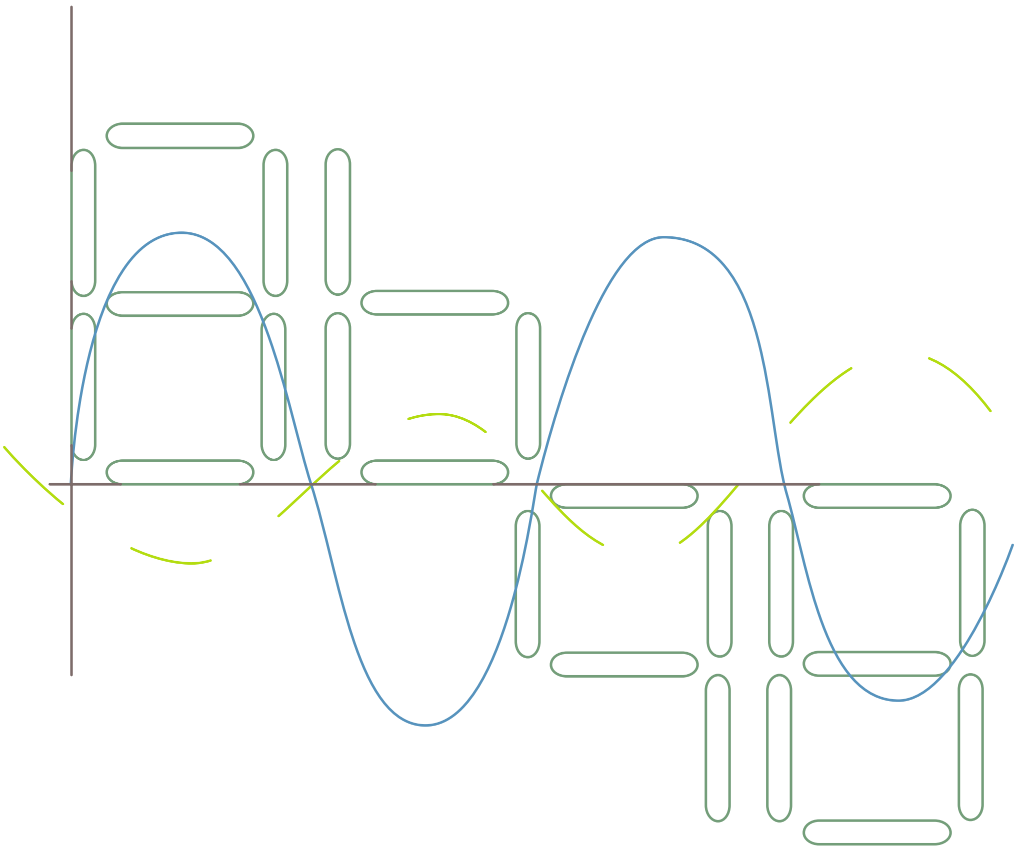
Report 33

GRDC Report Series

Trends in flood and low flow series



Report 33

GRDC Report Series

Trends in flood and low flow series

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Global Runoff Data Centre

GRDC operates under the auspices of the World Meteorological Organization (WMO) with the support of the Federal Republic of Germany within the Federal Institute of Hydrology (BfG)

Global Runoff Date Centre

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About the Global Runoff Data Centre (GRDC):

The GRDC is acting under the auspices of the World Meteorological Organization (WMO) and is supported by WMO Resolutions 21 (Cg XII, 1995) and 25 (Cg XIII, 1999). Its primary task is to maintain, extend and promote a global database on river discharge aimed at supporting international organisations and programmes by serving essential data and products to the international hydrological and climatological research and assessment community in their endeavour to better understand the earth system. The GRDC was established at the Federal Institute of Hydrology in 1988. The National Hydrological and Meteorological Services of the 187 member states of WMO are the principal data providers for GRDC.

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Executive summary

Major floods in Europe and North America during the past decade have provoked the question of whether they are an effect of a changing climate or not. The present study aims at investigating trends in observed river flows, using data from the Global Runoff Data Centre in Koblenz, Germany.

This study is a contribution to the WMO/UNESCO “World Climate Programme – Water” (WCP-Water) and in particular its programme working area on “Analysing Long Time Series of Hydrological Data and Indices with Respect to Climate Variability and Change”. It is the third and last of three work packages. The first work package involved the development of the software used for the analysis and the second investigated trends in annual maximum river flows at 195 stations with long records, world-wide. The third work package, which forms this report, uses a subset of these records to provide an in-depth study of the data, investigating trends using several different flood and drought indices.

Trends in three flood magnitude, two flood frequency and two low flow index series were estimated at 21 stations across the world. Two trend estimation methods were applied; linear regression and the Mann-Kendall test. Significance levels for both methods were obtained through block bootstrapping.

There is generally good agreement between the results of the trend analysis using the linear regression method and the Mann-Kendall method, except when there are outliers in the data series.

There is very good agreement between trends estimated for the two low flow indices. Agreement is also good for the three flood magnitude series, and, separately, for the two flood frequency series, but not between flood magnitude *and* frequency series. There is a larger number of both negative and positive significant trends in the annual maximum flood series, than in the peak-over-threshold series.

The trend analyses do not reveal any evidence of an intensification of the hydrological cycle, although such signals may be masked by a possible increase in the number of reservoirs in the catchments.

Contents

1. Introduction

1.1 Background

The World Climate Programme - Water (WCP-Water) is an international endeavour jointly implemented by the World Meteorological Organization (WMO) and the United Nations Educational, Scientific and Cultural Organization (UNESCO) in collaboration with national institutions. The WCP-Water promotes hydrological activities in the World Climate Programme and related conventions, and provides the water community with current data and information on hydrological and water resources conditions and variations, in a climatic context, over a wide range of time and space scales.

The present study is a contribution to the WCP-Water programmatic working area “Analysing Long Time Series of Hydrological Data and Indices with Respect to Climate Variability and Change”. It forms the third and final work package in the study “Change Detection in Hydrological Data”, and builds on the output from work packages 1, upgrade of the HYDROSPECT trend analysis software, and work package 2, investigating trends in annual maximum river flows at 195 stations with long records, world-wide (Kundzewicz *et al*., 2004). Work package 3 uses a subset of these records and makes a more in-depth study of the data, investigating trends using several different flood and drought indices.

1.2 Rationale and objectives

Major floods in Europe and North America during the past decade (e.g. Kunkel *et al*., 1994; CEH Wallingford/Met Office, 2001; Marsh and Bradford, 2003; Saurí *et al*., 2003) have provoked the question of whether they are an effect of a changing climate or not. Results from hydrological models that use output from general circulation models often suggest that river flows will increase in a greenhouse gas-induced warmer future climate (e.g. Miller and Russell, 1992; Nijssen *et al*., 2001; Reynard *et al*., 2001; Milly *et al*., 2002). Middelkoop *et al*. (2001) found that the flood risk in the Rhine basin can be expected to rise in winter, whereas at the same time summer droughts may become more severe.

In areas at risk from flooding, the threat of inundation has sometimes also been aggravated by man. The pressure from increasing populations has led to natural flood plains being brought into use for housing and commercial development. Whether floods are increasing or not has therefore become an even more acute issue to study.

The Intergovernmental Panel on Climate Change's Third Assessment Report (IPCC, 2001) concludes that an increasing body of observations gives a collective picture of a warming world and other changes in the climate system. Observational evidence suggests that it is likely that heavy precipitation events have increased at mid- and high northern latitudes, whereas the frequency and severity of droughts in some regions of Asia and Africa have also increased.

Although increasing temperatures may lead to an increase in heavy precipitation in the northern hemisphere through a more active hydrological cycle, higher temperatures also mean that evapotranspiration will increase. The effect on river flows, which in the longer term is the difference between precipitation and evapotranspiration, is therefore not obvious. The objective of the study is to investigate whether there is any support for increases in river floods in observational data. By using observations rather than model output, uncertainties inherent in the modelling procedure, such as simplifying assumptions and concepts, are avoided. However, using real data involves other problems, chiefly relating to data quality but also to quantity. Trend analysis requires long records to distinguish climate change-induced trends from climate variability, preferably in excess of about 50 years (Kundzewicz and Robson, 2000).

Work package 2 investigated trends in annual maximum daily mean river flows at 195 stations with a global spread (Kundzewicz *et al*., 2004). Using a subset of 21 stations, the present study (work package 3) extends the analysis to explore whether the results are similar when using peak-over-threshold (POT) methods as opposed to using annual maximum river flows. Trends in both POT magnitude, as well as in number of POTs per year, are estimated for an average number of 1 and 3 POTs per year. Studying the number of POTs per year will reveal if floods are becoming more frequent or not. To give an indication of whether more/less flooding tends to be accompanied by more/less drought, trends in low flow indices are also investigated.

Kundzewicz *et al.* (2004) found some spatial continuity in the trends of annual maximum river flows. However, generally the results were too inhomogeneous, and the density of stations too low, for the subset of individual stations used in the POT analysis to be regarded as representative for any particular region.

1.3 Brief literature review

1.3.1 Why would climate change involve a change in river flows?

The mechanism whereby an increase in greenhouse gases in the atmosphere would produce global warming is through an increase in downwelling infrared radiation. This would not only increase surface temperatures, but also enhance the hydrological cycle as much of the heating at the surface goes into evaporating surface moisture. With higher temperatures in the atmosphere, the water-holding capacity also increases, and together with an increase in evapotranspiration this suggests that the actual atmospheric moisture content would increase. Globally, it therefore seems reasonable that over time there must be an increase in precipitation to balance the enhanced evapotranspiration. However, the processes by which precipitation is altered locally is not well understood (Trenberth, 1998).

Trenberth (1998) argues that in general the increase in atmospheric moisture is likely to result in heavier rainfall and therefore also in an increased flood risk. At the same time, the increase in evapotranspiration - and in some areas decrease in precipitation - may lead to longer and more severe droughts in the dry season.

In the Arctic region, warming of the permafrost is expected to extend the thaw season and deepen the active layer of water infiltration. The spring melt period should be earlier and possibly stretch over a longer time period. Because a deeper active layer results in increased storage capacity, peak flows associated with both snowmelt and rainfall events would be similar or lower than at present (Rouse *et a*l., 1997).

1.3.2 Trend analyses of observed river floods

Global-, continental- or regional-scale studies of trends in river flows mainly use monthly, seasonal or annual flow data, e.g. globally (Probst and Tardy, 1989; Milly *et al.*, 2002), for the Asia-Pacific region (Cluis and Laberge, 2001), the Arctic region (Lammers *et al.*, 2001), south-eastern South America (Genta *et al.*, 1998), tropical South America (Marengo *et al.*, 1998).

Except for very large catchments, the low temporal resolution of the streamflow records of these studies is not necessarily indicative of the behaviour of floods, which tend to be of shorter duration. Studies using daily mean flow data are fewer, and regional studies of flood trends have mainly been undertaken for the United States (e.g. Douglas *et al*., 2000; Lins and Slack, 1999), Canada (e.g. Adamowski and Bocci, 2001; Burn and Hag Elnur, 2002) and for different parts of Europe (e.g. Robson *et al.*, 1998; Lindström and Bergström, 2003, 2004). Kundzewicz *et al.* (2004) studied trends in annual maximum daily mean river flows at 195 gauges with a worldwide spread, although relatively few gauges are located outside North America, Europe and Australia.

Because of land use changes, reservoir construction, and other local effects, there are seldom perfectly homogeneous spatial patterns emerging from regional studies of trends in floods. However, with some generalisation, the findings of the above studies can be summarised as follows (significance at the 95% level): there is some evidence of decreasing trends in floods in western Canada (Adamowski and Bocci, 2001; Burn and Hag Elnur, 2002; Kundzewicz *et al.*, 2004), whereas most of the United States have few significant trends, and the ones observed are of varying direction (Douglas *et al*., 2000; Lins and Slack, 1999; Kundzewicz *et al*., 2004). In Europe there is some evidence of significant positive flood trends in northern Scandinavia (Lindström and Bergström, 2003, 2004; Kundzewicz *et al.*, 2004), but no regional flood trends could be found in the UK (Robson *et al*., 1998). Although there are significant trends at a quarter of the stations in Central Europe (Kundzewicz *et al*., 2004), they are both positive and negative. The rest of Europe was not covered by the above studies.

Flood trend studies tend to focus on trends in the annual maximum flood series, which means that in years with many high flows still only one flood event per year will be selected, and in years with no large flows at all, a relatively low flow will be extracted. A more representative way of describing the occurrence of floods is to use a peak-over-threshold (POT) approach. This selects all floods above a certain threshold that occur in an entire flow record, provided that the floods extracted can be regarded as independent. This means that in one particular year several floods may be recorded, whereas in another year no floods may be recorded. Thus the use of POT series also allows an estimate of the trend in the frequency of floods (rather than just their magnitude), by calculating the number of POTs that occur each year and investigating the trend in this series.

Robson and Reed (1999) investigated British river flow trends in the annual maximum series as well as trends in POT magnitude and frequency series, selecting *on average* 1 and 3 POTs per year. They also used four different methods of estimating trends. Whereas the estimated trends in the magnitude series (annual maximum and POT magnitude series) and the POT frequency series may be rather different, there is generally good agreement between different methods for any one series.

1.3.3 Trend analyses of observed low flows

Using annual minimum 7-day flow and the annual minimum daily flow, respectively, Douglas *et al*. (2000) and Lins and Slack (1999) found increasing trends in low flows from the midwest towards the northeast of the United States, significant at the 95% level. Lins and Slack (1999) also found that the annual median streamflow is increasing, whereas floods are neither increasing nor decreasing, leading them to conclude that the nation appears to be getting wetter, but less extreme. Using annual minimum daily flow series for trend detection in Canada, Adamowski and Bocci (2001) found mainly increasing trends in the western regions of the country.

Using 600 daily streamflow records in Europe, Hisdal *et al*. (2001) conclude that it was not possible to establish that drought conditions in general have become more severe or frequent. Most stations did not show any significant trends, although for the relatively short period 1962-1990 some regional differences were found: examples of increasing drought deficit volumes were found in Spain, the eastern part of Eastern Europe and in large parts of the UK, whereas decreasing drought deficit volumes occurred in large parts of Central Europe and in the western part of Eastern Europe.

Because droughts tend to be longer lasting than floods, data of lower temporal resolution than daily are more likely to be sufficient for low flow studies than they are for flood events. Cluis and Laberge (2001) used minimum monthly discharges for investigation of trends in the Asia-Pacific region (including Oceania and the vast majority of Asia). Most areas do not exhibit consistent trends. However, in Central and Far-East Asia rivers to the north (between the 50^{th} and 75^{th} parallels) exhibit upward trends whereas more southern stations (around the 45^{th} parallel) show downward trends.

2. Data

Daily mean river flow data at 21 stations with a global distribution were used for the study (Table 1, Figure 1). Data were obtained from the Global Runoff Data Centre (GRDC, 2003) in Koblenz, Germany. The selected records are a subset of the 195 records used by Kundzewicz *et al.* (2004), in work package 2 of the project. The 21 stations were selected according to the following criteria:

1) Long records. The record lengths vary between 44 and 100 years, with an average of 68 years.
2) Few missing data. The selected series have few missing data, particularly in the flood season because the records are a subset of those used in Kundzewicz *et al*. (2004). This study investigated the annual maximum flood series, and therefore avoided series with gaps in the flood season.
3) Geographic distribution. Records were selected to obtain an even geographic cover worldwide of long records with few missing data.

Unfortunately, the GRDC does not have information about any changes to the stations or in the catchments, so the suitability of stations for this kind of analysis could not be assessed. Smaller catchments are less likely to be affected by anthropogenic activities. However, especially in Africa, Asia and South America there were not many long time series with few missing data available, so some large catchments have been included in the study.

The quality of the data was assessed by plotting the time series and scanning for irregularities. A few changes were made for stations 2907400 and 2912600, in consultation with the GRDC. Downward adjustments were made to two and four days, respectively for the two stations, to correct presumed digitisation and decimal point location errors.

Table 1. General information about the 21 daily mean river flow gauges used in the study. In the column for amount missing data, 0 means the record is complete, and 0.00 means that there is less than 0.005% data missing.

GRDC station number	Country	River and station location	Long-itude (°E)	Lat-itude (°N)	Area (km^2)	First and last years	Record length (years)	Amount missing (%)
1134100	ML	Niger at Koulikoro	-7.55	12.87	120000	1907-1987	81	0.10
1160650	ZA	Mtamvuna at Gundrift	29.83	-30.73	715	1956-2000	45	1.36
2907400	RU	Selenga at Mostovoy	107.48	52.03	440200	1936-1999	64	0
2912600	RU	Ob at Salekhard	66.53	66.57	2949998	1954-1999	46	0
2964130	TH	Chao Praya at Wat Pho Ngam (Ban Re Rai)	100.19	15.17	120693	1950-1999	50	0.83
3206720	VE	Orinoco at Puente Angostura	-63.6	8.15	836000	1926-1989	64	0
3512400	GF	Maroni at Langa Tabiki	-54.43	4.98	60930	1952-1995	44	0
4113300	US	Red River of the North Grand Forks, N.D.	-97.03	47.93	77959	1904-1999	96	0
4116300	US	Clearwater River at Spalding, ID	-116.82	46.44	24786	1926-1999	74	0
4148051	US	James at Cartersville, VA	-78.09	37.67	16205	1900-1999	100	0
4150503	US	Brazos River at Seymour, TX	-99.27	33.58	40243	1924-1999	76	0
5202065	AU	Styx River at Jeogla	152.16	-30.59	163	1919-1992	74	0.24
5204105	AU	Murrumbidgee River at Mittagang Crossing	149.09	-36.17	1891	1927-2000	74	0
5302250	AU	Thomson River at Cooper Creek	146.43	-37.99	906	1956-2001	46	0
5608024	AU	Fitzroy River at Fitzroy Crossing	125.58	-18.21	45300	1956-1999	44	0
6142100	CZ	Morava at Moravicany	16.98	49.76	1559	1912-2000	89	0.19
6335125	DE	Kinzig at Schweibach	8.03	48.39	954	1921-2000	80	0
6545200	SI	Krka at Podbocje	15.46	45.86	2238	1933-1999	67	0.00
6609400	GB	Avon at Evesham	-1.94	52.09	2210	1937-1999	63	0
6731300	NO	Etna at Etna	9.43	60.93	557	1920-2000	81	0
6855100	FI	Vantaanjoki at Oulunkyla (near the mouth)	24.98	60.23	1680	1937-2001	65	0

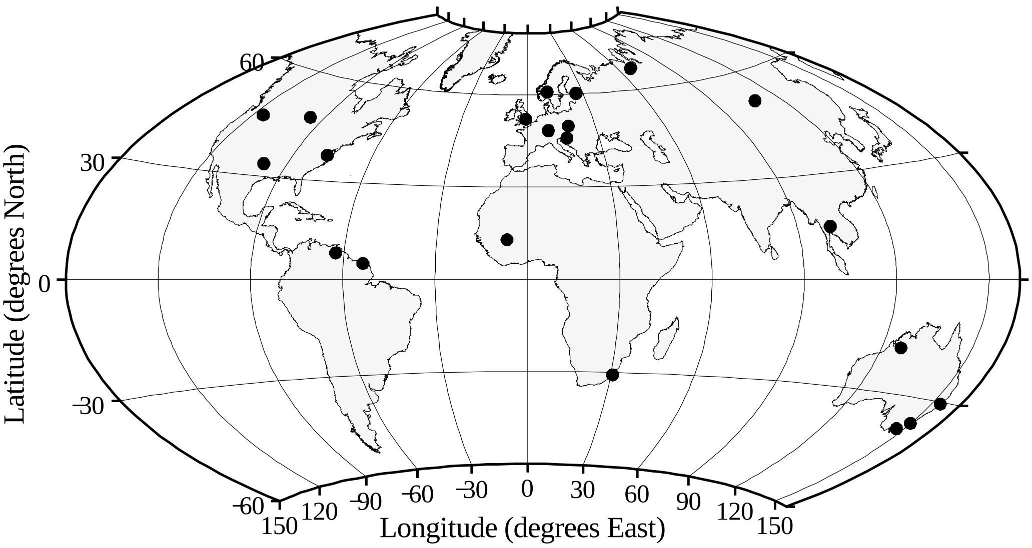

Figure 1. Location of the 21 daily mean river flow stations.

3. Methods

3.1 Flow indices

Five different indices were used to describe the characteristics of the upper end of the flow regime, i.e. the floods. The first of these is the annual maximum daily mean river flow (Ann. max.), which was used by Kundzewicz *et al.* (2004) in work package 2, for the analysis of trends in river floods at 195 stations worldwide. In flood-rich years the annual maximum series will only include one of the large floods, whereas in flood-poor years a small river flow will be selected that may not necessarily be a flood at all. One way of representing high river flows in a record, regardless of when they occur, is to use a peak-over-threshold (POT) approach (e.g Robson and Reed, 1999). Peak-over-threshold (POT) series consist of a series of independent daily mean river flows that exceed a certain threshold. The POTs have to be proper peaks, i.e. the river flow both before and after the peak has to be lower than at the peak itself. Two POT indices describing flood magnitude were used; the POT1 magnitude (POT1 mag.) and the POT3 magnitude (POT3 mag.) series. The magnitude of the threshold was set so that *on average* 1 and 3 POTs, respectively, were selected per year.

The peaks were considered to be independent of each other if they were separated by at least 5 days for catchments with areas < 45000 km^2, at least 10 days for catchments with areas between 45000 and 100000 km^2, and at least 20 days for catchments > 100000 km^2. These separation times generally allow for the flow to recede appreciably between peaks. However, individual flood peaks are less pronounced on large catchments with a strong seasonal component, notably at station 3206720 (Orinoco at Puente Angostura) but also at 1134100 (Niger at Koulikoro). For these two catchments 3 peaks per year on average could not be extracted for an independence criterion of 20 days. Because no other suitable stations were available in these regions, it was decided to keep these stations in the study, and bear in mind the difference in number of peaks when interpreting the results. On average 1.5 and 2.1 peaks per year, respectively, for stations 3206720 and 1134100, were used for the POT3 series.

The frequency of flood events can be described by counting the number of POTs occurring in each year. Two such flood frequency indices were used; the POT1 frequency (POT1 freq.) and the POT3 frequency (POT3 freq.). These annual frequency series were derived from the corresponding POT magnitude series.

The two POT1 series describe the magnitude and frequency of the most extreme floods, whereas the two POT3 series characterise the behaviour also of the more moderately sized floods.

Two low flow indices were used to describe the lower end of the flow spectrum; the series of annual minimum 7-day (Min. 7-day) and 30-day (Min. 30-day) mean river flow. Particularly the 7-day duration is commonly used for low flow analysis (e.g. Gustard *et al.*, 1992).

3.2 Missing data

The records generally have few missing data in the flood season because this was one of the record selection criteria. The flood indices are therefore straightforward to derive, and there are no missing data in the extracted flood index series. However, the HYDROSPECT software does not acknowledge any gap in the record due to missing data when computing indices based on moving n-day windows, such as the minimum 7-day and 30-day mean flows (it appends the record fragments directly after each other. The author of HYDROSPECT has confirmed that this behaviour will be corrected in the program version delivered to end users). Therefore, no low-flow indices were assigned for years that have missing data. All the annual index series were extracted based on the calendar year.

3.3 Trend detection

Two different methods were used to estimate whether there is a significant positive or negative trend in the river flow index series. Linear regression fits a regression line to the series, and the slope describes whether the trend is strong or not. The null hypothesis is that the slope of the line is zero. Because the linear regression is applied directly to the index series, rather than to ranks, it is very good for visual presentation.

However, the linear regression method requires the assumption of normal distribution and is very sensitive to outliers in the data. By ranking the observations and applying the non-parametric Mann-Kendall test, a more robust measure of trend is obtained. Kundzewicz and Robson (2000, 2004) and Radziejewski and Kundzewicz (2004) describe and discuss methods for trend detection in more detail.

3.4 Block bootstrapping for estimation of significance levels

The 90% significance level used by Kundzewicz *et al*. (2004) was adopted for presentation purposes also in this report. Because the statistical distributions of the index series are not necessarily known, and the observations may not be independent and identically distributed, significance levels were estimated using a block bootstrapping method (described below) rather than calculated from theoretical formulae. The independence criterion is frequently broken as there is serial dependence from one year to another, mainly in the low flow index series but also for some of the flood index series. The POT magnitude series may exhibit seasonality, i.e. the peaks may not be identically distributed.

Seasonality can be taken into account by using annual, or multiples of annual, blocks of data for the bootstrapping. Autocorrelation analysis was carried out for all the annual series to establish how long the blocks would need to be to take into account the serial correlation of the series. It revealed (see Chapter 4) that five-year-blocks would be sufficient for most of the series.

Bootstrapping (e.g. Efron, 1979) is based on the generation of many new data-sets, so-called resamples. The original sample of observations is used as the distribution from which the resamples are chosen randomly with replacement, i.e. each block of observations is returned to the original sample after it has been chosen, so that it can be chosen again. A large number of data-sets are generated and a test statistic, in our case a measure of the slope, is calculated for each of these new data-sets. This provides a sample of slopes that would occur for a range of situations. The slopes of the resamples are then ranked, and if the slope estimated from the *original* data sample is smaller than the 5% point or larger than the 95% point of the distribution of resampled slopes, then the slope is considered to be significant at the 90% level. After some initial tests, it was deemed suitable to make 2000 resamples per station and index to obtain good stability in the significance level estimates.

4. Results and discussion

4.1 Autocorrelation in annual series

Autocorrelations for the annual index series were calculated in order to determine what block size to use for the block bootstrapping method when estimating significance levels of trends. Diagrams of the correlations are shown in Appendix A. Most of the series suggest that a block size of five years should be sufficient to accommodate serial correlation in the series, and this was therefore used. For the few cases where autocorrelation was significant for more than a 4-year lag, the significance levels for the trend analysis were estimated using longer blocks. These cases are marked and footnoted in Table 2. When a longer block size was needed for the annual maximum flow series, the significance levels of trends for the POT magnitude series were also calculated using the larger blocks.

4.2 Trends in flood and low flow index series

Results of the trend analysis are presented in three ways. Firstly, plots of the entire index series and fitted regression lines for each station and index are shown in Appendix B. Secondly, the spatial distribution of significance levels of trends are shown on world maps in Figures 2-8. Thirdly, all the significance levels of the trends are shown in Table 2.

For each station, Table 2 shows the significance of the trends in the seven flow index series estimated using linear regression and the Mann-Kendall test. When the trend is negative, the significance level is also shown as negative, and in italic font. Absolute values of significance levels exceeding 90% are shown in bold font.

Table 2. Significance levels associated with trends for seven river flow index series. Trends are estimated using linear regression (LR) and the Mann-Kendall test (M-K). Negative trends are shown as having negative significance levels, and are in italic font. Absolute values of significance levels exceeding 90% are shown in bold font.

GRDC station number	**River and station location**	**Flood magnitude**						**Flood frequency**				**Low flow**			
		Ann. max.		**POT1 mag.**		**POT3 mag.**		**POT1 freq.**		**POT3 freq.**		**Min. 7-day**		**Min. 30-day**	
		LR	**M-K**	**LR**	**M-K**	**LR**	**M-K**	**LR**	**M-K**	**LR**	**M-K**	**LR**	**M-K**	**LR**	**M-K**
1134100	Niger at Koulikoro	*-78.83*[1]	*-66.69*[1]	*-35.30*[1]	*-30.40*[1]	*-81.18*[1]	*-74.43*[1]	*-53.54*	*-51.14*	**92.70**	89.18	69.19	37.70	64.79	46.70
1160650	Mtamvuna at Gundrift	*-54.79*	3.19	*-83.63*	*-70.16*	*-67.94*	19.76	57.49	71.30	40.75	24.81	*-78.68*	*-84.78*	*-67.94*	*-75.68*
2907400	Selenga at Mostovoy	*-17.76*	*-30.10*	42.80	68.79	18.76	*-20.71*	*-30.60*	*-47.15*	***-93.77***	***-92.87***	**98.22**	**96.52**	**98.22**	**97.27**
2912600	Ob at Salekhard	72.80	65.44	44.60	28.86	20.31	33.85	47.40	45.35	*-48.12*	*-43.85*	**98.97**	**99.52**	**99.27**	**98.77**
2964130	Chao Praya at Wat Pho Ngam (Ban Re Rai)	***-98.17***	***-99.70***	***-91.32***	***-95.72***	***-92.42***	*-65.64*	*-81.88*	*-89.98*	25.76	25.91	11.21	10.86	*-6.17*	*-11.36*
3206720	Orinoco at Puente Angostura	52.79	60.59	15.96	32.65	*-72.38*	*-13.76*	56.87	56.52	63.21	56.24	87.18	88.73	80.53	79.63
3512400	Maroni at Langa Tabiki	32.85	13.46	39.65	48.45	*-12.10*	*-17.86*	*-31.80*	*-6.42*	*-46.35*	*-38.50*	26.71	11.56	22.60	12.86
4113300	Red River of the North Grand Forks, N.D.	**99.77**	**97.92**	**98.22**	**98.70**	**98.12**	79.88	**99.67**	**98.47**	**99.70**	**98.70**	**95.77**	**91.32**	**98.20**	**93.92**
4116300	Clearwater River at Spalding, ID	***-97.62***	***-95.92***	***-93.47***	*-88.73*	***-98.97***	***-96.37***	***-94.20***	***-93.12***	*-83.63*	*-81.48*	**99.62**[2]	**99.77**[2]	**98.72**[2]	**99.12**[2]
4148051	James at Cartersville, VA	**96.82**	**97.22**	89.23	**90.62**	**93.47**	82.53	79.63	88.13	22.51	21.71	*-44.95*	*-46.60*	*-78.28*	*-72.58*
4150503	Brazos River at Seymour, TX	***-99.77***	***-99.67***	***-98.77***	***-97.32***	***-98.97***	*-87.88*	***-99.82***	***-99.77***	***-99.97***	***-99.92***	**99.70**	**99.92**	**98.97**	**99.82**
5202065	Styx River at Jeogla	57.99	63.29	*-1.32*	45.55	81.30	**92.37**	89.73	89.48	*-35.70*	*-40.90*	44.60	87.38	*-42.45*	75.53
5204105	Murrumbidgee River at Mittagang Crossing	***-92.37***	***-98.22***	*-36.65*	0.92	41.85	63.34	***-93.22***	***-94.20***	***-98.72***[1]	***-98.87***[1]	*-89.73*	*-84.73*	***-95.12***	***-91.77***
5302250	Thomson River at Cooper Creek	***-91.20***	***-98.27***	66.69	73.98	61.40	*-3.22*	***-98.22***	***-97.97***	***-99.57***	***-99.82***	86.13	75.93	88.93	81.13
5608024	Fitzroy River at Fitzroy Crossing	86.38	84.80	72.80	52.74	37.15	*-48.20*	80.40	80.48	**93.72**	**95.17**	71.23	**97.57**	71.63	**98.12**
6142100	Morava at Moravicany	78.73	45.65	77.53	52.84	84.98	18.81	43.40	54.24	*-69.24*	*-60.89*	**92.22**	**90.22**	69.74	73.80
6335125	Kinzig at Schweibach	**97.37**	**97.20**	**94.92**	**98.57**	**96.77**	78.33	83.33	**91.17**	28.16	45.12	**98.47**	**98.97**	**91.17**	**96.42**
6545200	Krka at Podbocje	***-98.32***	***-97.72***	*-82.13*	*-64.89*	***-99.47***	***-98.72***	***-99.97***	***-99.82***	***-99.42***	***-98.62***	74.30	72.18	52.74	58.84
6609400	Avon at Evesham	**95.77**	**95.62**	75.18	41.40	**93.27**	70.38	79.93	88.93	30.10	49.20	**96.37**[3]	**97.32**[3]	**99.92**	**99.87**
6731300	Etna at Etna	*-89.83*	***-91.22***	***-96.32***	***-98.22***	*-83.88*	*-81.73*	*-78.83*	*-68.49*	*-86.13*	*-89.53*	79.93	87.68	89.28	**93.77**
6855100	Vantaanjoki at Oulunkyla (near the mouth)	*-19.76*	*-24.91*	*-75.53*	*-86.28*	*-88.80*	*-69.24*	0.70	67.94	72.91	89.93	**97.42**	**99.52**	**98.87**	**99.77**

[1] Bootstrapping in 6-year blocks
[2] Bootstrapping in 10-year blocks
[3] Bootstrapping in 14-year blocks

The similarity between the columns in Table 2 can be assessed using correlation analysis. This shows that there is generally good agreement between the outcome for the linear regression and Mann-Kendall methods, except when there are one or more outliers in the index series. This may result in the two methods showing trends of the opposite sign. Examples of this are the flood magnitude indices Ann. max. and POT3 mag. for station 1160650. The effect of outliers can also be seen for this station in the linear regression diagrams in Appendix B. Because the results of the Mann-Kendall tests are more robust, they have been used for the presentation in Figures 2-7, and in the following discussion unless otherwise stated.

There is also very good agreement between the columns for the two low flow indices, and generally between the different flood indices. However, the column for POT3 freq. is not significantly correlated with either the POT3 or POT1 magnitude columns at the 90% level. This means that an increase (decrease) in the magnitude of floods is not necessarily associated with an increase (decrease) in the frequency with which they occur.

Figure 2. Trends in the annual maximum daily mean river flow series at 21 stations, estimated using the Mann-Kendall test and block bootstrapping. Negative trends are shown in gray dots, and positive trends in black dots. The largest dot size marks trends significant at the 90% level (two-sided test).

Figure 3. As in Figure 2, but for trends in the peak-over-threshold magnitude series, with on average 1 daily mean river flow peak per year selected.

Figure 4. As in Figure 2, but for trends in the peak-over-threshold magnitude series, with on average 3 daily mean river flow peaks per year selected.

Figure 5. As in Figure 2, but for trends in the peak-over-threshold frequency series, with on average 1 daily mean river flow peak per year selected.

Figure 6. As in Figure 2, but for trends in the peak-over-threshold frequency series, with on average 3 daily mean river flow peaks per year selected.

The two stations for which 3 peaks per year on average could not be extracted (1134100 and 3206720) do not show widely different behaviour for the POT3 series compared with other stations. For the two stations, a couple of non-significant POT3 magnitude and frequency trends are of opposite direction to the corresponding POT1 trends, but 4-5 other stations show the same behaviour.

For the flood index series, there are generally slightly more stations showing a significant negative trend than a significant positive trend. The Ann. max. index has the highest number of both negative and positive significant trends: 7 and 4, respectively. A more significant trend may occur in the Ann. max. series than in the POT magnitude series, when a series of low peaks occur at the beginning or end of a time series with trend. These peaks may be too low to be selected for the POT analysis, whereas one per year will be included in the Ann. max. series. For example, compare the Ann. max. and POT1 mag. time series plots for stations 4116300 and 6545200 in Appendix B.

A correlation analysis between the Table 2 columns for flood indices on the one hand, and the low flow indices on the other, does not reveal anything of significance.

Figures 7 and 8 suggest that many of the stations have experienced an increase in the low flows, with 10 stations showing significant trends for each of the Min. 7-day and Min. 30-day flow series. The increase in low flows would be consistent with an increasing number of reservoirs becoming operational in the catchments over the period of record. A reservoir's capacity to store the incoming flood flows and slowly release the water over time generally means that low flows are augmented and flood flows are mitigated downstream of the reservoir (Vörösmarty *et al.*, 1997).

The increases in low flows do not support the theory of an intensification of the hydrological cycle in a warming climate, which would involve more severe droughts (Trenberth, 1998). However, if there is a change in the river flow regime due to reservoir construction in the catchments, this is likely to partly or completely mask changes in the hydrological cycle due to climate change. It should also be borne in mind that any climate change impacts on river flow regimes would be a recent phenomenon, and that statistical tests for trend are not able to detect changes which have not lasted long, or are weak (Radziejewski and Kundzewicz, 2004).

Figure 7. As in Figure 2, but for trends in the annual minimum 7-day mean river flow series.

Figure 8. As in Figure 2, but for trends in the annual minimum 30-day mean river flow series.

5. Conclusions

The investigation into trends in observed high and low flow index series at 21 daily mean river flow stations across the world suggest the following:

- There is generally good agreement between the results of the trend analysis using the linear regression method and the Mann-Kendall method (significance levels for both estimated using block bootstrapping), except when there are outliers in the data series.
- There is very good agreement between trends estimated for the two low flow indices, annual minimum 7-day and 30-day mean flows. There is also good agreement between trends in the three flood magnitude series, and, separately, in the two flood frequency series, but not between flood magnitude *and* frequency series.
- There is a larger number of both negative and positive significant trends in the annual maximum flood series, than in the peak-over-threshold series.
- The trend analyses do not reveal any evidence of an intensification of the hydrological cycle, as manifesting itself in an increase in floods and more severe dry spells. Rather, statistically significant increases in the low flow series are consistent with a surmised increasing number of reservoirs becoming operational in the catchments. This imposed modification to the river flow regime would be likely to obscure any recent alteration in the hydrological cycle due to climate change.

Acknowledgements

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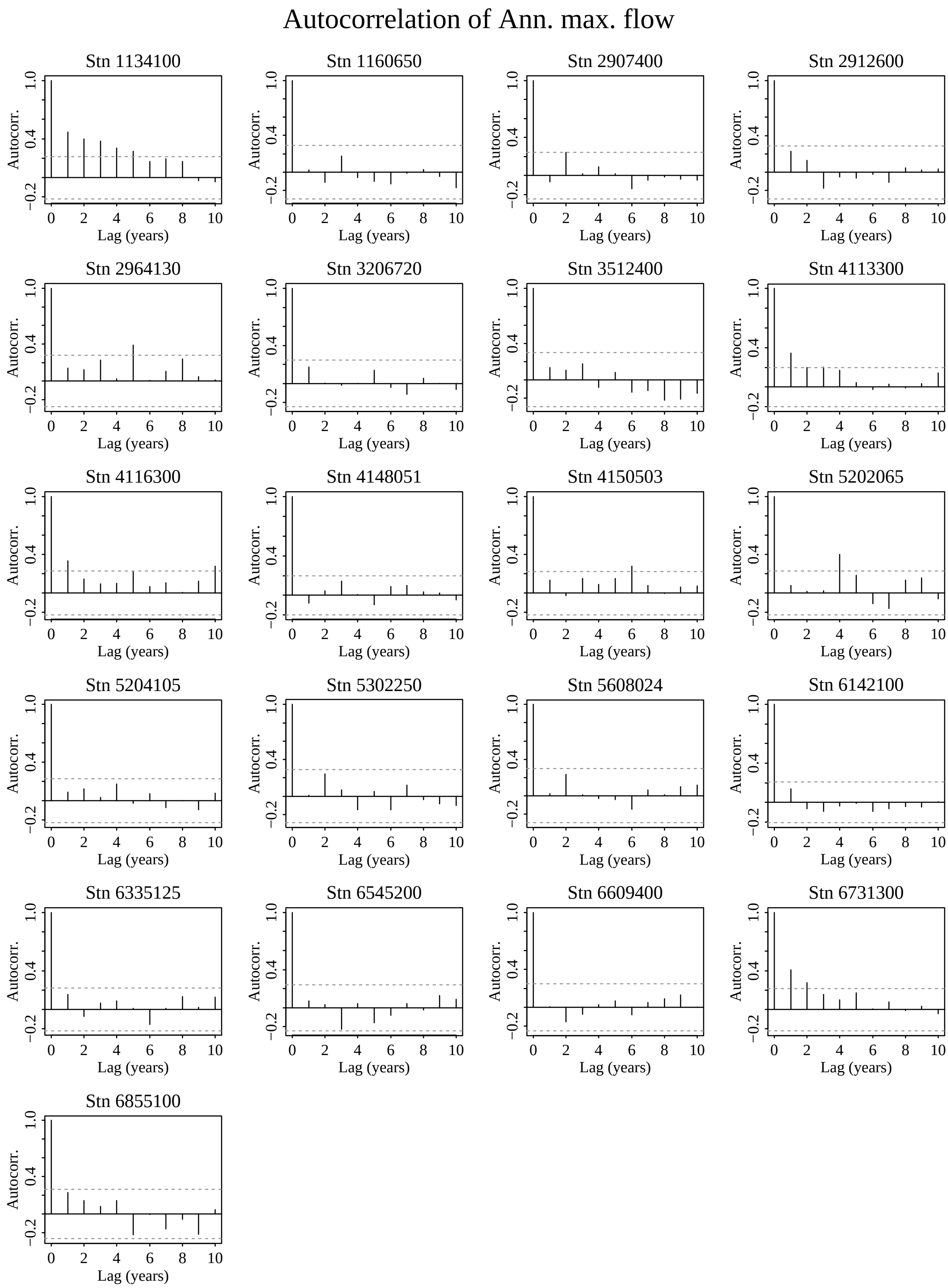
Appendix A
Autocorrelation in annual index series

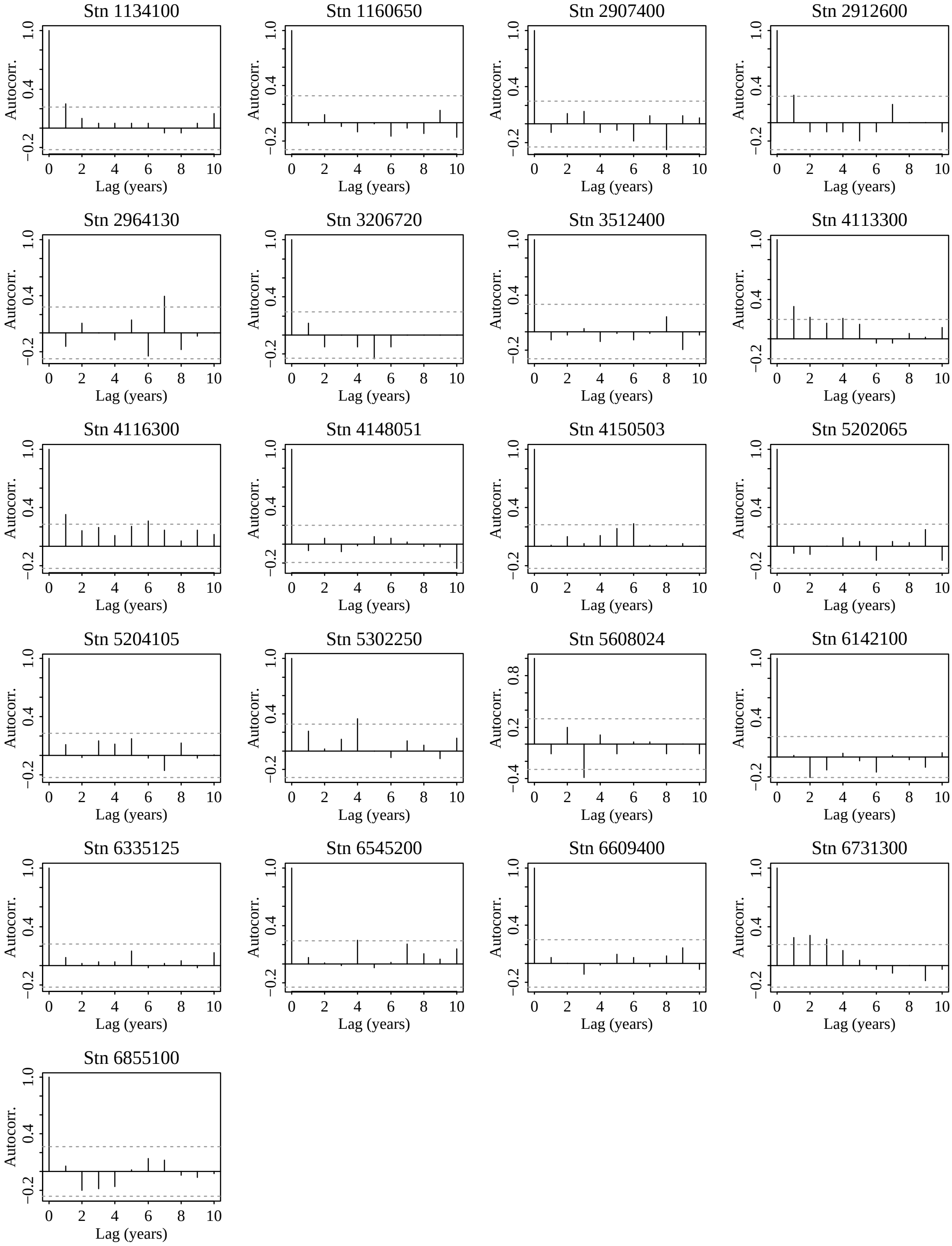
Autocorrelations in annual flood and low flow index series are shown for each station, for lags of 0 to 10 years. The dashed lines denote 95% significance levels.

The annual flow index series are:

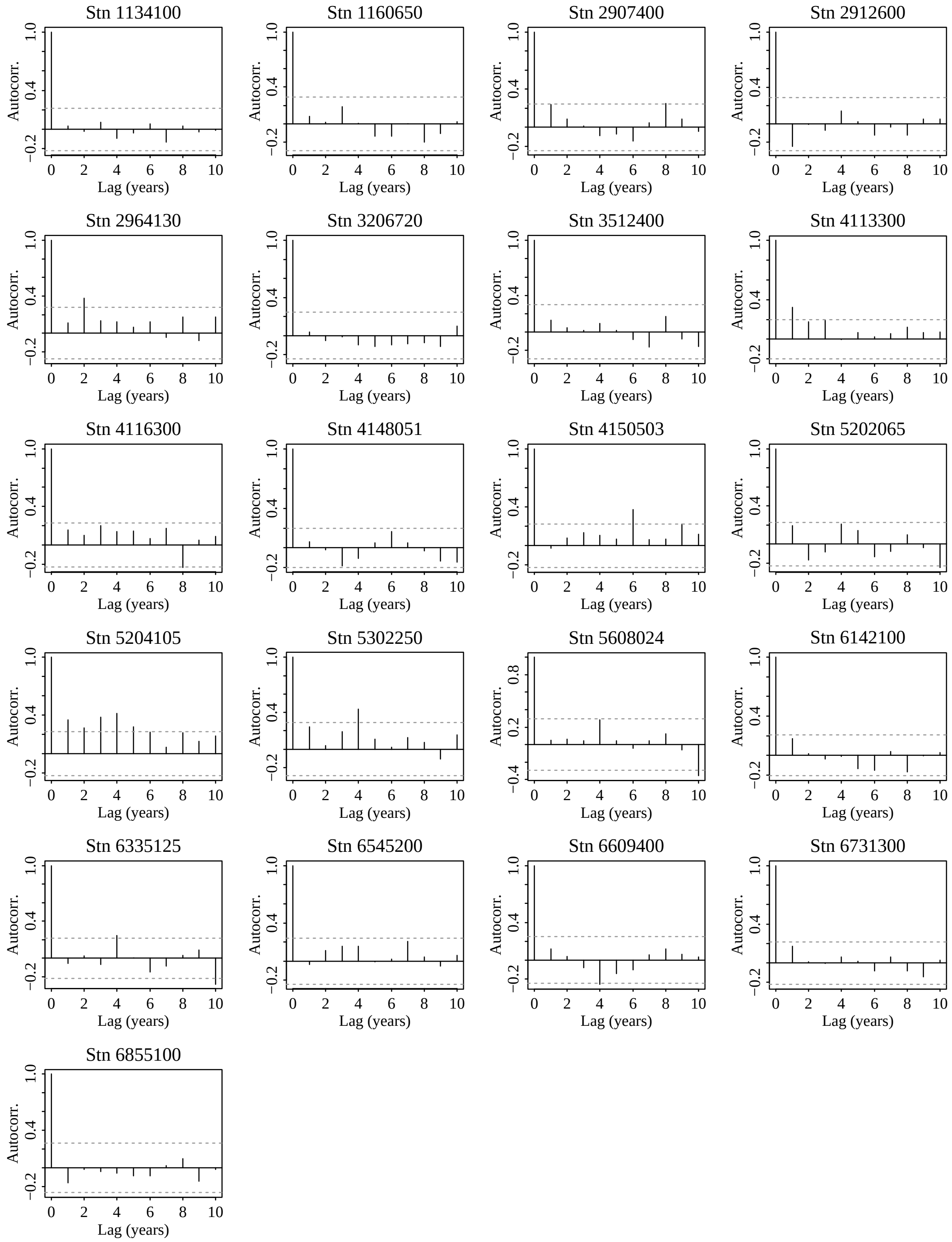
Ann. max.:	Annual maximum daily mean river flow.
POT1 freq.:	Peak-over-threshold frequency series with on average 1 peak per year.
POT3 freq.:	Peak-over-threshold frequency series with on average 3 peaks per year, except for stations 1134100 and 3206720 which have on average 2.1 and 1.5 peaks per year, respectively.
Min. 7-day:	Annual minimum 7-day mean river flow.
Min. 30-day:	Annual minimum 30-day mean river flow.

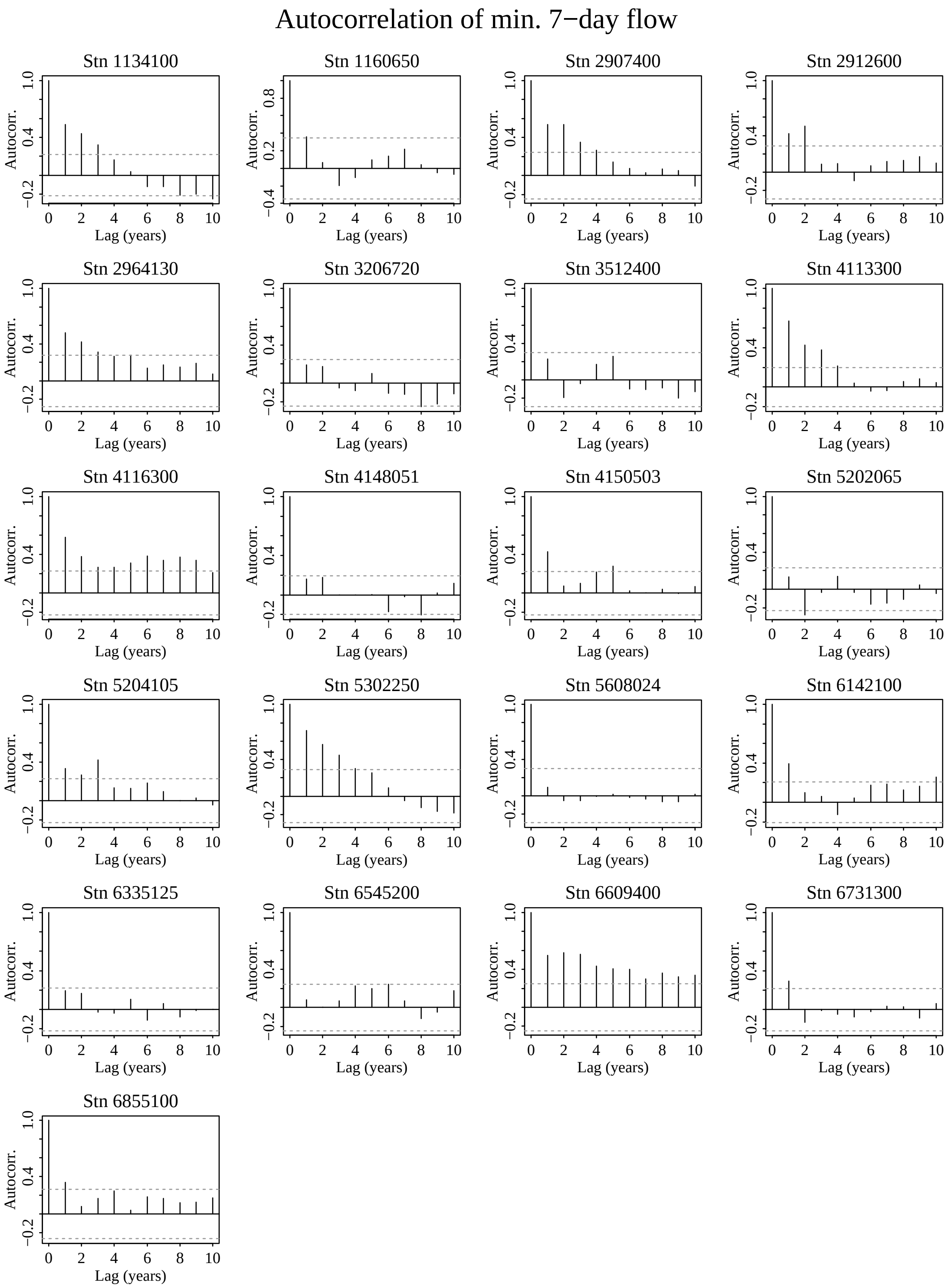

Autocorrelation of Ann. max. flow
Stn 1134100
Stn 1160650
Stn 2907400
Stn 2912600
Stn 2964130
Stn 3206720
Stn 3512400
Stn 4113300
Stn 4116300
Stn 4148051
Stn 4150503
Stn 5202065
Stn 5204105
Stn 5302250
Stn 5608024
Stn 6142100
Stn 6335125
Stn 6545200
Stn 6609400
Stn 6731300
Stn 6855100
Autocorr.
−0.2
0.4
1.0
0
2
4
6
8
10
Lag (years)

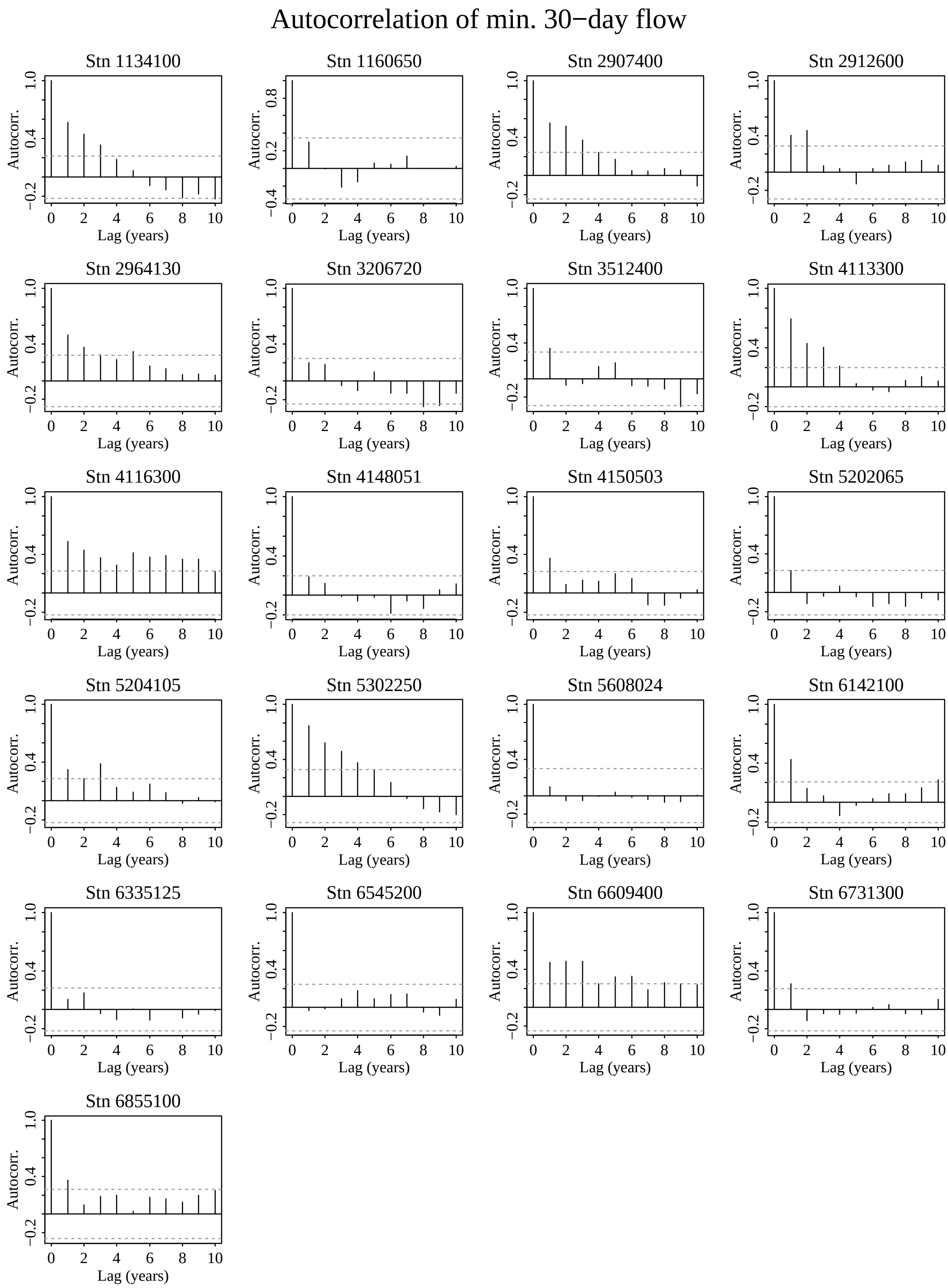
Autocorrelation of POT1 frequency



Autocorrelation of POT3 frequency




Autocorrelation of min. 7−day flow
Stn 1134100
Stn 1160650
Stn 2907400
Stn 2912600
Stn 2964130
Stn 3206720
Stn 3512400
Stn 4113300
Stn 4116300
Stn 4148051
Stn 4150503
Stn 5202065
Stn 5204105
Stn 5302250
Stn 5608024
Stn 6142100
Stn 6335125
Stn 6545200
Stn 6609400
Stn 6731300
Stn 6855100
Autocorr.
Lag (years)


Autocorrelation of min. 30−day flow
Stn 1134100
Stn 1160650
Stn 2907400
Stn 2912600
Stn 2964130
Stn 3206720
Stn 3512400
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Stn 4116300
Stn 4148051
Stn 4150503
Stn 5202065
Stn 5204105
Stn 5302250
Stn 5608024
Stn 6142100
Stn 6335125
Stn 6545200
Stn 6609400
Stn 6731300
Stn 6855100
Autocorr.
Lag (years)

Appendix B
Index series and fitted linear regressions

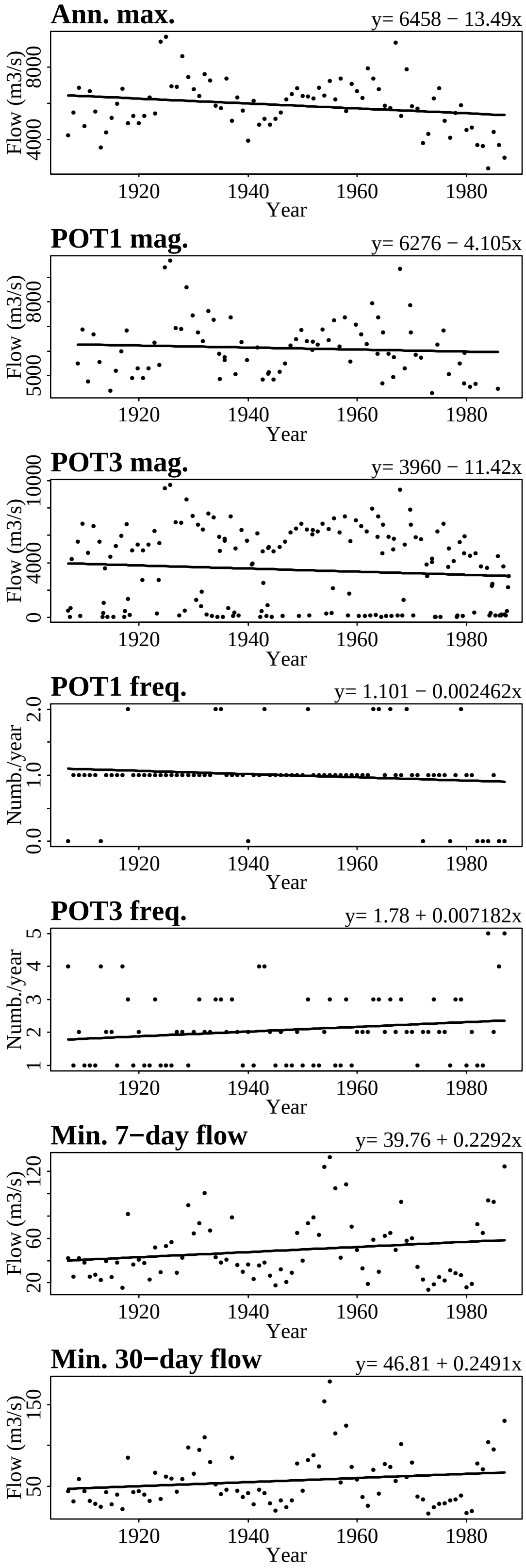
The diagrams in this appendix show time series of the seven different flow index series, and fitted linear regressions, for each of the 21 river flow stations used in the analysis. The intercept of the regression equations relate to the first year in each series.

The flow index series are:

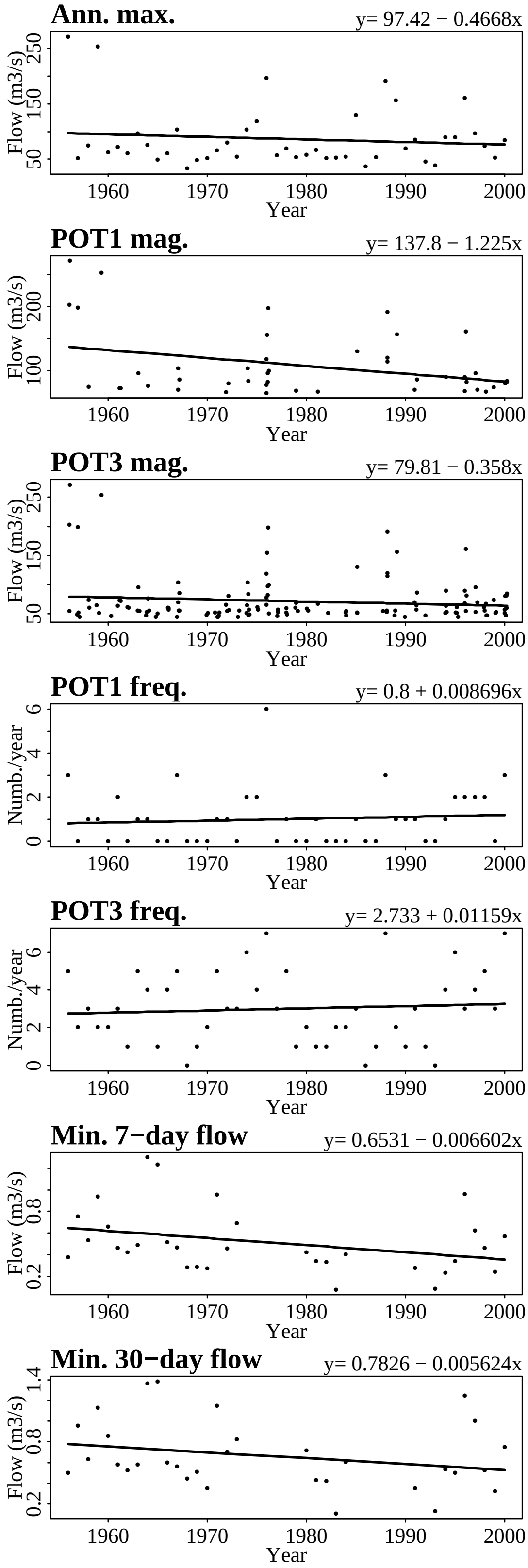
Ann. max.: Annual maximum daily mean river flow.
POT1 mag.: Peak-over-threshold magnitude series with on average 1 peak per year.
POT3 mag.: Peak-over-threshold magnitude series with on average 3 peaks per year*.
POT1 freq.: Peak-over-threshold frequency series with on average 1 peak per year.
POT3 freq.: Peak-over-threshold frequency series with on average 3 peaks per year*.
Min. 7-day: Annual minimum 7-day mean river flow.
Min. 30-day: Annual minimum 30-day mean river flow.

* The POT3 series for two stations have less than 3 peaks per year on average. The stations are 1134100 and 3206720, and have on average 2.1 and 1.5 peaks per year, respectively.

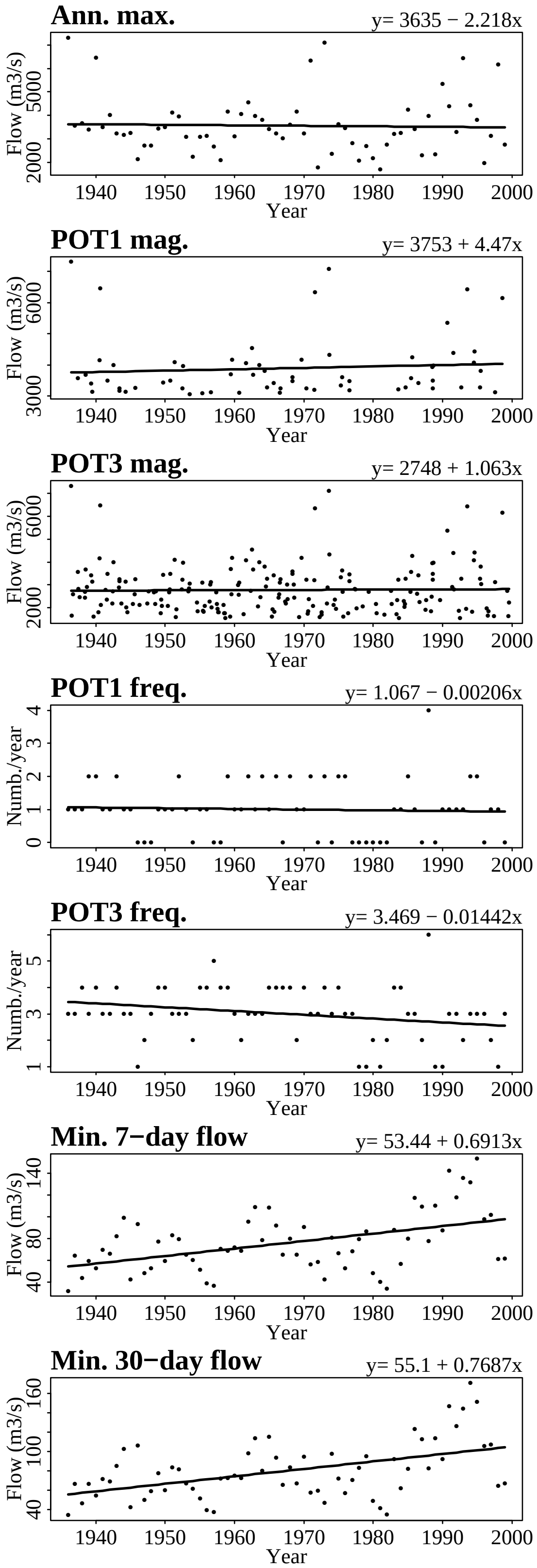
1134100 *
Niger at Koulikoro



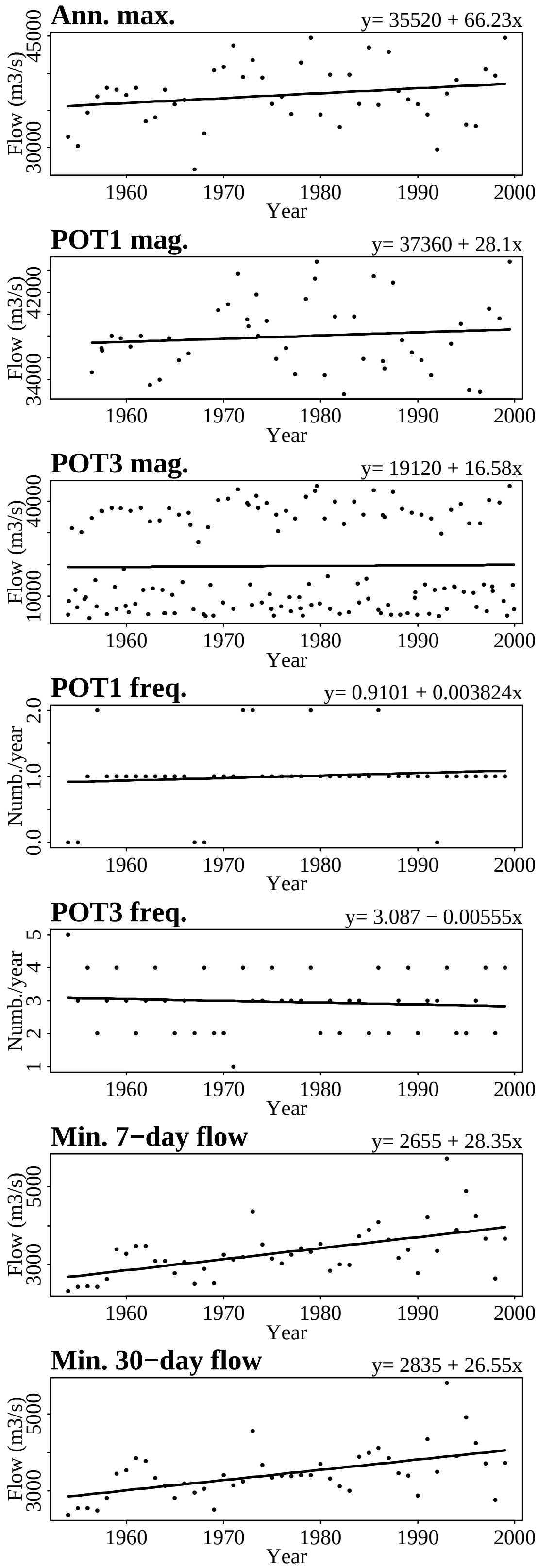
1160650
Mtamvuna at Gundrift



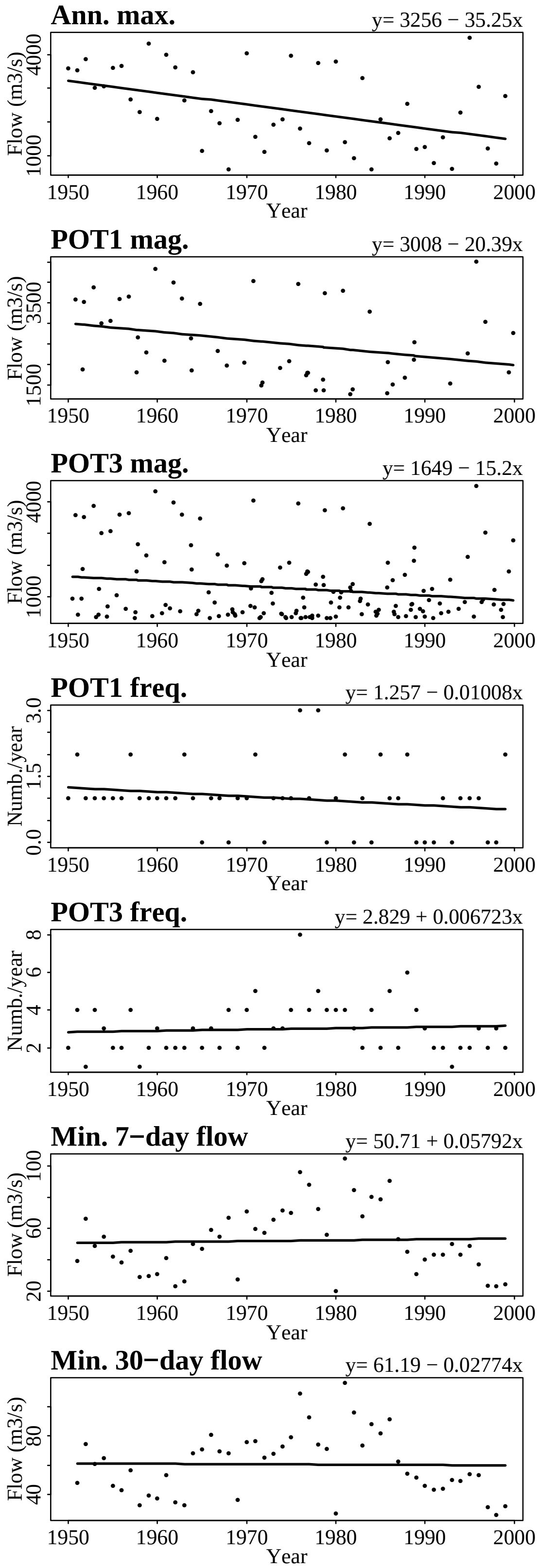
2907400
Selenga at Mostovoy



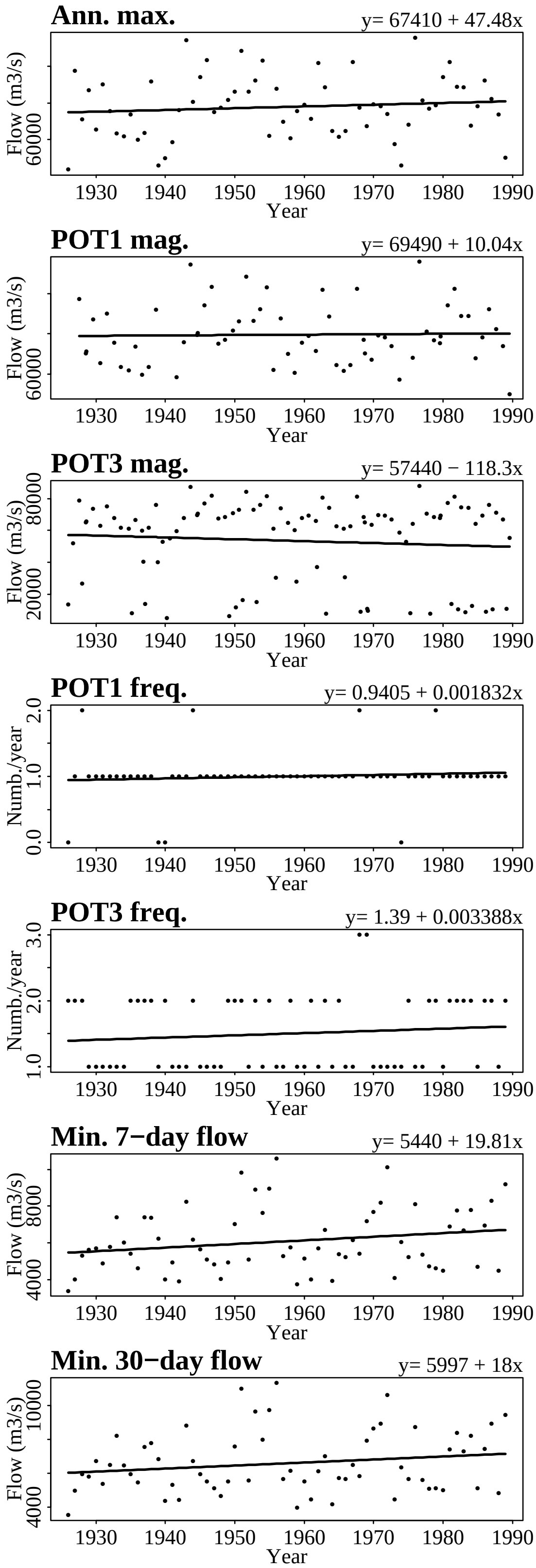
2912600
Ob at Salekhard



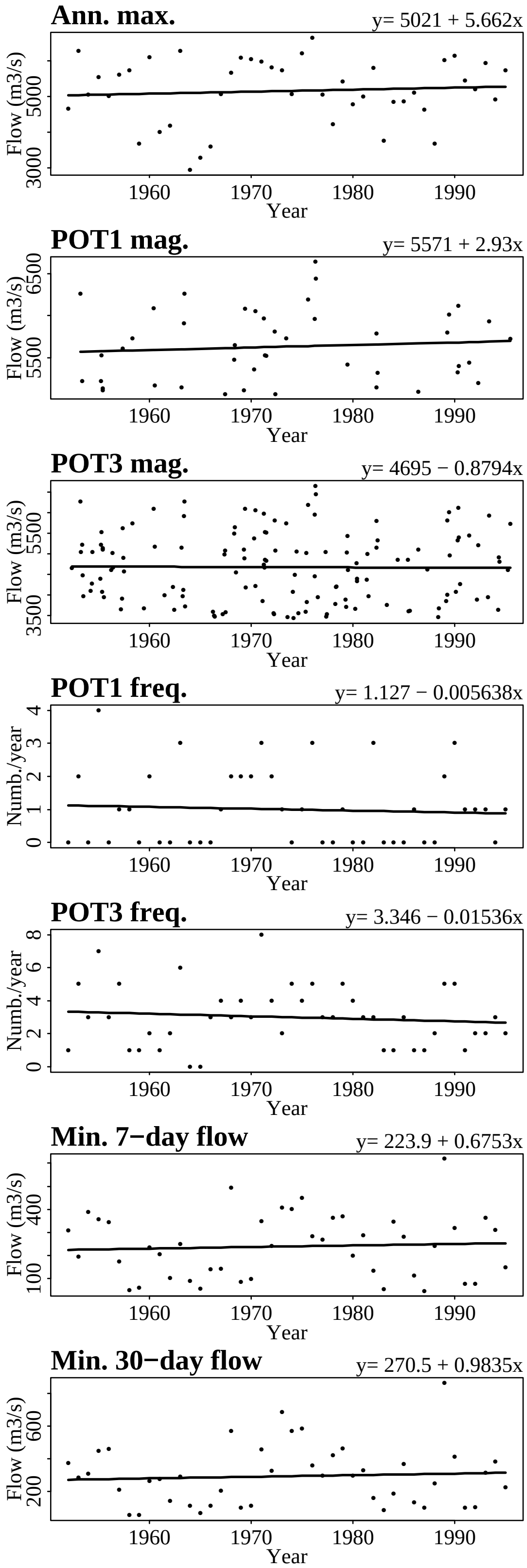
2964130
Chao Praya at Wat Pho Ngam (Ban Re Rai)



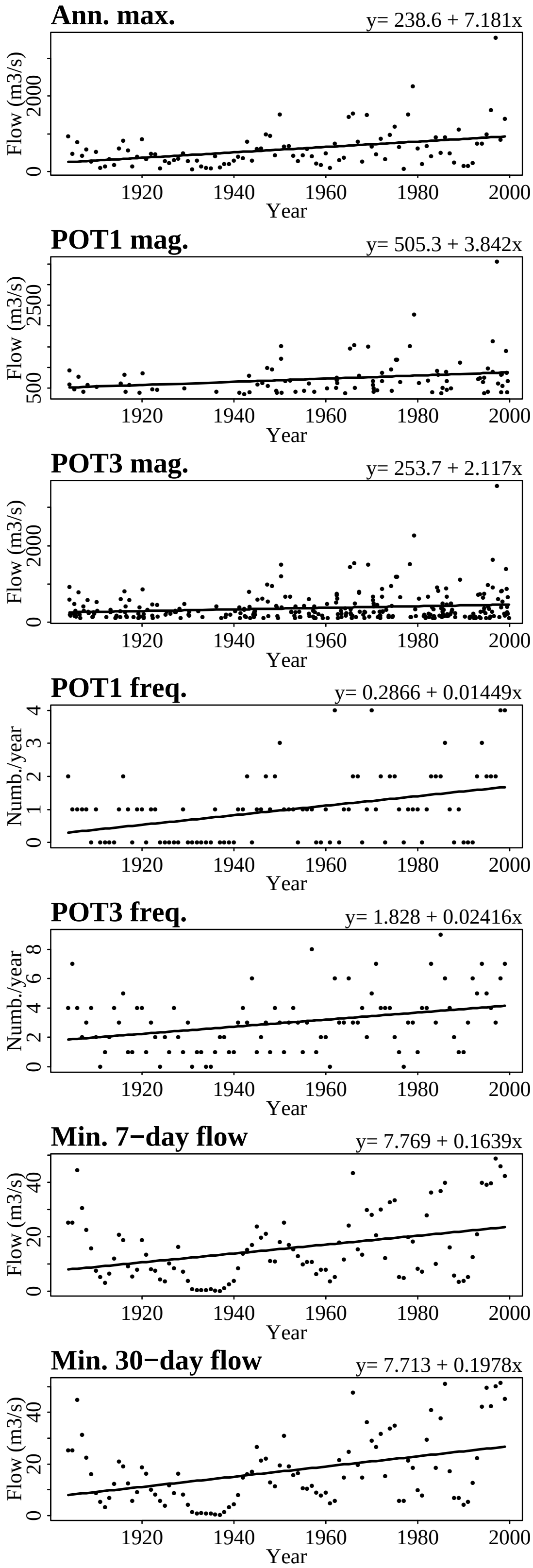
3206720 *
Orinoco at Puente Angostura



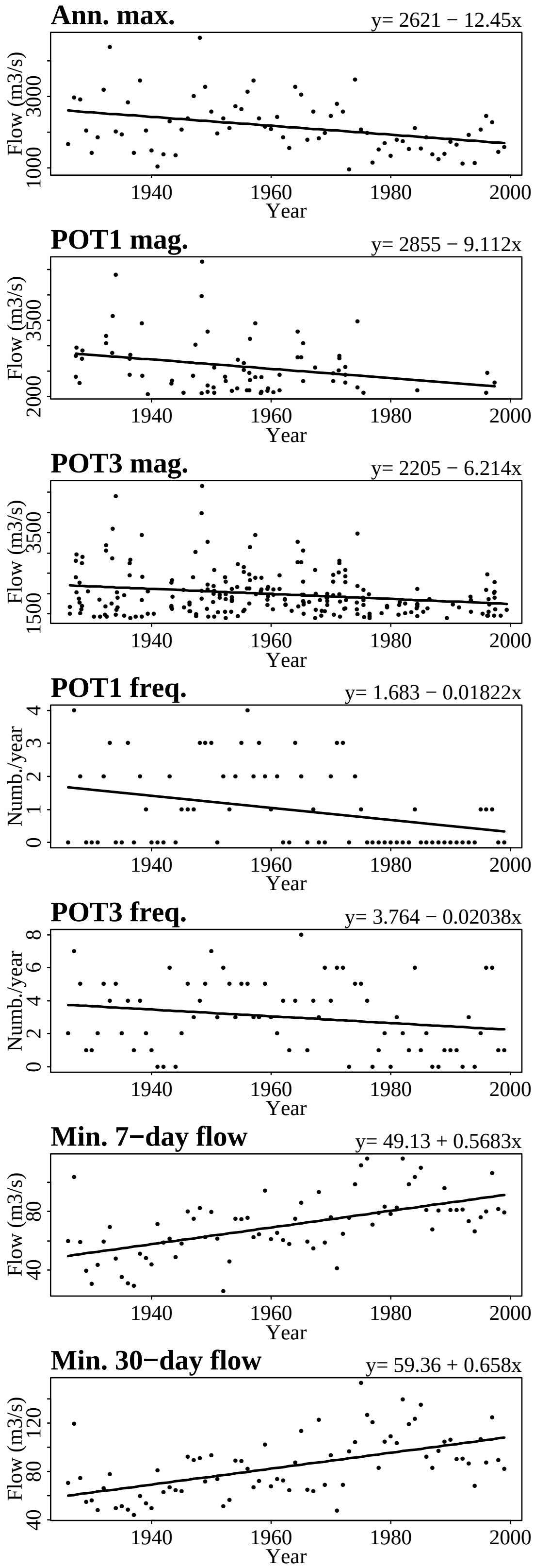
3512400
Maroni at Langa Tabiki



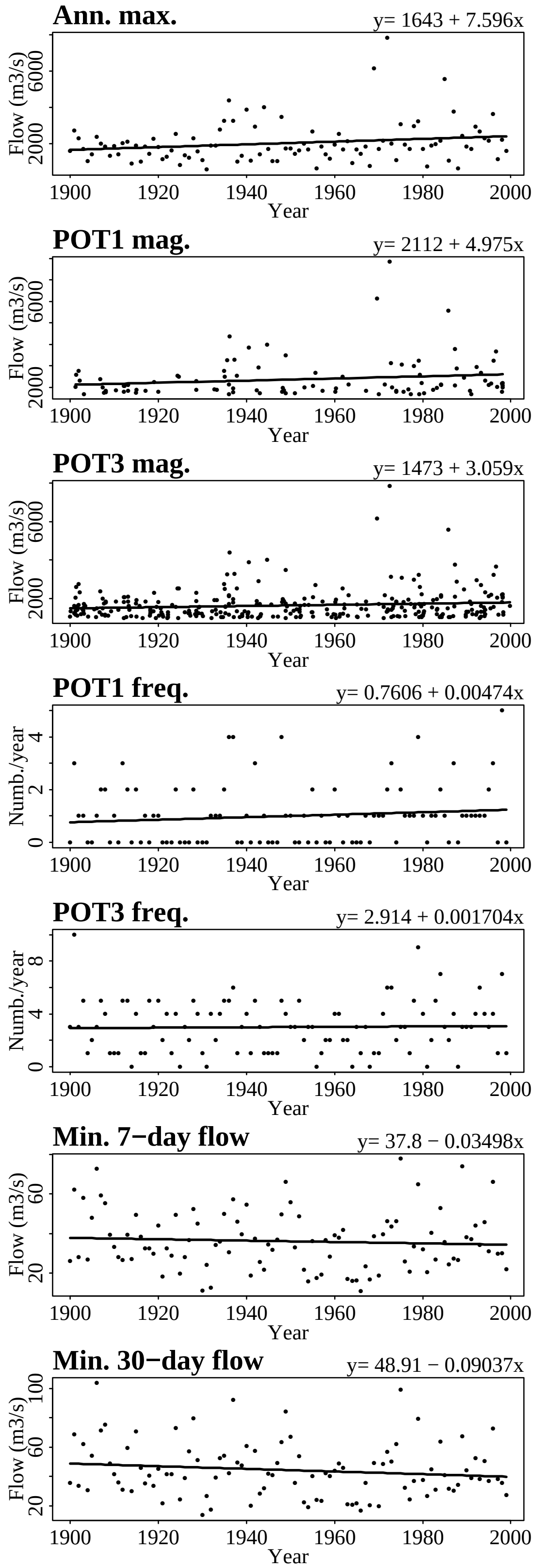
4113300
Red River of the North Grand Forks, N.D.



4116300
Clearwater River at Spalding, ID



4148051
James at Cartersville, VA



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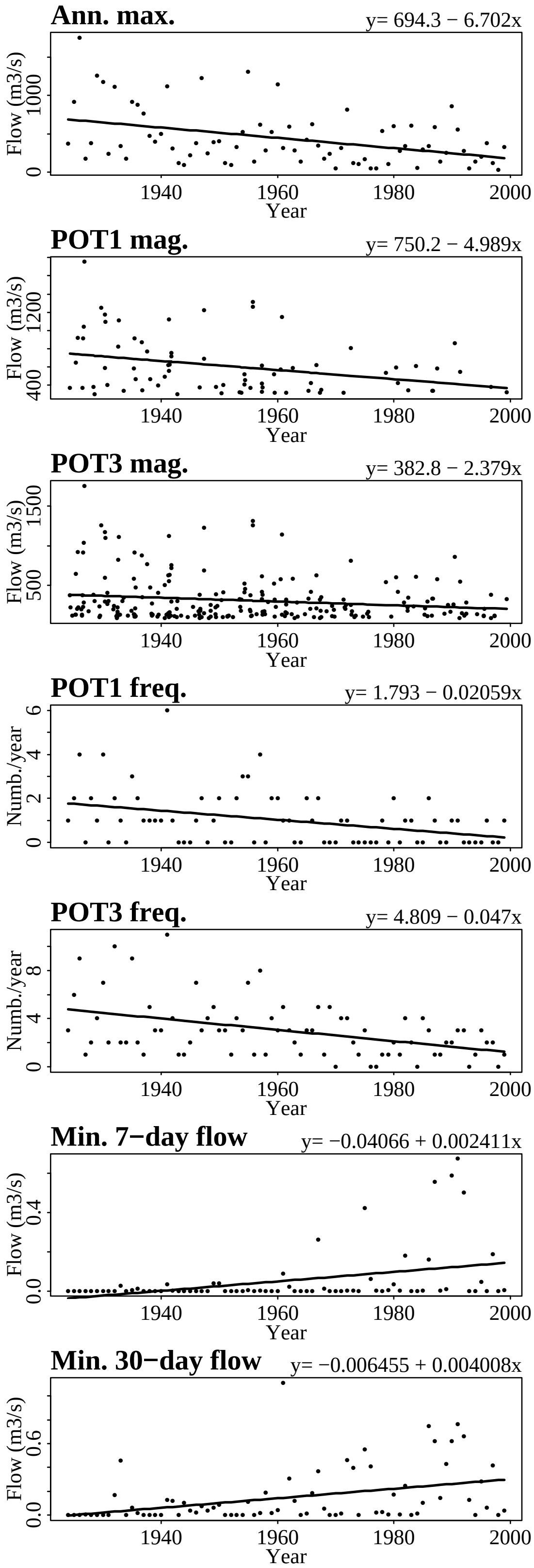
Brazos River at Seymour, TX



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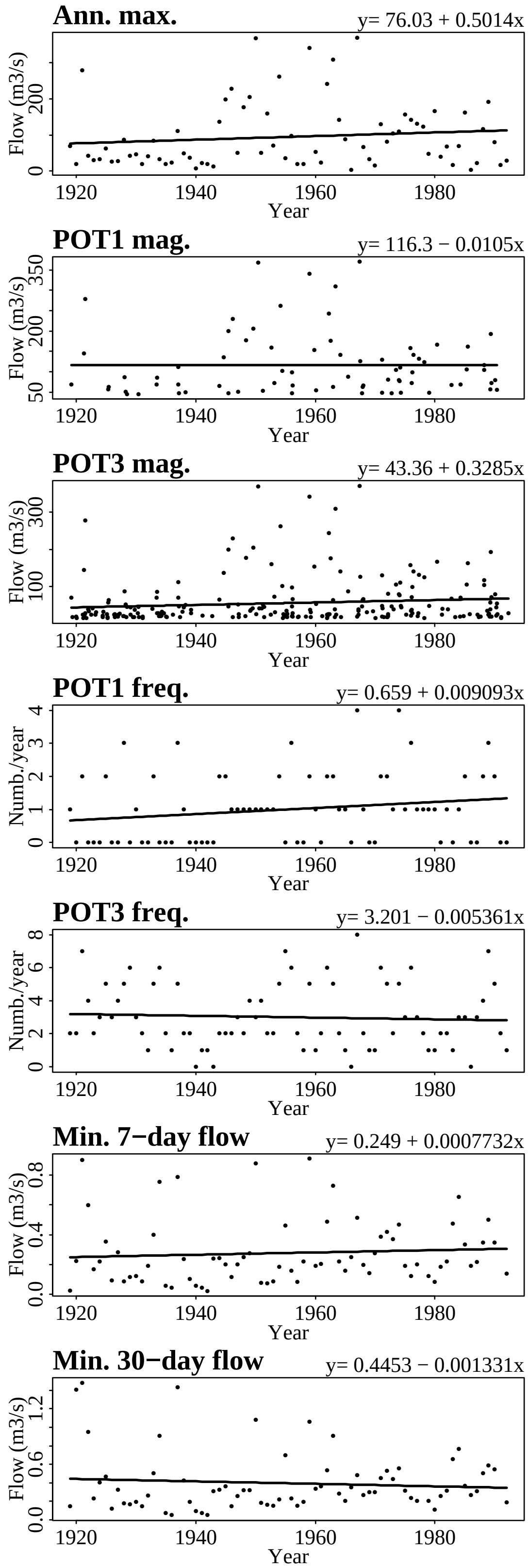
Styx River at Jeogla



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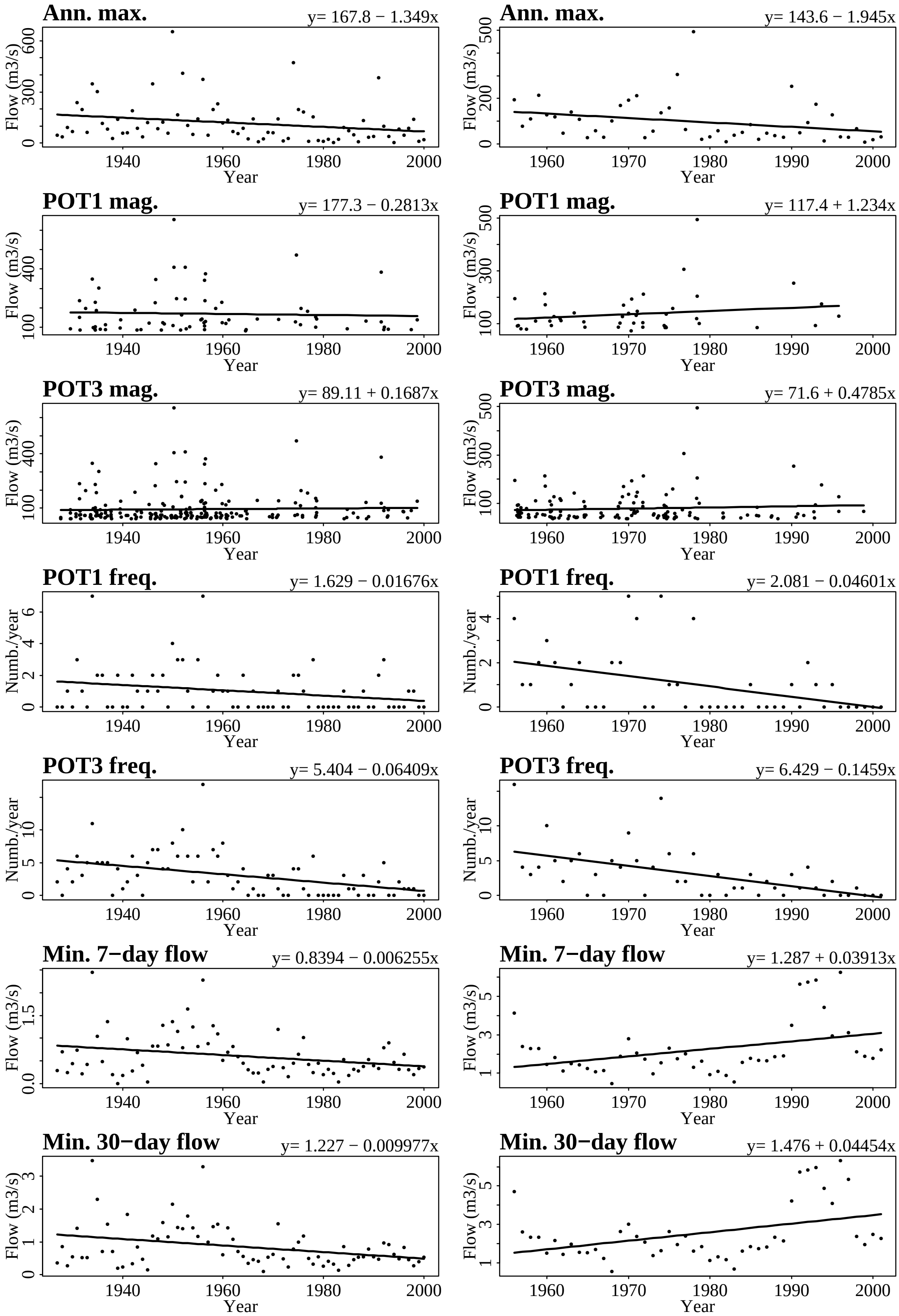
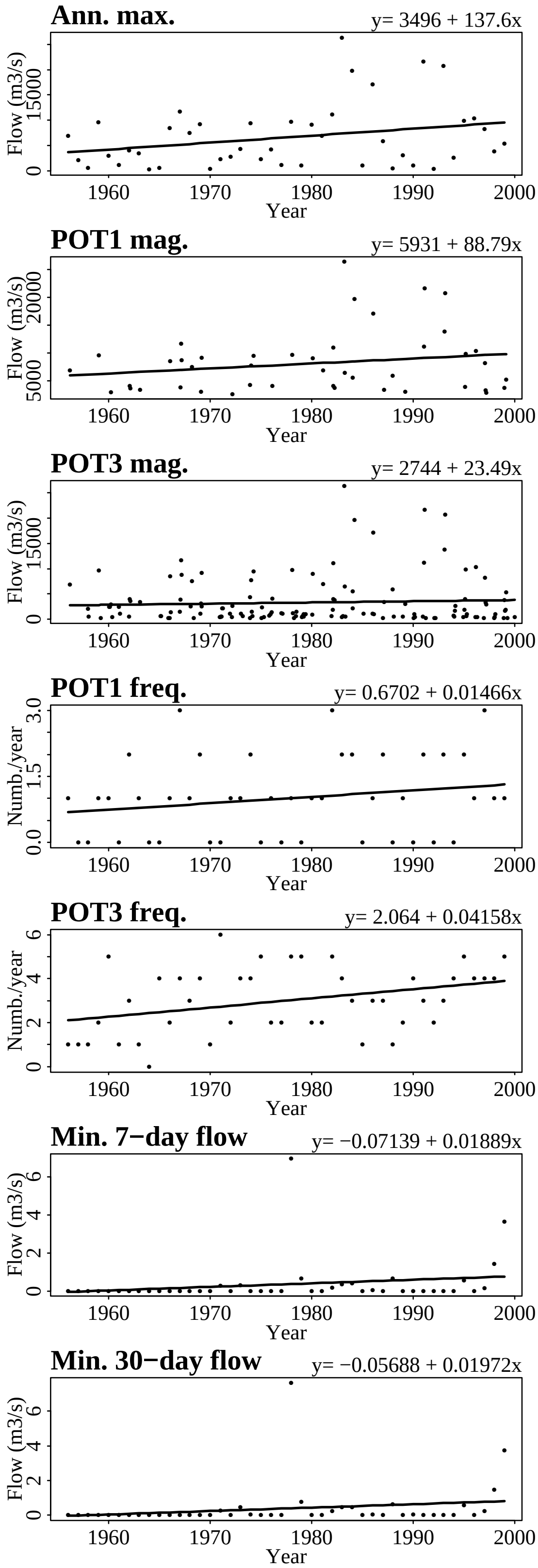
Murrumbidgee River at Mittagang Crossing

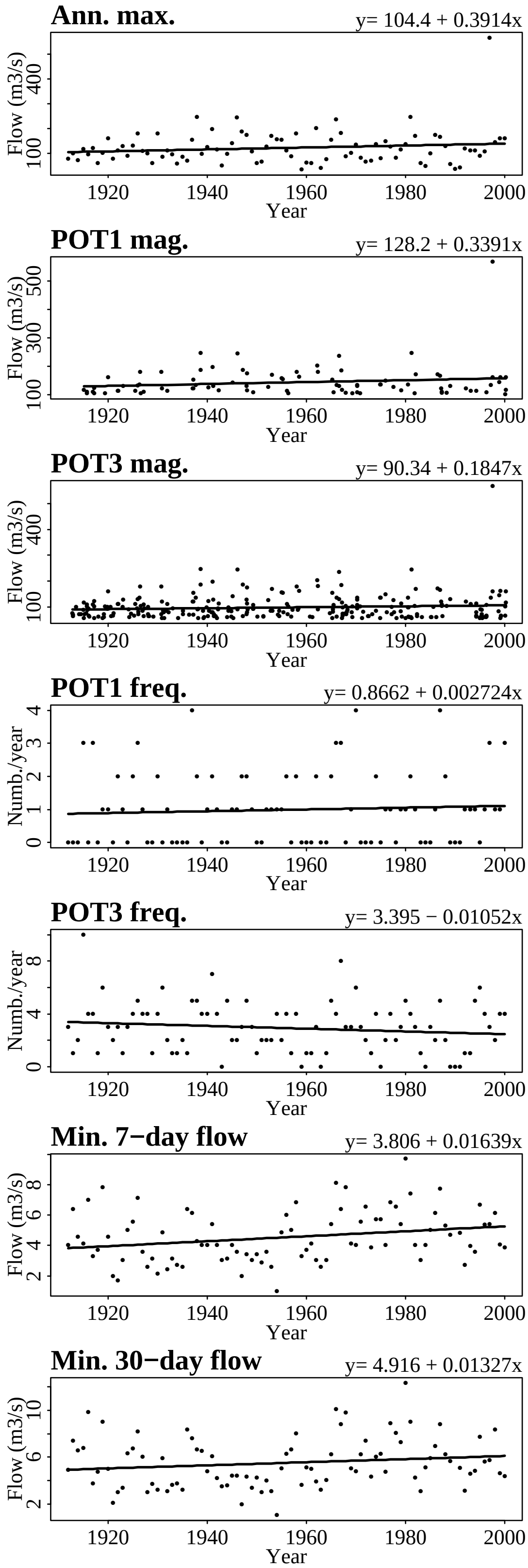
5302250
Thomson River at Cooper Creek



5608024
Fitzroy River at Fitzroy Crossing

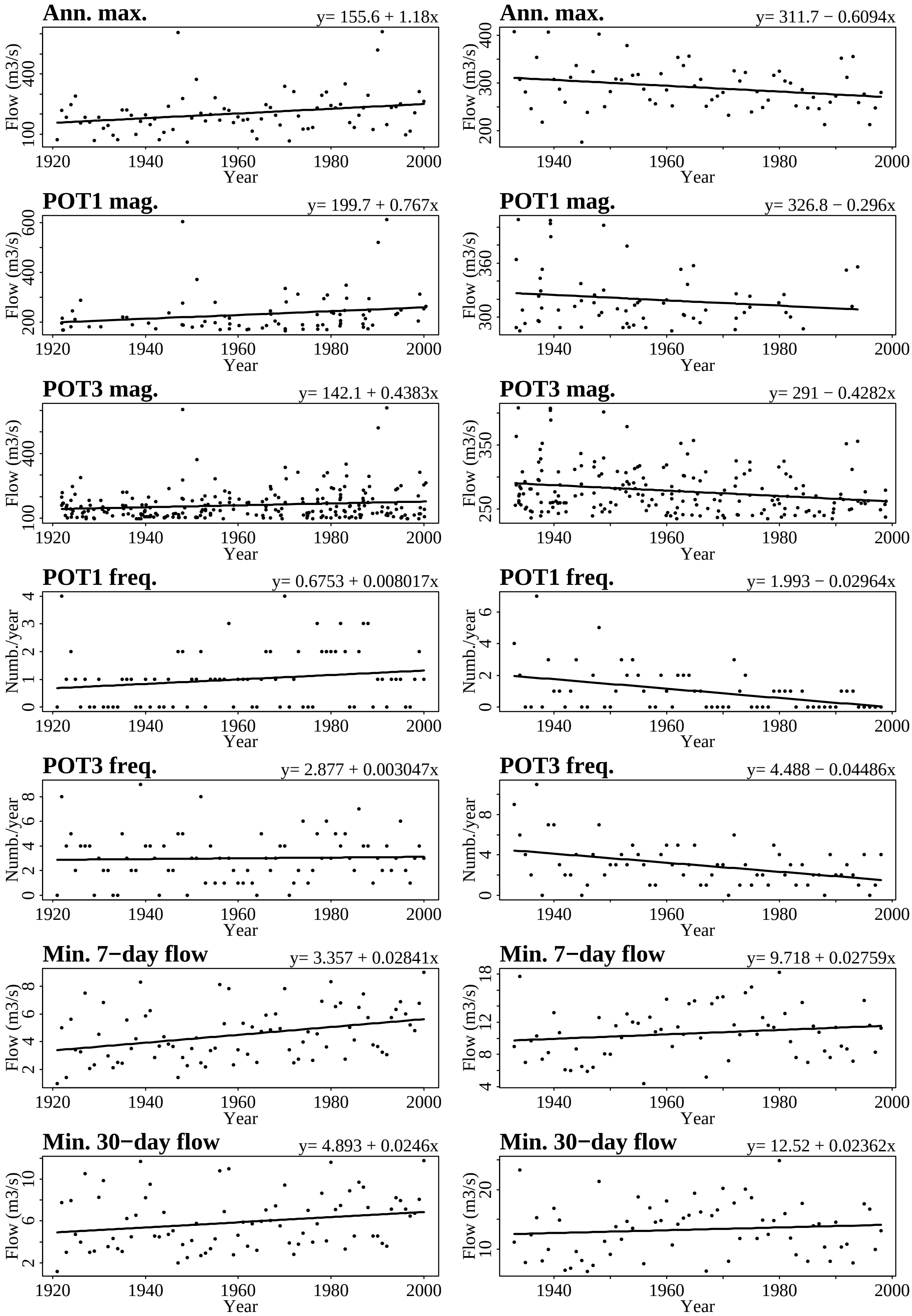


6142100
Morava at Moravicany

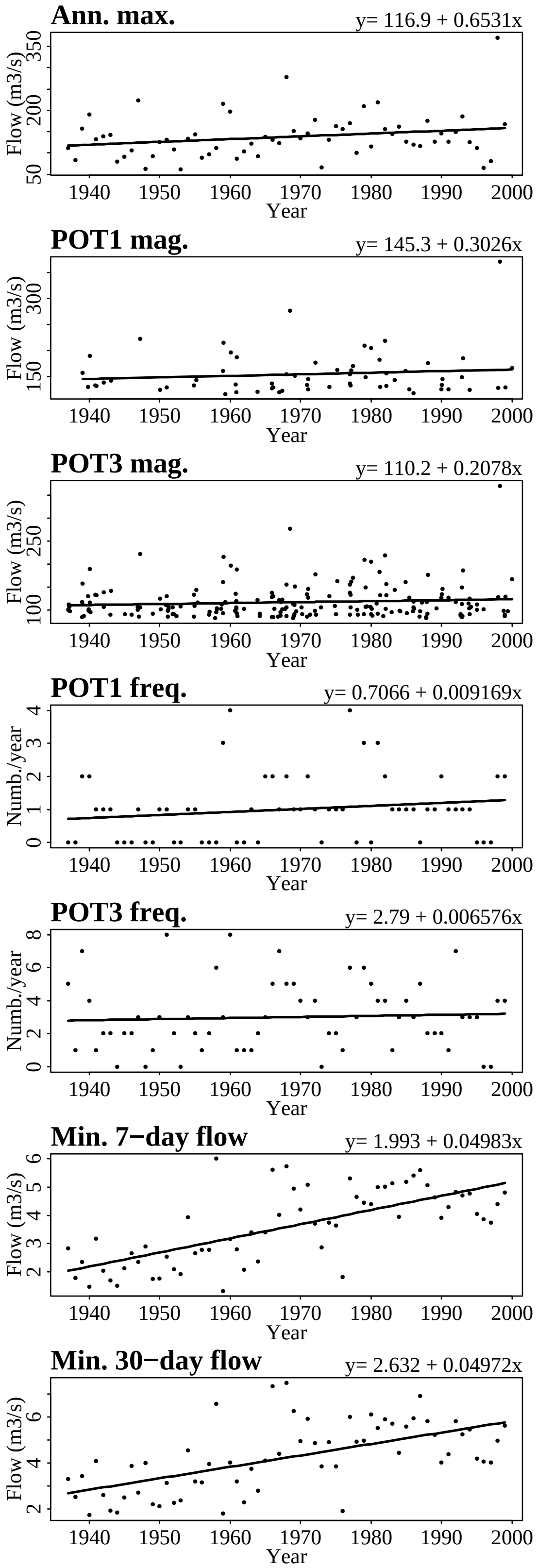


6335125
Kinzig at Schweibach

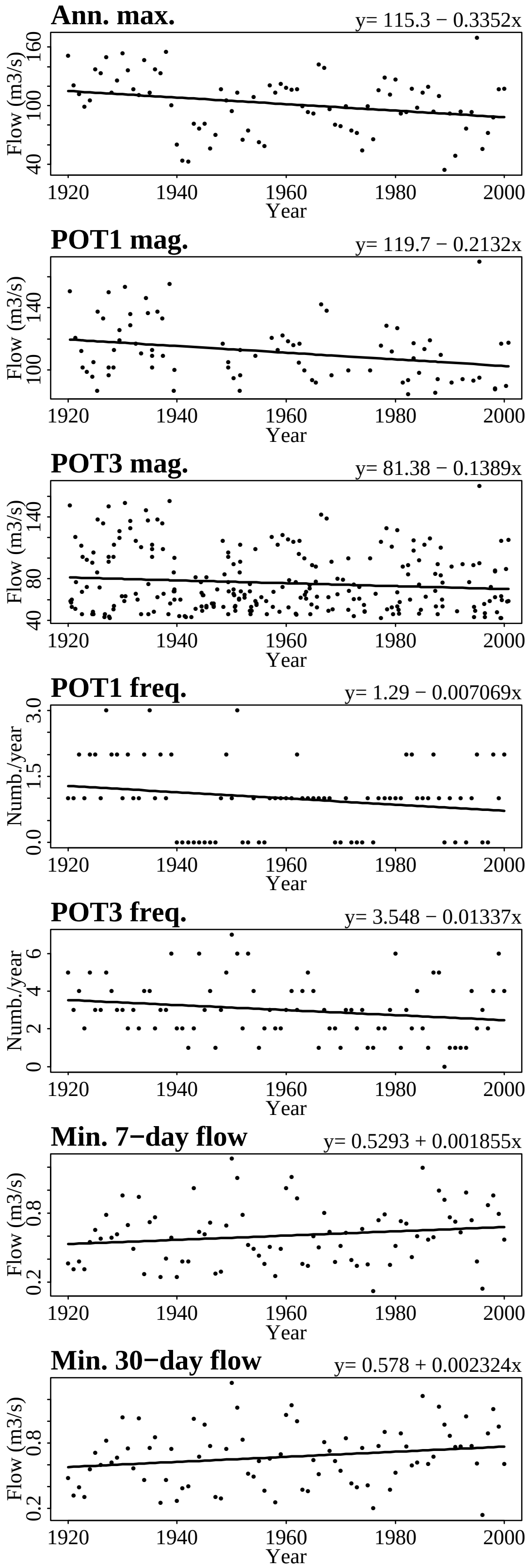
6545200
Krka at Podbocje



6609400
Avon at Evesham

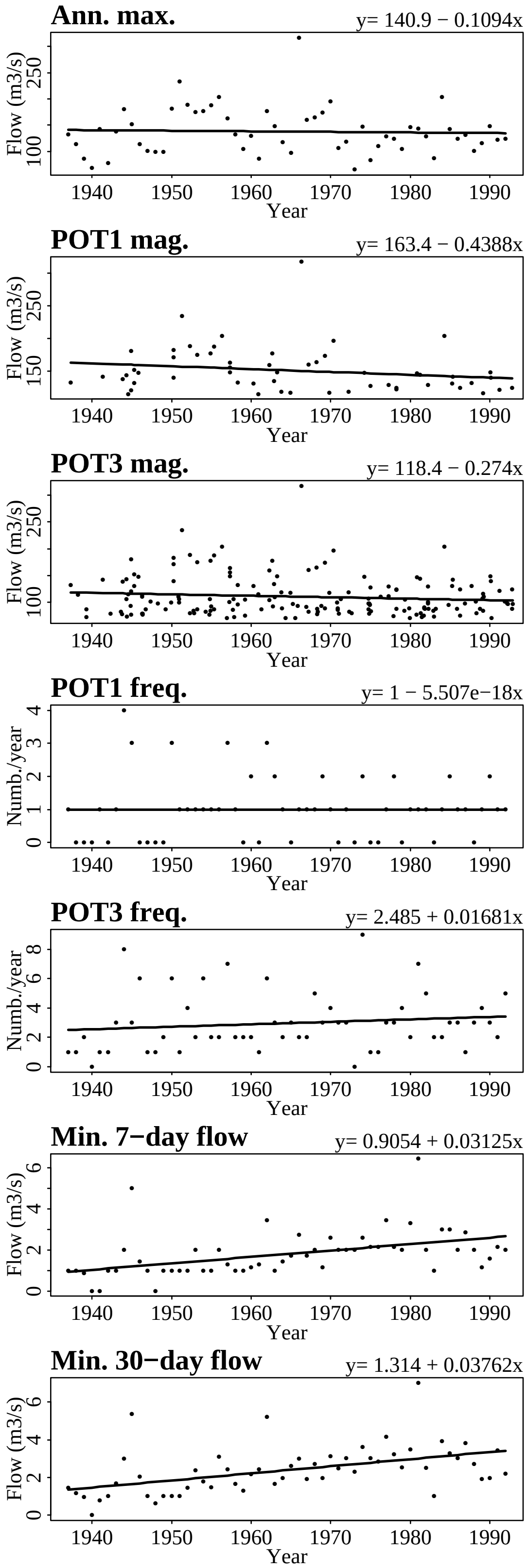


6731300
Etna at Etna



6855100

Vantaanjoki at Oulunkyla (near the mouth)



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