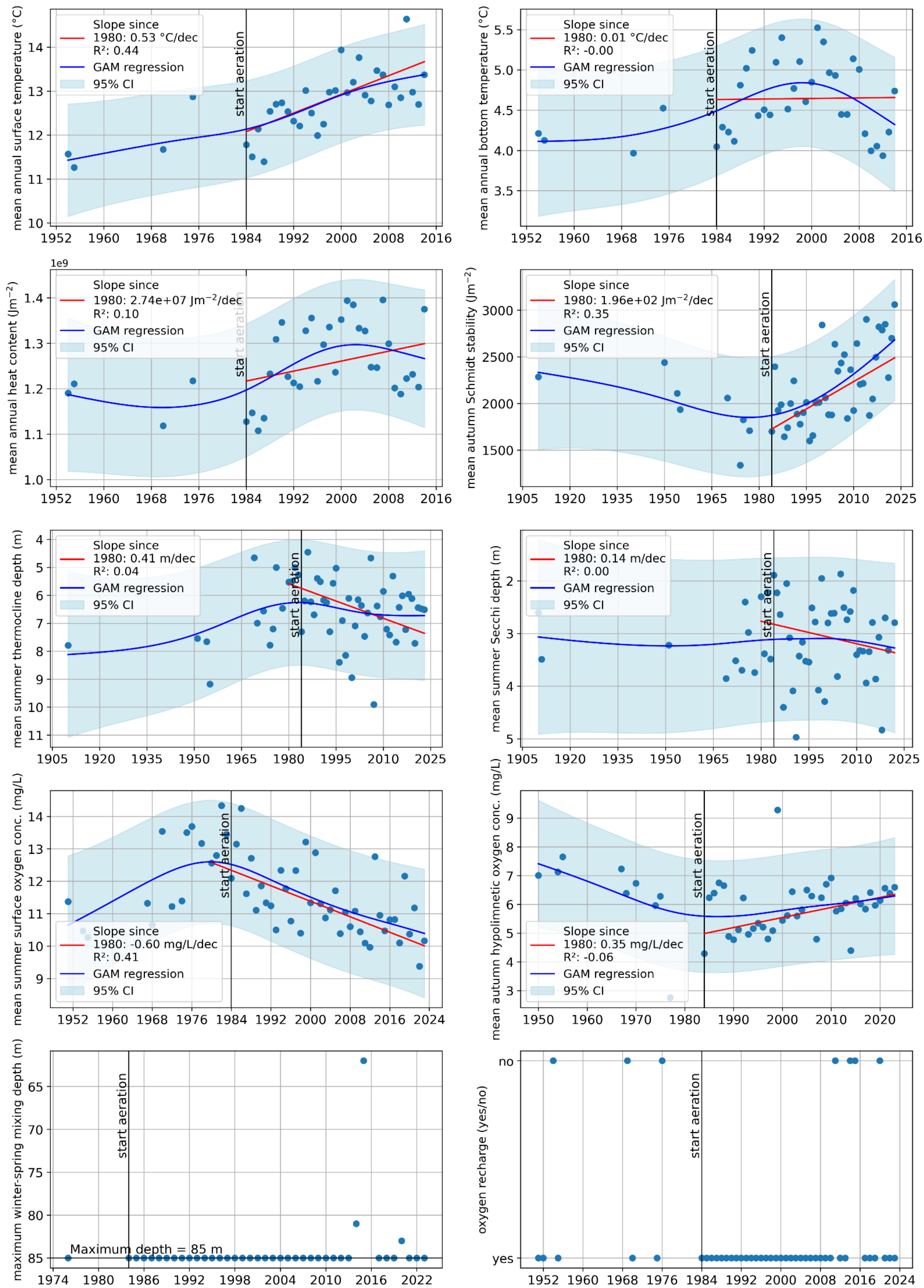

Figure S19: Detailed results of Lake Sempach. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

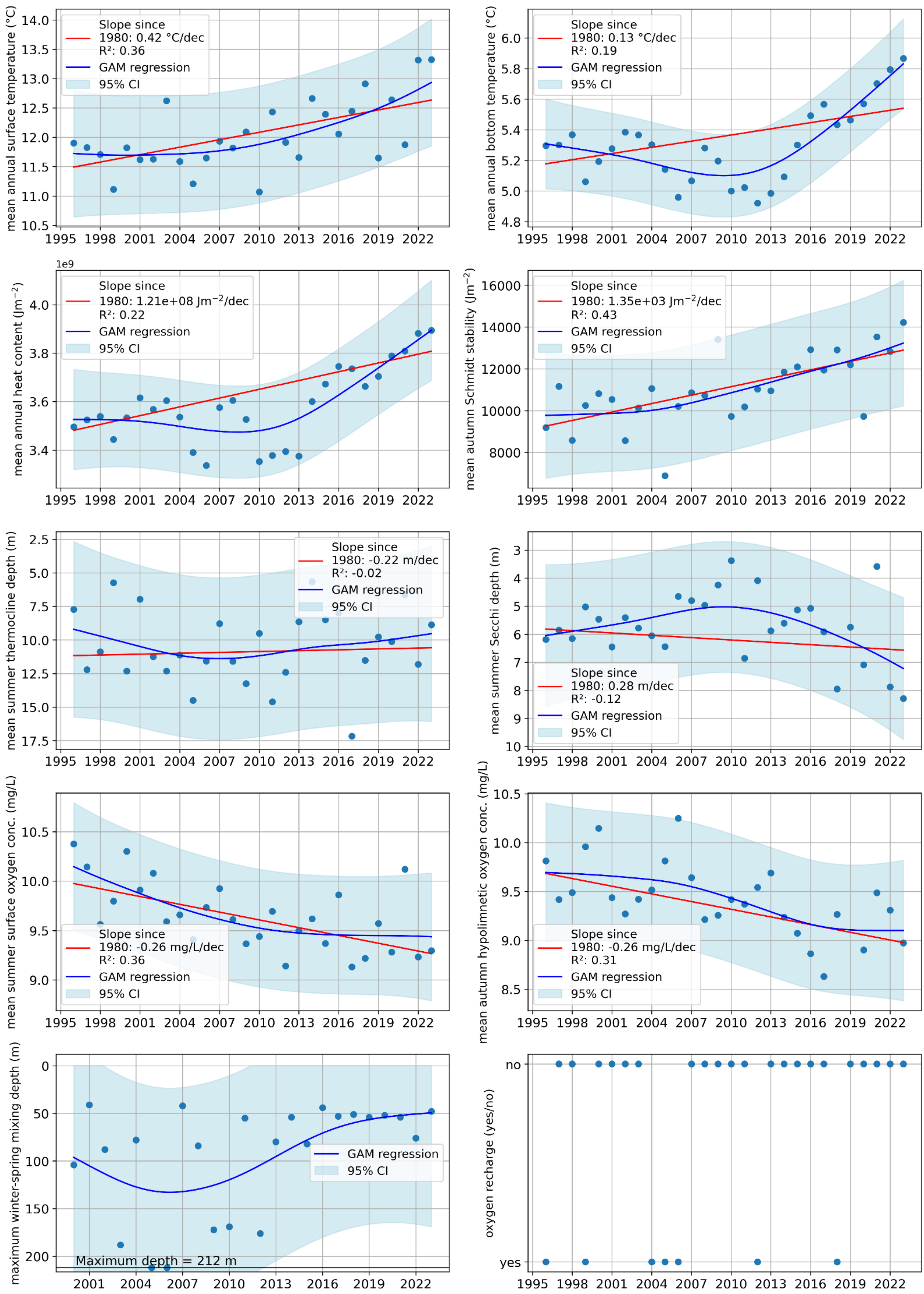

Figure S20: Detailed results of Lake Thun. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

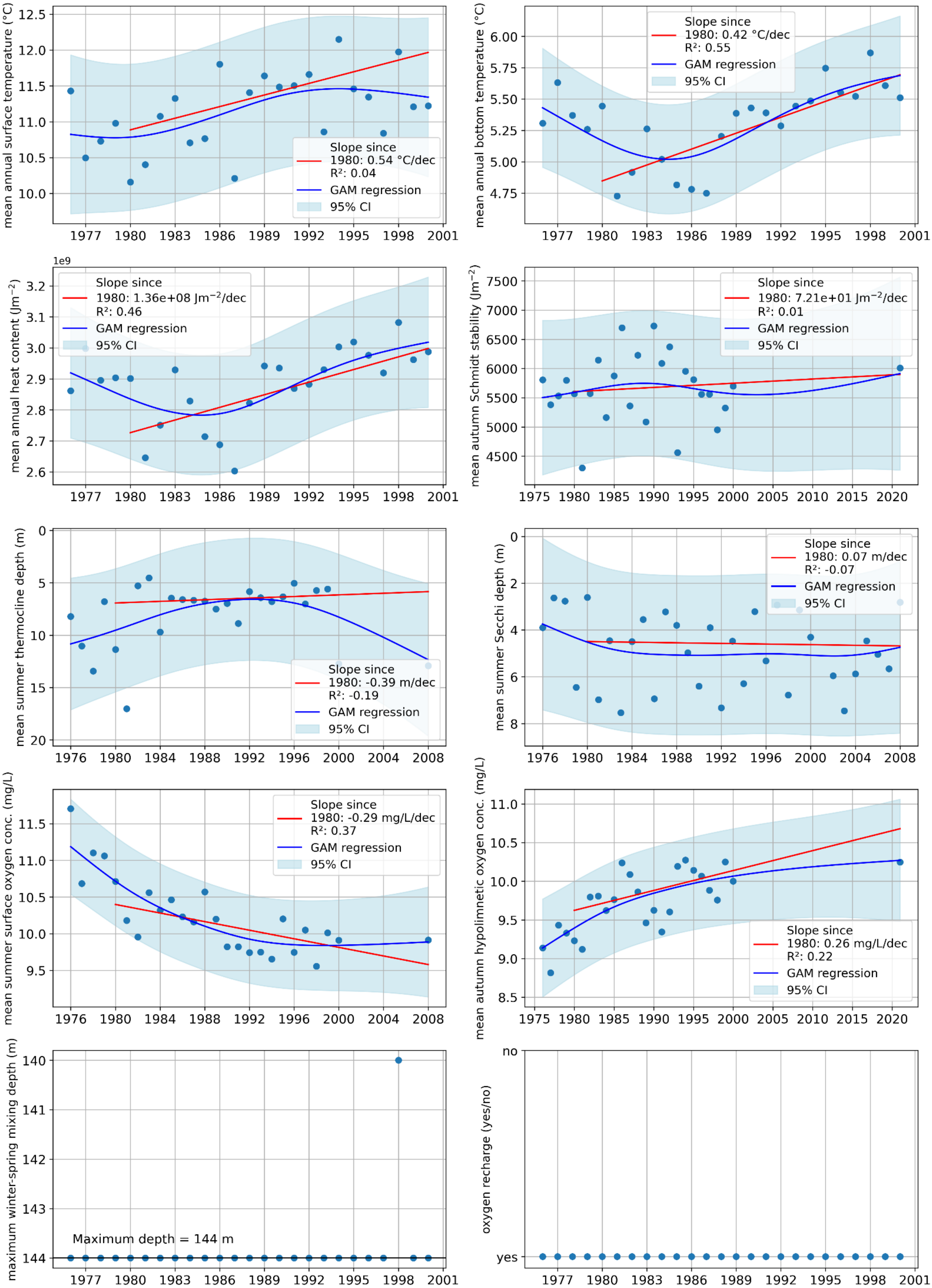

Figure S21: Detailed results of Walensee. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

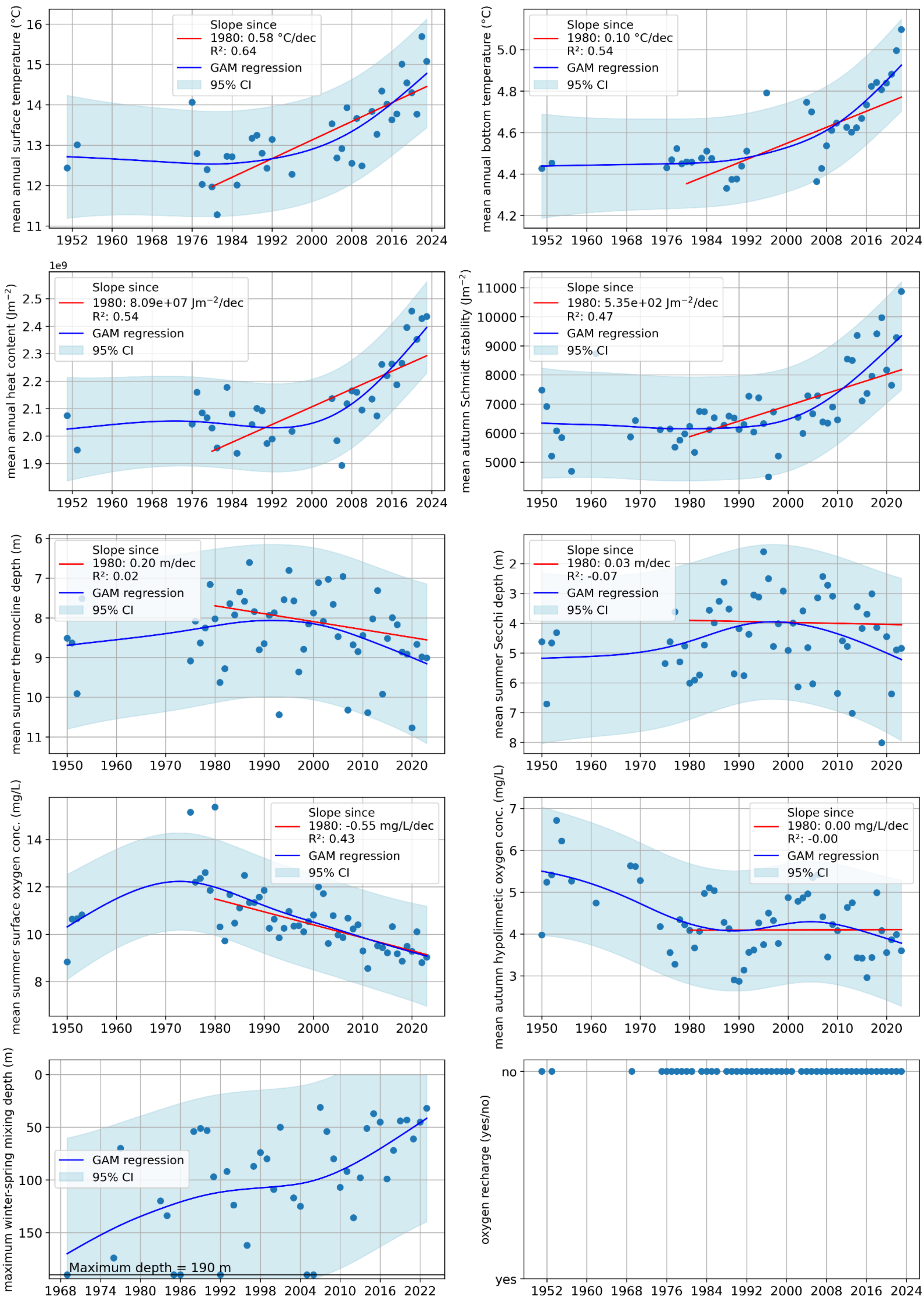

Figure S22: Detailed results of Lake Zug. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

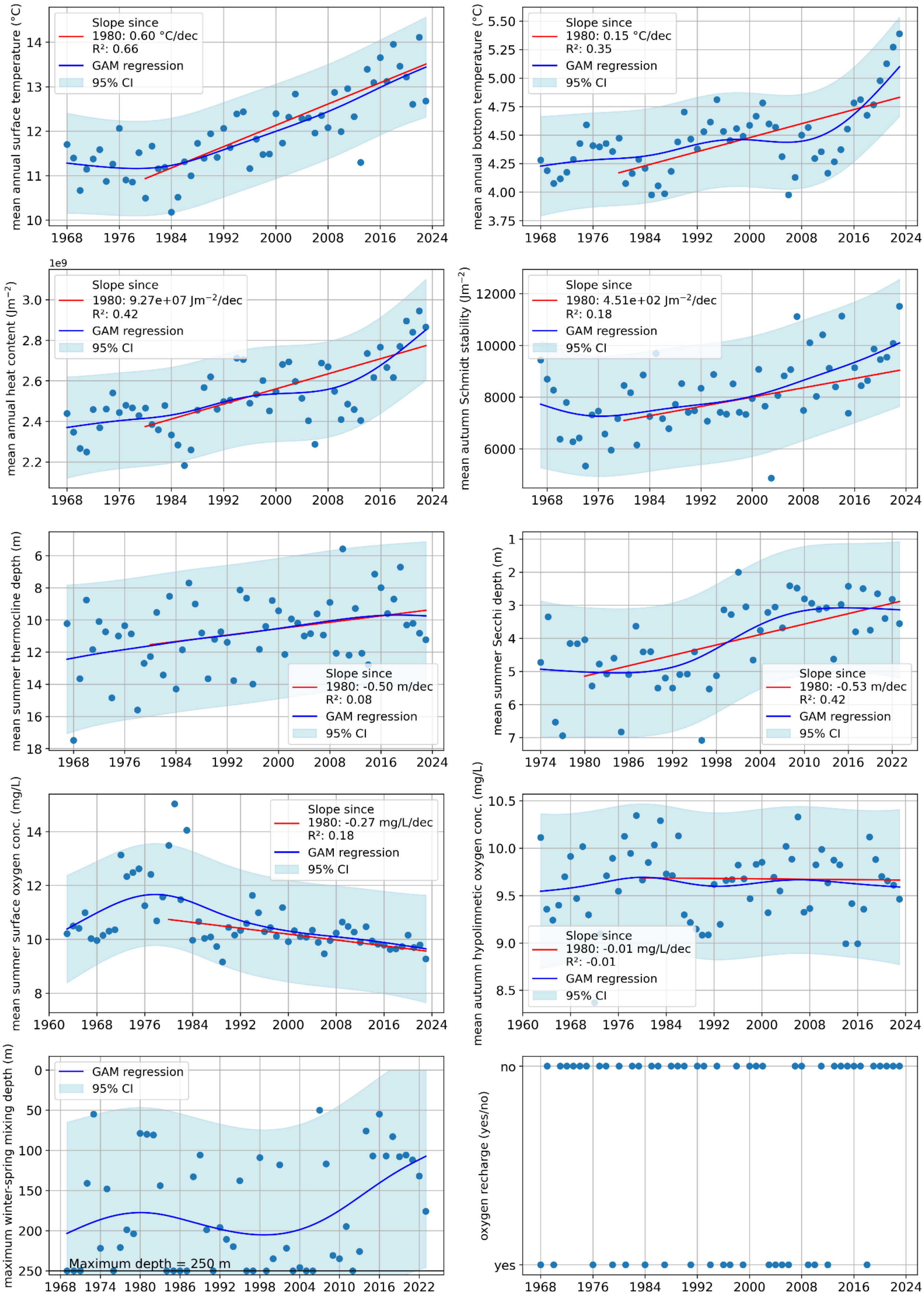

Figure S23: Detailed results of Upper Lake Constance. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

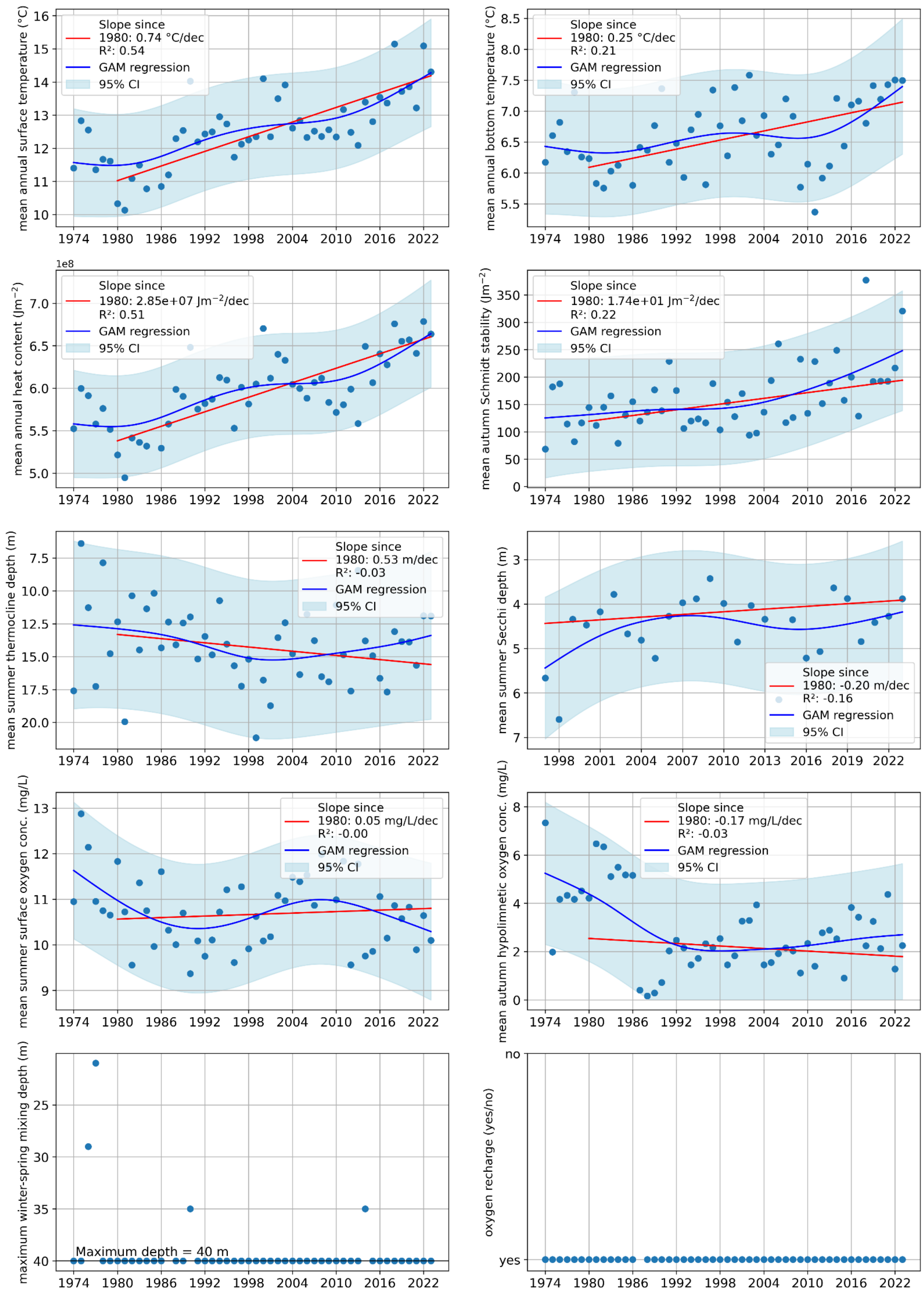

Figure S24: Detailed results of Lower Lake Constance. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

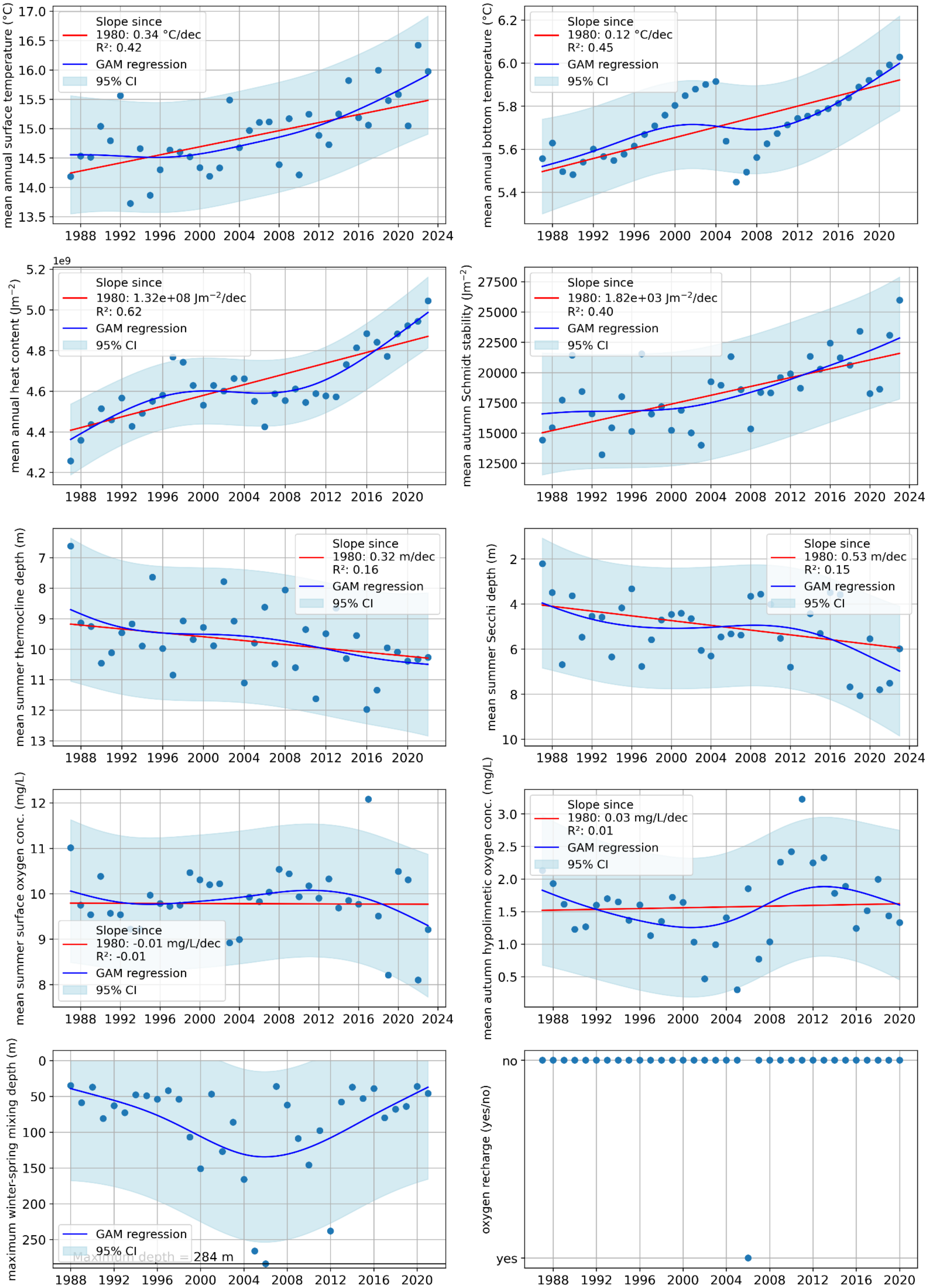

Figure S25: Detailed results of Upper Lake Lugano. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

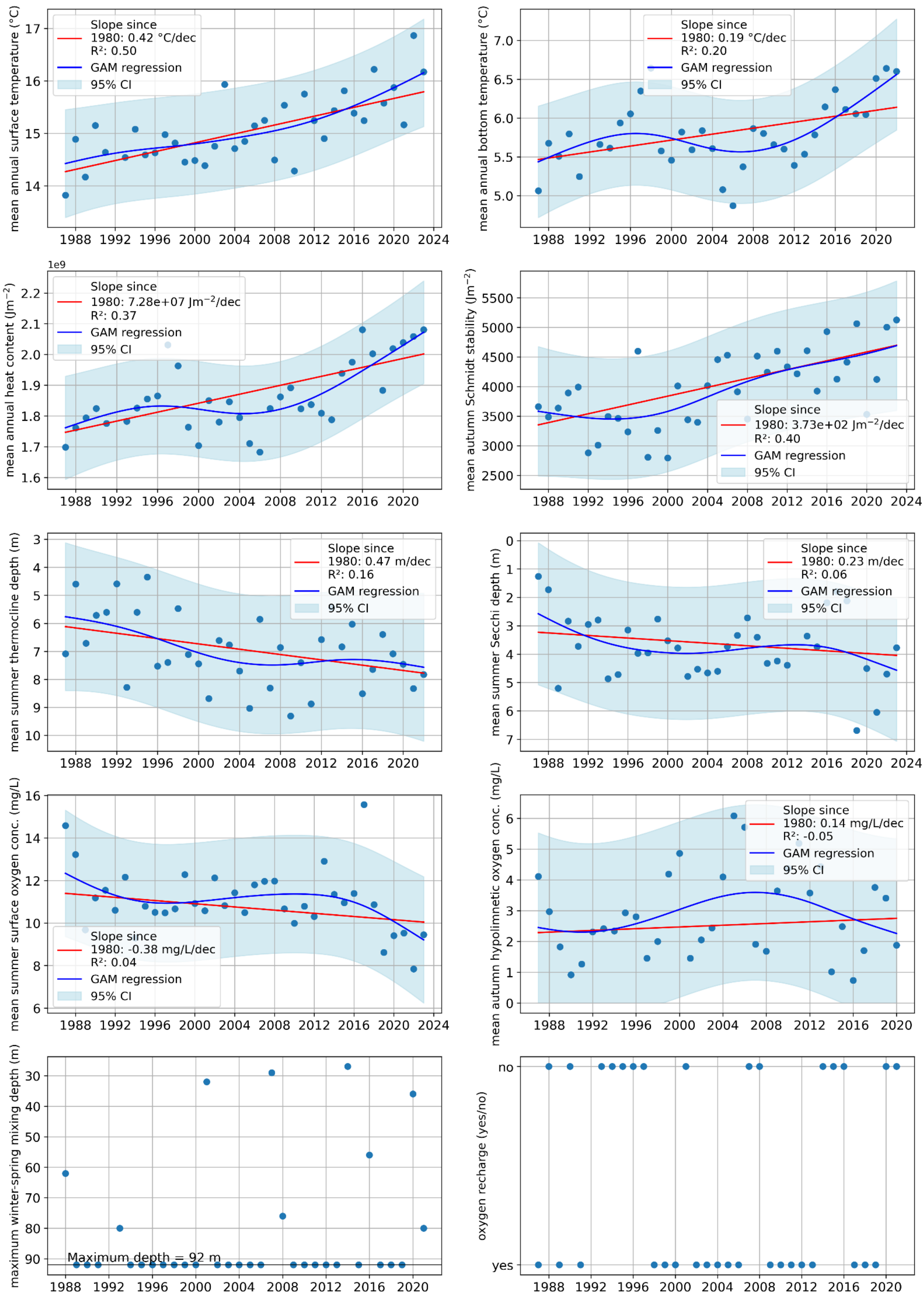

Figure S26: Detailed results of Lower Lake Lugano. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

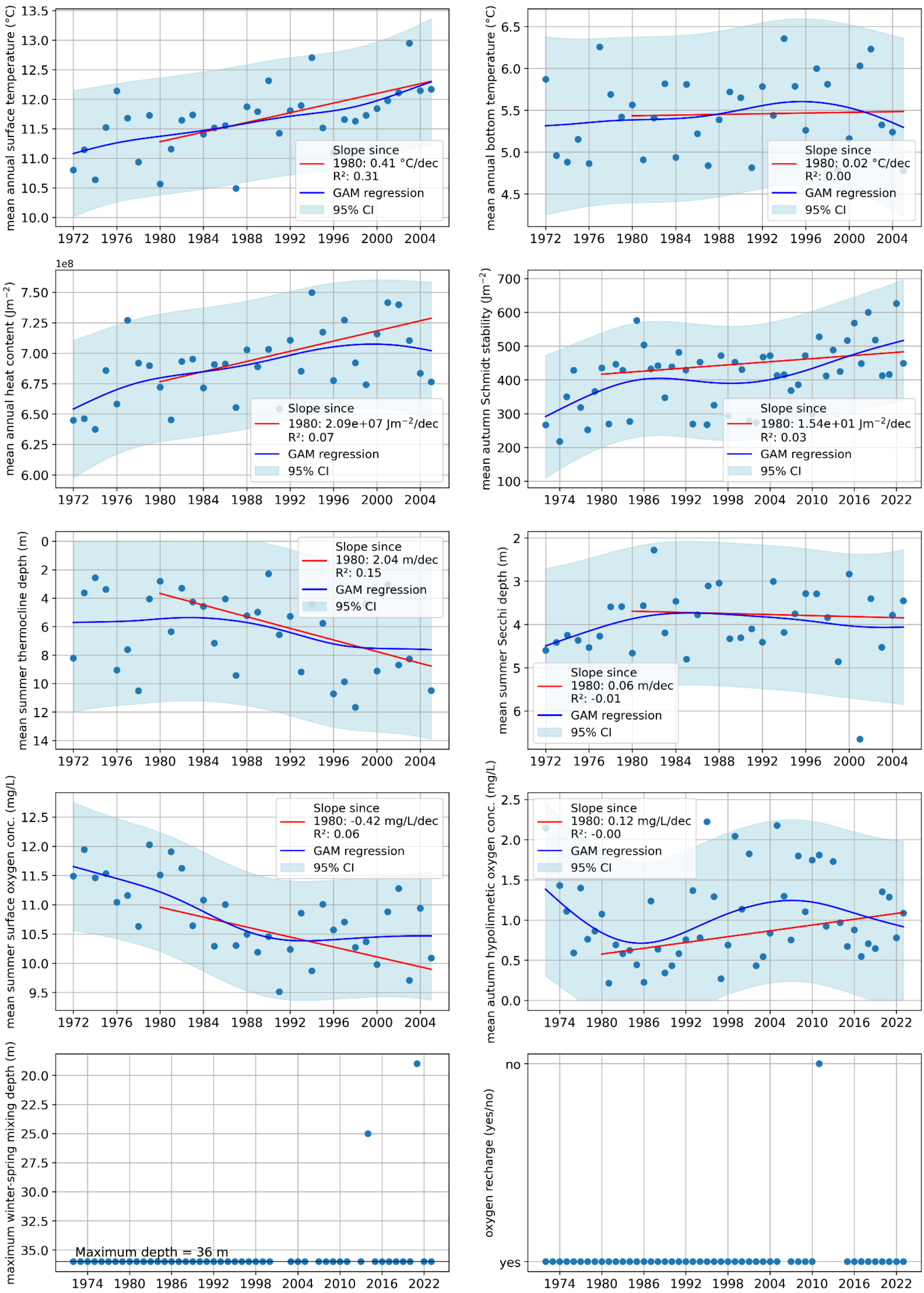

Figure S27: Detailed results of Upper Lake Zurich. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

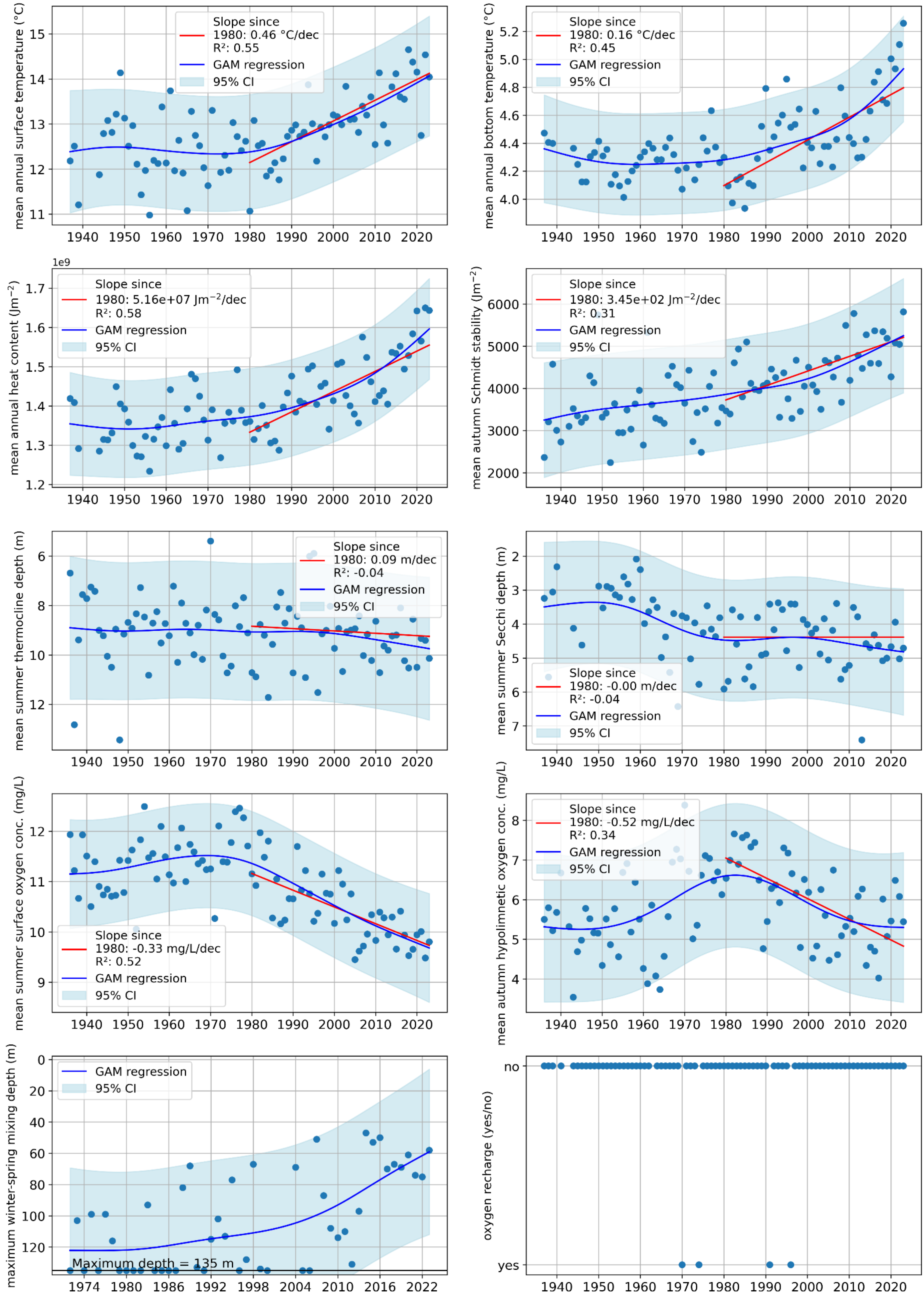

Figure S28: Detailed results of Lower Lake Zurich. Blue dots are calculated data points, red lines are linear Theil-Sen regressions of the data points since 1980, and blue lines are GAM regression lines since beginning of monitoring with 95 % confidence interval in light blue.

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