EXTREME LOW FLOW AND WATER QUALITY – A LONG-TERM VIEW ON THE RIVER ELBE

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With 8 figures and 5 tables
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Summary: Effects of extreme low flow on the water quality of the River Elbe (Germany) were assessed by the example of the summer low flow events in 1904, 1911, 1921, 1934, 1935, 1952, 1964, 2003, and 2015 using numerous unpublished historical data. The month with the most pronounced low flow was usually August, except in 1934, when it was July. Oxygen content, permanganate index, chloride concentration, and water hardness of the Elbe during the low flow months were compared with the annual range. The annual maximum of these water quality parameters (or in the case of oxygen, the annual minimum) was often observed in the low flow month. Water quality during low flow corresponded to the general pollution level, most elevated in 1952 and 1964. During low flows in 2003 and 2015, the reduced input of easily oxidisable organic matter resulted in a stable oxygen regime. Chloride concentration and hardness of the Elbe were mostly determined by the tributary Saale and in 2003 and 2015 still considerably elevated against the natural background. The transferable method of a systematic comparison of several low flow events of a river over a long period of time facilitates the differentiation between event-specific influences (e.g. proportion of tributaries on the total discharge) and common influences (e.g. accumulation of substances due to a lack of dilution). At the same time, basics for characterisation and classification of former and present low flow events are provided.

Zusammenfassung: Die Auswirkungen extrem niedriger Wasserführung auf die Wasserbeschaffenheit der Elbe wurden am Beispiel der Sommer-Niedrigwasserereignisse 1904, 1911, 1921, 1934, 1935, 1952, 1964, 2003 und 2015 untersucht, wobei zahlreiche unveröffentlichte historische Daten einflossen. Der Monat mit der ausgeprägtesten Niedrigwasserführung war der August, nur 1934 war es der Juli. Sauerstoffgehalt, Permanganat-Index, Chloridkonzentration und Wasserhärte der Elbe während der Niedrigwassermonate wurden mit der jährlichen Spannweite verglichen. Das jährliche Maximum (bzw. Sauerstoffminimum) dieser Kenngrößen trat häufig im Niedrigwassermonat auf. Die Wasserbeschaffenheit während des Niedrigwassers korrespondierte mit dem allgemeinen Belastungsniveau, das 1952 und 1964 sehr hoch war. Beim Niedrigwasser 2003 und 2015 spiegelte das stabile Sauerstoffregime den verminderten Eintrag leicht abbaubarer organischer Substanzen wider. Chloridkonzentration und Wasserhärte der Elbe werden nach wie vor entscheidend von der Saale bestimmt und waren 2003 und 2015 gegenüber der natürlichen Hintergrundkonzentration noch deutlich erhöht. Die übertragbare Methode des systematischen Vergleichs mehrerer Niedrigwasserereignisse eines Flusses über einen langen Zeitraum erleichtert die Unterscheidung ereignisspezifischer Einflüsse auf die Wasserbeschaffenheit (z. B. Anteil bestimmter Zuflüsse am Gesamtdurchfluss) von allgemeinen Effekten (z. B. Aufkonzentration von Substanzen). Gleichzeitig entstehen Grundlagen für eine fundierte Charakterisierung und Einordnung vergangener und aktueller Niedrigwasserereignisse.

Keywords: Hydrology, running waters, low flow history, water pollution, monitoring, Eastern Germany

1 Introduction

1.1 General introduction and aim of the study

With climate change, an increase in the frequency of summer droughts in Central Europe is expected (e.g. Schwarzak et al. 2015; Sedlmeier et al. 2018). Thus, more frequent summer low flow periods will occur resulting in a lack of (dilution) water, reduced flow velocity in running waters and stronger warming.

The specific effects on the physico-chemical water quality that go along with low flow in streams and rivers are of high interest internationally (e.g. Mosley 2015). However, there are relatively few studies explicitly dealing with this subject on the basis of monitoring campaigns in European rivers (e.g. Zwolsman and Borkhoven 2007; Vliet and Zwolsman 2008; Worrall and Burt 2008; Zielinski et al. 2009; Hanslik et al. 2016; Hellwig et al. 2017). Results are diverse and show a need for further research. To our knowledge, there is currently no study available that consequently includes the historical dimension in its research.

The River Elbe, the third longest river in Central Europe (1094 km), flows from the Czech

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Giant Mountains to the North Sea (Pusch et al. 2009). Its catchment area covers more than 148000 km², one third in the Czech Republic and two thirds in east and northern Germany. The flow regime is pluvio-nival. The largest tributaries are Vltava and Saale.

Until the 1960s, the Elbe experienced at least one extreme low flow period in every decade of the 20th century. After 40 years without a single low flow event, in summer 2003 the flow of the Elbe below the Saale confluence was extremely low. And quite recently, from July to the beginning of October 2015, an extraordinary low flow was observed at the Elbe and its major tributaries, as reported by the International Commission for the Protection of the Elbe River (IKSE 2017), when large parts of Europe were affected by drought (Hoy et al. 2017; Laaha et al. 2017).

The Elbe is a source for drinking-water, industrial processing-water and fisheries. Regular measurements of the quality of the river water started in the last decades of the 19th century (Hübner and Schwandt 2013). With the growth of industries and urbanisation, water quality problems exacerbated. Technical solutions such as wastewater treatment plants (WWTP) were only implemented reluctantly at least until the 1950s. Only the disruption of industries during and after World War II (Bauch 1958) and the discontinuation of industries after the German reunification in combination with an ambitious development of WWTP led to a considerable reduction in the pollution of the Elbe (Guhr et al. 2006). However, compared to other Central European Rivers pollution levels are still high (EEA 2012).

Modern water analysis methods are different from those in the past and there are only few water quality parameters that have been measured regularly for 100 years or longer. This strongly limits the choice of parameters for long-term comparisons. Historic water quality data are largely not published but stored in many different archives. In the former German Democratic Republic, from the 1970s onwards, these data were subject to strict non-disclosure and in some cases data are lost or missing. Additionally, institutional responsibilities for water quality management changed as well as sampling sites.

In this paper we investigate 1) the impact of extreme low flow events on the physico-chemical water quality of the Elbe since the beginning of the 20th century. Common and specific water quality aspects of low flows are identified. It is analysed whether the impairment of water quality during extreme low flow is always topmost. For correct interpretation of the measuring results during the special low flow time periods, background information on the general water pollution level throughout history is necessary. Therefore, 2) we give a short overview of the Elbe water quality evolution and the underlying monitoring. Due to the well-known, important role of the Saale River for Elbe water quality (e.g. Mirsch 1967; Weigold and Barborowski 2009) there is 3) a special focus on the impact of the Saale. The approach of this study assists characterisation, classification and interpretation of historical and present low flow events and can be transferred to other rivers.

1.2 Study area and hydrological background

A map of the study area with sampling sites and gauges is shown in figure 1. Until 1930, only small dams with local influences on the flow conditions were present in the Elbe catchment. In 1932 the first large dam in the Upper Saale catchment began its operation. In the Vltava and Ohře catchment (Czech Republic) several large dams were completed between 1957 and 1968 (Simon and Böhme 2012). Faist (1965) concluded in a description of the low flow in summer 1964 that future low flow periods will not reach such low levels again due to the low flow elevation by Czech reservoirs. In 2003, reservoirs (size > 0.3 Mio. m³) in the whole Elbe catchment had a capacity of 4.08 billion m³ (IKSE 2005). Until December 2011, this capacity expanded only marginally to 4.12 billion m³ (IKSE 2012).

As shown in figure 2, the frequency and severity of contemporary low flows is on a different level than in 1964 and before. At the gauge Dresden, from 1900 – 1964 the yearly 7-day mean low flow discharge (NM7Q: lowest arithmetic mean of the discharge on 7 consecutive days of a reference period) was below 100 m³/s more than 30 times, but from 1965 – 2015 only 7 times. At the gauge Wittenberge, the NM7Q was below 200 m³/s from 1900 – 1964 for 14 times, but from 1965 – 2015 only twice.

During the second half of the 20th century the flow of the Elbe was continuously elevated by a discernible supply of mining drainage water from open pit lignite mines especially into the tributaries Schwarze Elster and Spree (Havel) (Grünewald 2001). Lignite mining decreased in the early 1990s which resulted in a substantial decline in the discharge of mining drainage water.

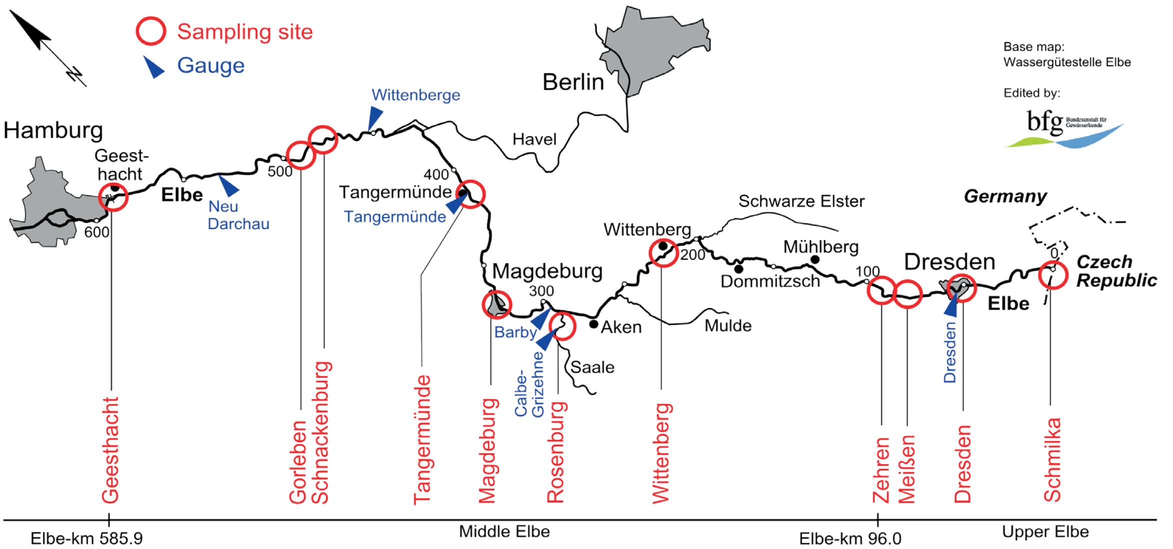

Fig. 1: Study area with sampling sites and gauges

1.3 History of water quality monitoring

Various institutions had a vital interest in monitoring the water quality of the Elbe. The municipal waterworks of Magdeburg-Buckau abstracted water directly from the Elbe from 1859 to 1990. Their monitoring frequency of the Elbe water evolved from rather sporadic in the 1870s, monthly in the 1880s, and three times a month from 1896 to weekly from 1904. Samples were regularly taken from the left side of the river. From 1909 the waterworks of Magdeburg-Buckau changed the abstraction point and the sampling position from the left to the right side of the Elbe (Dieckmann 1909), because water quality on the left side was impaired by the highly salt loaded Saale.

The introduction of limits for chloride and water hardness at the mouth of the Saale and for the Elbe at Magdeburg and Hamburg by the Prussian State Institute for Water Hygiene (IWH) (1921) was decisive for the establishment of a systematic monitoring by the River Water Inspection Office (FLUA - Flußwasseruntersuchungsamt Magdeburg). From 1925-1952, the FLUA monitored industrial and urban effluents into the catchments of Mulde, Saale and the Middle Elbe from Mühlberg to Tangermünde (see Fig. 1). In 1934, fifty monitoring sites (nine directly

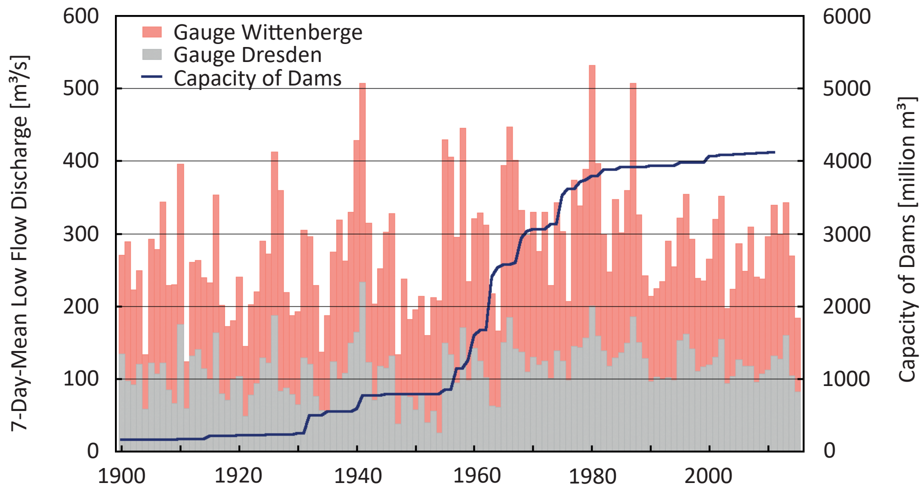

Fig. 2: Yearly 7-day mean low flow discharge (NM7Q; calendar year) for the gauges Dresden (Elbe) and Wittenberge (Elbe) in comparison to the development of the capacity of dams in the entire Elbe catchment (IKSE 2005, 2012) from 1900 until 2015

at the Elbe) were sampled at intervals from weekly to every working day. Following reorganisation, the monitoring sites were run subsequently by the Water Management Directorate Middle Elbe – Sude – Elde (WWD ME).

From the 1950s until 1976, a special water quality laboratory at the Waterways and Shipping Directorate Hamburg (WSD HH) regularly measured at sampling sites of the Elbe below the inner-German border. This work was continued by the Working Group for the Water Quality Preservation of the Elbe (ARGE Elbe) and later by the River Basin Community (FGG) Elbe. An overview of the measurement activities of federal authorities and institutions at the Elbe is given in Schwandt and Hübner (2016).

The water quality of the Elbe during the 2015 low flow period was investigated by a special "Monitoring Programme for Hydrological Extreme Events (MPE)". The MPE is directed by the FGG Elbe and coordinated by the Federal Institute of Hydrology (BfG) (FGG Elbe 2015). It was run for the first time during the June 2013 flood (Schwandt and Hübner 2014). Results from the 2015 low flow period (biweekly sampling from July until October) with focus on basic water quality parameters, chloride concentration, and trace substances are given in Hübner and Schwandt (2016). Data are reported in BfG (2017) or can be retrieved from the Elbe Data Information System of the FGG Elbe (see FGG Elbe 2017).

2 Methods

In the 20th century, extreme low flow events in the entire German part of the Elbe occurred during the years 1904, 1911, 1921, 1933, 1934, 1935, 1947, 1952, 1954, and 1964 (BfG 2018, event selection after Schwandt and Hübner 2009). Two low flows (1933 and 1954) took place in winter with specific water quality conditions (primarily oxygen deficiency due to ice cover, see FLUA 1934, Bauch 1958) and were omitted from this study as well as the low flow in 1947 as almost no water quality data were available. The remaining seven low flow events occurred in summer / autumn, like the low flows in 2003 and 2015. All nine events were labelled "summer low flow events" and compared with each other. The hydrological analysis is based on calendar years not on hydrological years. All discharge data used in this study are based on values of mean daily discharge, gathered by the Federal Waterways and Shipping Administration.

The month with the most pronounced low flow based on the yearly 7-day (NM7Q) and 21-day (NM21Q) mean low flow discharge at representative gauges along the Elbe is shown in table 1 for years with extreme summer low flow. The month of August was selected as "low flow month", except for 1934 for which July was selected. However, the mean discharge and mean low flow discharge (NM7Q and NM21Q) for the selected years and months differs considerably (Tab. 2). In the period until 1964, especially in the year 1904, the mean low flow discharge (NM7Q and NM21Q) was lower than in the following years, reflecting an inverse relationship to the capacity of dams (see Fig. 2).

Historical and present monitoring data from various sources have been gathered to describe and assess the water quality of the Elbe during the extreme summer low flow events. Table 3 gives an overview of the main data sources, sampling sites and sampling frequencies. Measurements of physico-chemical water quality parameters during the low flow months are compared to the data range in the entire year and to past and present levels. Due to the available data this study focuses on the Middle Elbe at Magdeburg. Data permitting, further sampling sites along the course of the river are included.

Tab. 1: Months of years with most pronounced low flow associated with the yearly 7-day (NM7Q) and 21-day (NM21Q) mean low flow discharge at representative gauges along the Elbe

Gauge	Dresden		Barby		Wittenberge		Neu Darchau	
Year	NM7Q	NM21Q	NM7Q	NM21Q	NM7Q	NM21Q	NM7Q	NM21Q
1904	August	August	August	August	August	August	September	September
1911	August	August	August	August	September	September	September	September
1921	August	August	August	August	August	September	August	September
1934	July	July	July	July	July	July	July	July
1935	September	August	July	July	August	August	August	August
1952	August	August	August	August	August	August	August	August
1964	August	August	August	August	August	August	August	August
2003	August	August	August	August	August	August	August	August
2015	August	August	August	August	August	August	August	August

Tab. 2: Mean discharge (MQ) and mean low flow discharge (NM7Q, NM21Q) at the gauge Barby [m³/s] for selected years and months with low flow of the Elbe

Year	MQ Year	NM7Q Year	NM21Q Year	MQ August
1904	397	95.0 (23 – 29 Aug.)	98.6 (15 Aug. – 04 Sep.)	106
1911	428	109 (14 – 20 Aug.)	112 (10 – 30 Aug.)	116
1921	344	109 (08 – 14 Aug.)	125 (26 Jul. – 15 Aug.)	149
1934	278	101 (21 – 27 Jul.)	107 (16 Jul. – 05 Aug.)	137 (July)
1935	435	133 (22 – 28 Jul.)	140 (19 Jul. – 08 Aug.)	153
1952	461	116 (09 – 15 Aug.)	129 (02 – 22 Aug.)	136
1964	311	126 (31 Jul. – 06 Aug.)	133 (22 Jul. – 11 Aug.)	237
2003	477	156 (13 – 19 Aug.)	160 (11 Aug. – 31 Aug.)	169
2015	365	153 (10 – 16 Aug.)	167 (28 Jul. – 17 Aug.)	201
1900-2015	553			361

3 Water quality during low flow events – a journey through time

3.1 Permanganate index / organic carbon

In the 19th and 20th century, the pollution of river water with organic matter was estimated by oxidation with $KMnO_4$. Results were given as $KMnO_4$-demand [mg/l $KMnO_4$] or, after multiplication of this value with the factor 0.25 (Klut 1911) as oxidability [mg/l O_2]. Nowadays the analytical method is standardised by ISO 8467:1993 (Water quality – Determination of permanganate index). Since the methodical bases are similar, we only use the term permanganate index [mg/l O_2] hereafter.

Since the end of the 19th century, it was known that the concentration of organic matter cannot be determined by the permanganate index as such, because the same quantities of different kinds of organic substances result in different values of $KMnO_4$-demand and inorganic compounds are also oxidised (Klut 1911). However, the permanganate index was employed as a measure for easily oxidisable organic matter of the Elbe until the 1990s, in Saxony until 2006.

During a sampling campaign by boat on the Elbe from Bad Schandau to Hamburg in August 1904 (Kolkwitz and Ehrlich 1907) higher organic loads were only detected locally (Dresden 17.5 mg/l O_2, Magdeburg 11.4 – 13.4 mg/l O_2). The Magdeburg results correspond with figure 3.

Permanganate index at Magdeburg was in a similar range in the years 1904, 1911 and 1921 (Fig. 3). The annual maximum values were measured outside of the extreme low flow period (in autumn or early winter). During the low flow events in 1934 and 1935, the organic load of the Elbe was higher upstream as well as downstream from Magdeburg (FLUA 1935b, 1936b). Within the service area of the FLUA, in 1934 and 1935 the organic load of the Elbe was highest at Mühlberg (Elbe-km 127), downstream of the industrial complex of Riesa (Saxony). Here, the permanganate index reached a maximum value of 40.0 mg/l O_2 in August 1935 (mean August: 36.4 mg/l O_2) (FLUA 1936b). The annual maximum values of permanganate index at most sampling sites at the Elbe in the years 1934 and 1935 were reached in July / August, otherwise in autumn (e.g. 1935 at Magdeburg in October).

Growing population, increasing industries and lack of WWTP were the main reasons for extraordinarily high loads of easily oxidisable organic matter of the Elbe in the 1950s and with rising intensity in the 1960s. At Magdeburg, the permanganate index exceeded 40 mg/l O_2 in August 1952 and was almost twice as high during the extreme low flow period as on average of the year (Fig. 3). Upstream and downstream also high values of permanganate index were measured (FLUA 1952a/b). During August 1964, permanganate index reached the same high level at Magdeburg as in 1952, but in 1964 this level was equal to the mean level of the entire year (Fig. 3).

During the low flow period in 2003, only water samples of the Elbe in Saxony were analysed for permanganate index. Samples were taken monthly from the Elbe at Schmilka, Zehren and

Tab. 3: Main data sources, sampling sites (cf. Fig. 1) and sampling frequency of water quality parameters of the Elbe during years with extreme low flow since 1904

Year	Data sources	Sampling site, side of the river	Elbe-km	Sampling frequency
1904	MMD 1904, 1905	Magdeburg, left	324	weekly
	Wendel 1911	Magdeburg, right	324	16.3.-29.12.: weekly
1911	MMD 1911	Magdeburg, right	324	weekly
	Lehmann 1912	Magdeburg, left	324	Cl^-: 4.8.-21.9.: mainly daily
1921	MMD 1921, 1922	Magdeburg, right	324	1-2 times a week
1934	FLUA 1934, 1935a/b	Wittenberg, right	214	weekly
		Magdeburg, left	324	about every working day
		Magdeburg, right	324	about every working day
		Tangermünde, midstream	389	3 times a week
1935	FLUA 1935b, 1936a/b	see year 1934		see year 1934
1952	FLUA 1952a	Meißen (upstream)	81	3-4 times a month
	FLUA 1952b	Magdeburg, left	324	(1-)2 times a week; no data: Apr. + Dec.
		Magdeburg, right	324	every working day
		Tangermünde, midstream	389	2 times a week
	WSD HH 1952	Schnackenburg, left	475	O_2: 10-20 times monthly; no data Apr.-Jun., 3.11. et seq.
1964	DREWAG 1965	Dresden-Saloppe, right	52	weekly
	WWD ME 1965	Magdeburg, left Magdeburg, right	324	unknown; data derived from graphs of monthly mean values
	WSD HH 1965a	Gorleben, right	492	O_2, water temperature: every working day
2003	FGG Elbe 2017	Schmilka, right	4	TOC, DOC: weekly
		Zehren, left	90	O_2: continuously (with gaps)
		Wittenberg, midstream	214	TOC, DOC, O_2: 2 times a month
		Magdeburg, left	318	TOC, DOC, O_2: 2 times a month; Cl^-, Ca^{2+}, Mg^{2+}: monthly
		Magdeburg, right	318	TOC, DOC, O_2: 2 times a month; Cl^-, Ca^{2+}, Mg^{2+}: monthly
	ARGE Elbe (undated)	Tangermünde, Ø left/right	389	O_2: 2 times a month
	FGG Elbe 2017	Schnackenburg, left	475	TOC, DOC: 2 times a month; O_2: continuously (with gaps)
2015	FGG Elbe 2017	Schmilka, right	4	TOC, DOC: 1-2 times a month
	FGG Elbe 2017	Zehren, left	90	O_2: continuously
	FGG Elbe 2017	Wittenberg, midstream	214	TOC, DOC: 1-2 times a month
	BfG 2016	Wittenberg, right	217	O_2: continuously
	FGG Elbe 2017	Magdeburg, left	318	TOC, DOC, O_2, Cl^-, Ca^{2+}, Mg^{2+}: 1-2 times a month
	LHW 2016	Magdeburg, right	318	TOC, DOC, O_2, Cl^-, Ca^{2+}, Mg^{2+}: monthly
		Tangermünde, Ø left/right	389	O_2: monthly
	FGG Elbe 2017	Schnackenburg, left	475	TOC, DOC: 2 times a month
	NLWKN 2017/2018			O_2, water temperature: continuously
	BfG 2015	Geesthacht	586	Cl^-: Jul./Aug.; every other day

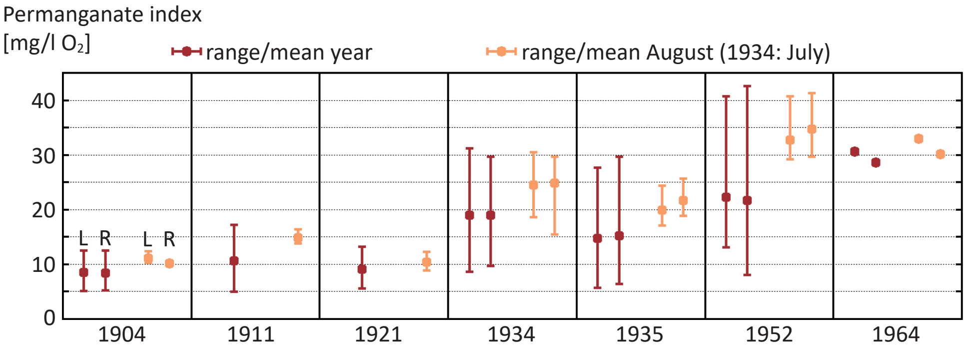

Fig. 3: Permanganate index of water samples of the River Elbe at Magdeburg (km 324) on the left (L) and right (R) riverside during years and months with extreme low flow from 1904 to 1964. For sampling frequency (highly variable) and data sources refer to table 3.

Dommitzsch. Throughout 2003, the range of permanganate index was 3.6 – 10.0 mg/l O_2 (LFULG 2017). The highest values at each site were measured in summer and autumn, except at Schmilka (right) the peak for the year occurred in January. In August 2003, the measured permanganate index in Saxony was even lower than measured by Kolkwitz and Ehrlich (1907) in August 1904 although the sampling sites were different.

The organic load during the low flow in 2015 and in 2003 was measured by total (TOC) and dissolved (DOC) organic carbon (Tab. 4). In August the mean concentration of TOC and DOC was predominantly at the same level as the average of the year, only at Schnackenburg TOC was clearly higher in August 2003. In the year and in August 2015 the concentration of TOC was lower than in 2003, while the concentration of DOC was similar.

3.2 Oxygen content

The 1904 low flow event can be characterised after Kolkwitz and Ehrlich (1907) by a stable oxygen balance along the entire river course. For the low flow events 1911 and 1921 data for oxygen concentration in the Elbe are missing. In 1934 and 1935 critical oxygen concentrations were short local phenomena. At Wittenberg, Magdeburg, and Tangermünde mean oxygen concentrations of the Elbe during July 1934 and August 1935 showed a similar level as the average of the year (Fig. 4). The minimum oxygen concentration of the low flow month was mostly higher than the yearly minimum. However, at Mühlberg, a hotspot of organic load, the minimum oxygen concentration momentarily fell to 0.0 mg/l in July and August 1935 (FLUA 1936a).

Tab. 4: Mean concentration of TOC and DOC [mg/l] in the Elbe in 2003 and 2015. Number of samples in brackets; for data sources refer to table 3.

Sampling site	Elbe-km		year 2003		August 2003		year 2015		August 2015	
Schmilka (right)	4	TOC	7.4	(53)	8.2	(4)	6.0	(16)	6.5	(2)
		DOC	5.9	(52)	6.5		5.2		5.8	
Wittenberg (midstream)	214	TOC	8.0	(26)	10.1	(2)	6.6	(16)	6.3	(2)
		DOC	5.1		5.5		5.1		5.3	
Magdeburg (left)	318	TOC	9.4	(26)	10.0	(2)	6.6	(16)	5.9	(2)
		DOC	4.9		4.6		4.8		4.6	
Magdeburg (right)	318	TOC	10.4	(25)	9.0	(2)	7.4	(12)	5.7	(1)
		DOC	5.0		4.4		5.1		4.6	
Schnackenburg (left)	475	TOC	11.6	(26)	18.0	(2)	8.0	(24)	10.2	(2)
		DOC	5.7		6.0		5.4		5.6	

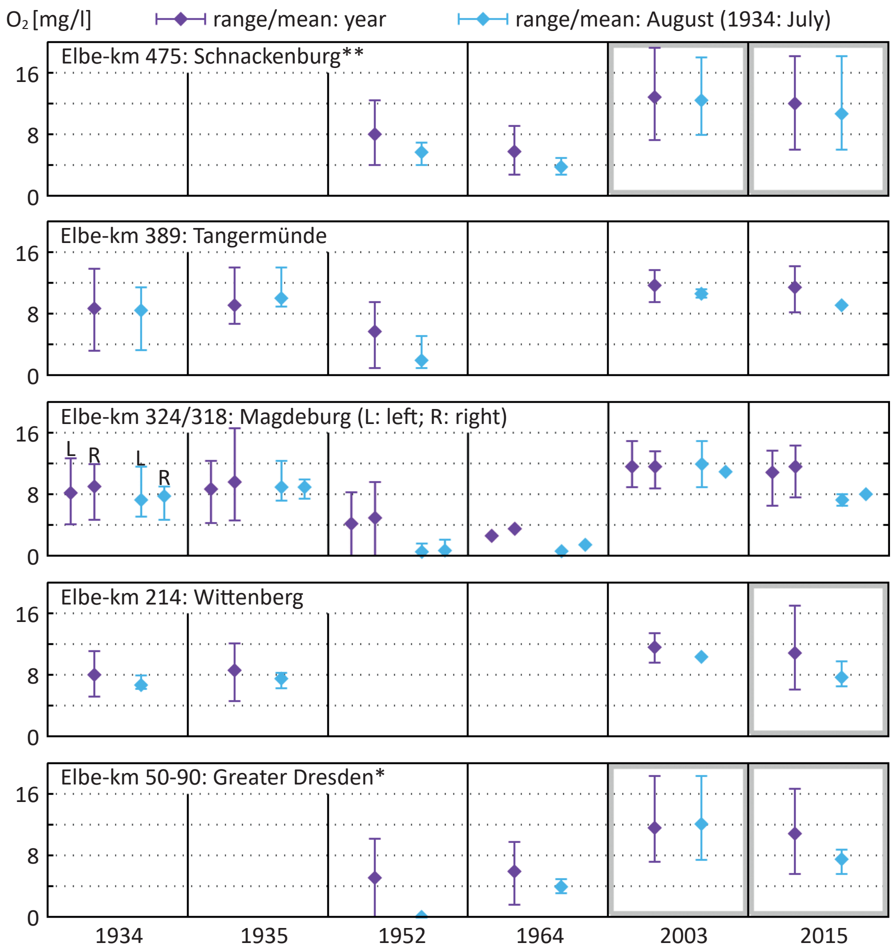

Fig. 4: Oxygen concentration of the River Elbe during years and months with extreme low flow from 1934 to 2015. For sampling frequency (highly variable) and data sources refer to table 3. Gray inner frame: data from automatic continuous measurements; * sampling site in 1952: Meißen, in 1964: Dresden-Saloppe, in 2003 and 2015: Zehren; ** sampling site in 1964: Gorleben.

During the low flow in 1952, oxygen concentrations of zero or near zero prevailed for weeks at different places (e.g. Meißen, Magdeburg) (FLUA 1952a/b). In August 1952, the maximum oxygen concentration at every sampling site was below the mean oxygen concentration of the year (Fig. 4). The minimum of August represents the minimum of the entire year. In August 1964, mean oxygen concentration at Magdeburg showed a level close to zero. Also, the mean values of the entire year can be classified as critical for the river ecosystem. Very low oxygen concentrations were also measured between Aken and Tangermünde during a sampling campaign along the Middle Elbe from 3 – 6 August 1964 (Günther undated). The oxygen concentrations at Magdeburg during the low flows in 1934, 1935, 1952, and 1964 correspond to the permanganate index (Fig. 3) in inverse proportion. In 2003 and 2015, oxygen concentrations were above critical levels. In both years, the minimum of August was at the same level as the minimum of the year.

Figure 5 shows individual oxygen concentrations measured at the neighbouring sampling sites Gorleben and Schnackenburg for the years 1964 and 2015, compared with water temperature and discharge (gauge Wittenberge). In the period from April to October, oxygen concentration and discharge follow a similar trend, while water temperature trend tends to be inverse. The lowest oxygen concentrations at Gorleben (2.8 – 2.9 mg/l) were measured from June to the middle of August 1964. The 2015 minimum at Schnackenburg was 6.0 mg/l on 19 August. Generally in 2015, the level of oxygen concentration was much higher than in 1964, even in the beginning of July and during August, when water temperatures were higher

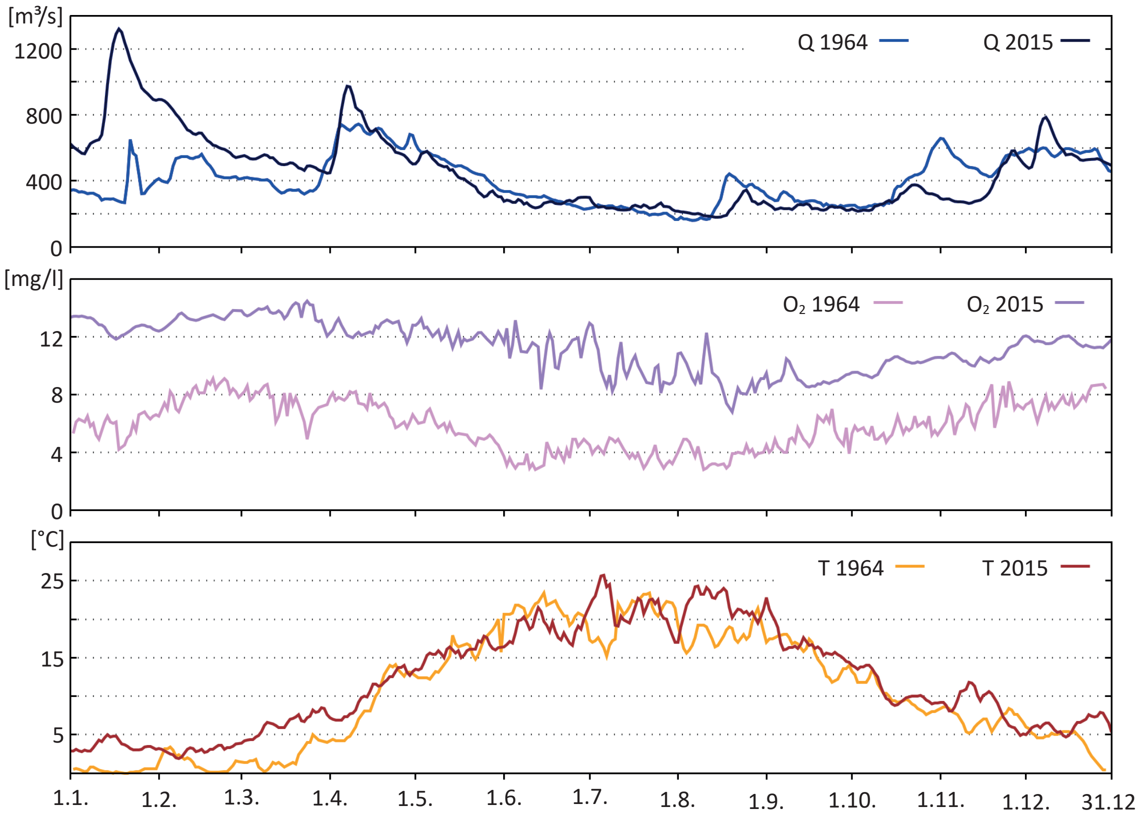

Fig. 5: Daily oxygen concentration and water temperature of the River Elbe measured at 8:00 am at Gorleben in 1964 and at Schnackenburg in 2015 (for data sources refer to table 3) and daily mean discharge (Q) at the gauge Wittenberge

than in 1964. In summer 2015, oxygen fluctuations were more pronounced than in 1964, whereas in winter and autumn it was vice versa. The period of high oxygen fluctuations at Schnackenburg was associated with the warmest water temperatures, suggesting stronger impact of phytoplankton.

3.3 Chloride and hardness

Chloride concentration and hardness of the Elbe are heavily influenced by the Saale especially due to former (e.g. potassium, soda, copper) and present (e.g. soda, rock salt) mining activities and industrial production with salted effluents in the Saale catchment area (Mirsch 1967; Schultze and Knappe 2001; Lindenschmidt 2006). The long-term mean discharge of the lower Saale at gauge Calbe-Grizehne ($MQ_{1932-2015}$: 115 m³/s) is about 21 % of the discharge of the Elbe just below the Saale mouth at gauge Barby ($MQ_{1932-2015}$: 555 m³/s). Because of the importance of the Saale for the chloride concentration and hardness of the Elbe, figure 6 displays the development of the concentrations in the Lower Saale for the most relevant parameters in this context. For the time period 1986-2015, hardness as well as calcium and chloride concentrations inversely correspond to the discharge, whereas the magnesium concentration appears to be less dependent on the flow regime. The closure of the potash mining in the southern Harz mountains in the first half of the 1990s (Ziemann et al. 2001; Lindenschmidt 2006) distinctly decreased chloride concentration and hardness in the Saale. While magnesium concentrations decreased after 1990, calcium concentrations remained on a relative high level. Accordingly, the Ca^{2+}/Mg^{2+} ratio increased. Since the beginning of the 21st century this ratio tends to be between 4 and 5. Since about 1995, no further decrease of hardness or chloride concentration of the Saale can be observed. Chloride concentration and hardness in the years with extreme low flow were highest in the year 1964 (Fig. 6).

Chloride concentration and hardness measured in the Elbe at Magdeburg were higher on the left than on the right side of the river, reflecting the influence of the Saale (Fig. 7). Furthermore, mean chloride concentration and hardness in the months with extreme low flow were elevated and in general higher than the average of the year.

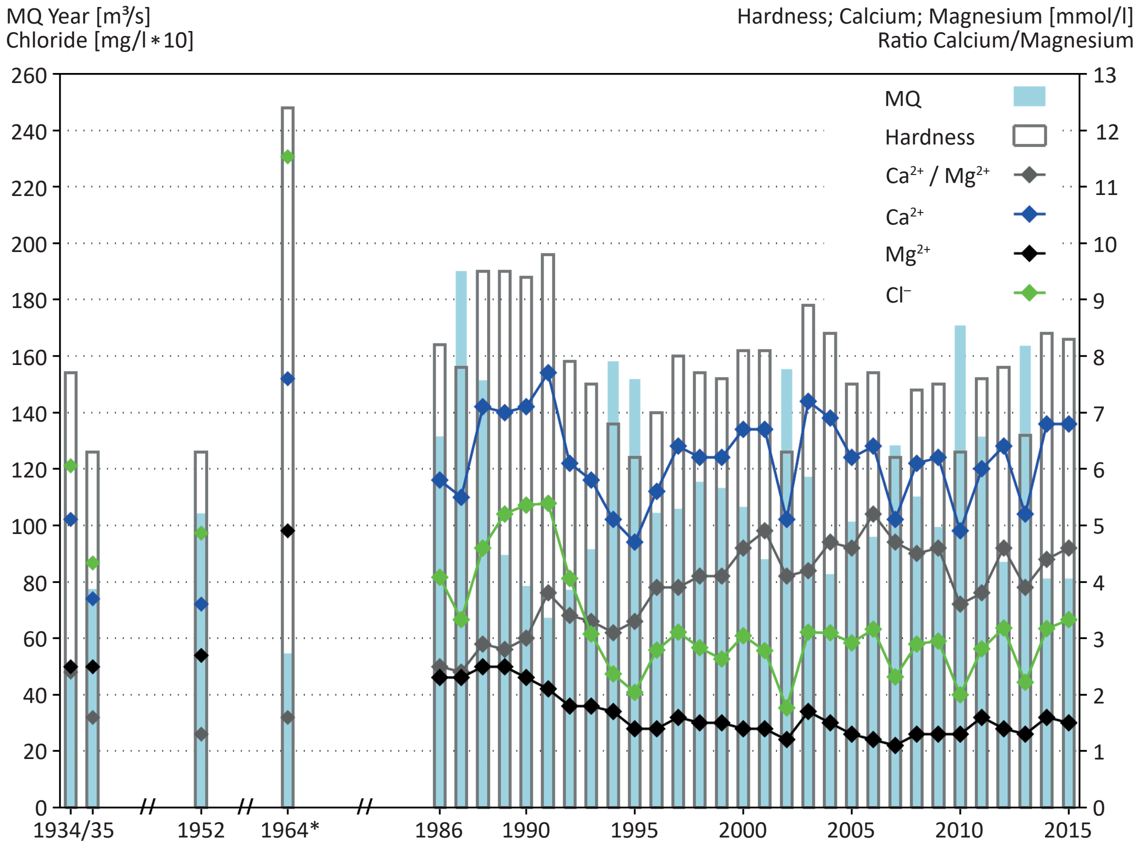

Fig. 6: Annual mean discharge (MQ Year), hardness, Ca^{2+}/Mg^{2+} ratio, and concentrations of calcium, magnesium, and chloride ions of the River Saale at Rosenburg from 1986 to 2015 (after FGG Elbe 2017) and in previous years with extreme low flow in the River Elbe (after Mirsch 1967, FLUA 1936c; sampling frequency highly variable; * sampling period Jan.-Oct.)

From 1904 to 1935, chloride concentration of the Elbe at Magdeburg was on a comparable level (Fig. 7). Upper limits for chloride (250 mg/l) and hardness (3.0 mmol/l) at the right river side, implemented since the 1920s (IWH 1921), have been exceeded several times especially in summers of 1934 and 1935. During the 1950s and 1960s, extraordinarily high concentrations of chloride and hardness were measured. In August 1952, the highest chloride concentration and the highest hardness at both sides of the Elbe at Magdeburg represent also the highest measurements of the year. In this month, the proportion of the Saale discharge to the Elbe discharge at Barby was above average (32 %). In the Elbe at Meißen and at Tangermünde, the highest chloride concentrations of the year 1952 were also reached in August (FLUA 1952a/b).

In 1964, the mean chloride concentration and hardness of the Elbe at Magdeburg (derived from graphs of monthly mean values, see Tab. 3) was even higher than in 1952 (Fig. 7). During the sampling campaign on the Middle Elbe (3 – 6 August 1964) immediately downstream of the mouth of the Saale at Barby, chloride concentrations of over 2000 mg/l and about 12 mmol/l hardness were measured (Günther undated). In 1964, the discharge of the Saale was relatively small (Fig. 6), in August only 16 % of the Elbe discharge at Barby. However, hardness and chloride concentration in the Saale were at an extraordinarily high level. At the Elbe-Weir Geesthacht, chloride concentration in 1964 ranged from 255 to 740 mg/l and hardness from 2.4 to 5.1 mmol/l (WSD HH 1965b, 1966). In both cases, peak values were measured in August.

With respect to 1964, the 2003 chloride concentration of the Elbe at Magdeburg has decreased distinctly (Fig. 7). During the low flow in 2003 and 2015, the chloride pollution of the Elbe was relatively similar. Also, the proportion of the Saale discharge to the discharge of the Elbe at Barby was similar in August 2003 and 2015 (about 25 %). At the Weir Geesthacht, the monthly peak values of July and August 2015 were about 280 mg/l (BfG 2015). Hardness decreased until 2003 only on the

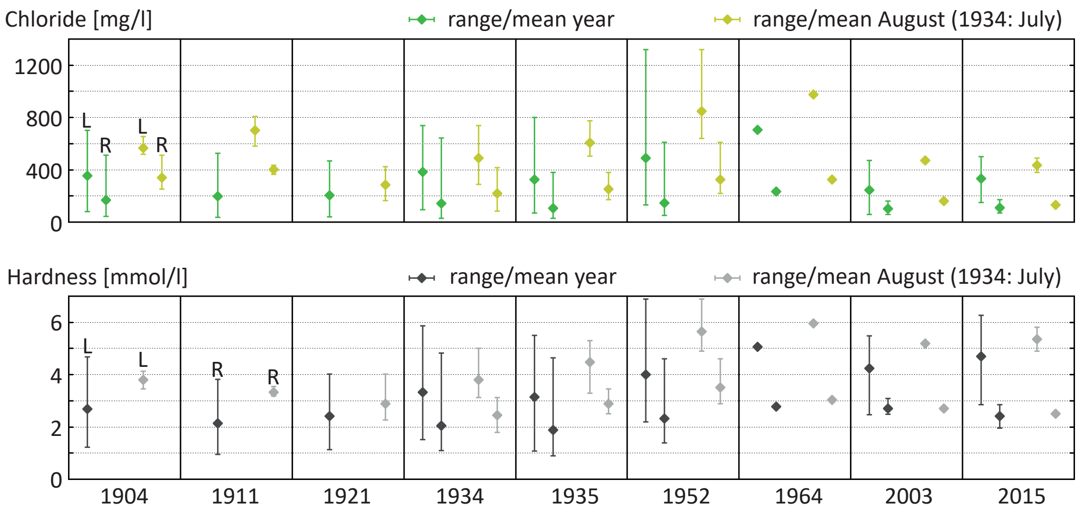

Fig. 7: Chloride concentration and hardness on the left (L) and right (R) side of the River Elbe at Magdeburg (km 324/318) during years and months with extreme low flow from 1904 until 2015. For sampling frequency (highly variable) and data sources refer to table 3.

left side of the Elbe at Magdeburg (Fig. 7) where it was slightly higher in the year and in August 2015 than in 2003.

In general, our results show that chloride concentration and hardness are inversely related to the discharge. This is illustrated for the Elbe at Tangermünde (Fig. 8) making use of numerous measurements in the year 1952. The lowest discharges coincide with the highest chloride concentrations and hardness and vice versa. The low water month (August) measurements mark the highest concentration and other top values of the year.

The relatively high values of hardness during the extreme low flow periods of the Elbe in the 21th century and the increased Ca^{2+}/Mg^{2+} ratio of the Saale (Fig. 6) motivated us to take a look at this ratio in the Elbe at Magdeburg in different years (Tab. 5). The ratio between calcium and magnesium ions on the left side of the Elbe in 2003 and 2015 was wider than in previous years and also wider than on the right side of the river. In the low flow months, the Ca^{2+}/Mg^{2+} ratio was mostly slightly lower.

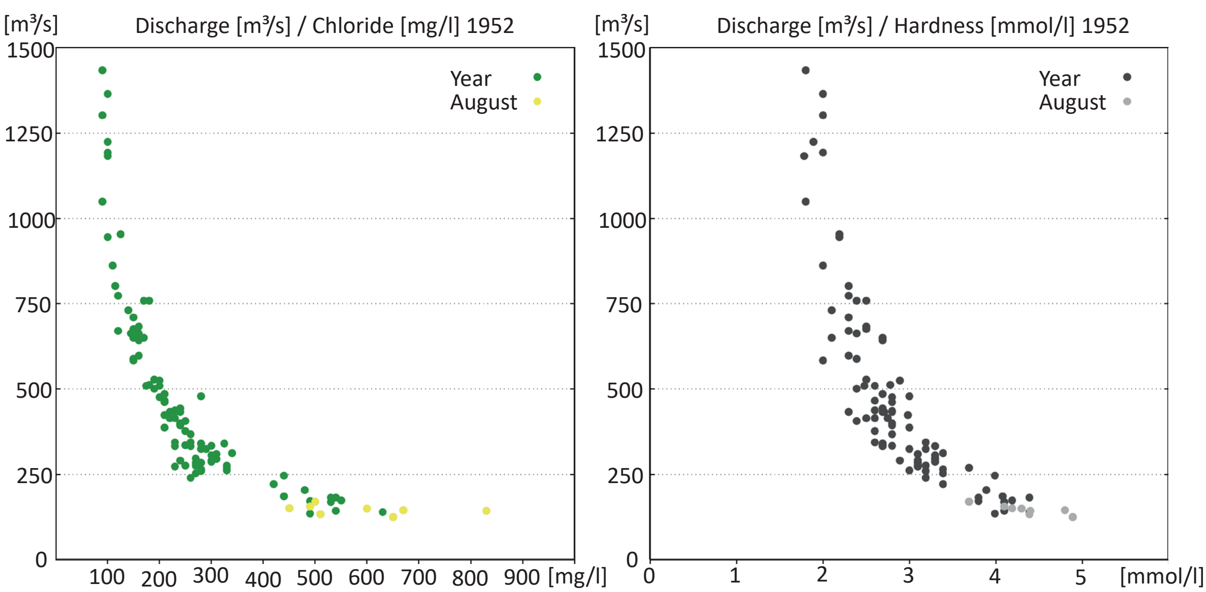

Fig. 8: Relation of chloride concentration (left; n = 105) and hardness (right; n = 104) to discharge in the River Elbe at Tangermünde (Elbe-km 389) in August and the entire year 1952; after FLUA (1952 b), discharge at gauge Tangermünde after Helms et al. (2016)

Tab. 5: Ratio between calcium and magnesium ions in the Elbe at Magdeburg during years and months with extreme low flow. For sampling frequency (highly variable) and data sources refer to table 3 and FLUA (1936c).

Year	Magdeburg, left riverside Ca^{2+} [mmol/l] : Mg^{2+} [mmol/l]		Magdeburg, right riverside Ca^{2+} [mmol/l] : Mg^{2+} [mmol/l]	
	mean year	mean August	mean year	mean August
1904	1.8	1.5	no data	no data
1911	no data	no data	1.7	1.4
1921			1.7	1.5
1934			3.2	2.7*
1935			2.9	1.9
1952	1.6	1.3	2.0	1.7
1964**	2.2	2.1	3.0	3.2
2003	3.6	4.5	3.3	3.1
2015	4.2	4.4	3.4	3.3

* mean July / ** ratio Ca^{2+} : Mg^{2+} calculated from monthly mean values

4 Discussion

The evolution of the pollution in the Elbe from the beginning of the 20th century with respect to low flow events is evaluated with monitoring parameters connected to the amount of easily oxidisable organic matter (permanganate index and oxygen concentration) and salted effluents (chloride concentration and hardness). Fecal pollution and salinisation were the first major water quality challenges also from European perspective (Meybeck and Helmer 1989).

Monitoring up to the 1960s concentrated on a few parameters with high sampling frequencies, whereas nowadays numerous parameters are measured with low frequencies (one or two times per month). With high sampling frequencies there is an increased possibility of detecting extreme substance concentrations caused by natural and anthropogenic influences. Therefore, the comparison of high and low frequency measurements as undertaken in this study is especially problematic with respect to the range of measured values. However, the mean values already reflect different pollution levels during the considered period. The MPE 2015 doubled the regular sampling frequency and supported the past – present comparison.

The given selection of low flow months deals with the dilemma of the variation of the severity of low flow in space and time along the river (Tab. 1). Furthermore, the discharge of the selected low flow months is often not continuously low but can be partly above the mean low flow discharge. Depending on the sampling frequency, these periods with higher discharge may have an influence on the mean and the range of water quality parameters. The mean discharge of the low flow months varies from 106 m³/s in 1904 to 237 m³/s in 1964 (Tab. 2). Since the 1960s, water from reservoirs supports the discharge during low flows markedly (for 2015 see ČHMÚ 2015) enhancing dilution.

After Vliet and Zwolsman (2008) rivers with normally low summer discharge (like the Elbe) and relative high pollution level by point sources are more sensitive to droughts than rivers with nivo-pluvial discharge regimes (like the River Rhine) and predominant pollution by diffuse sources. This finding corresponds with the extreme low oxygen concentrations in the Elbe during the low flow periods in 1952 and 1964 when pollution by untreated waste water from municipalities and industries was at a very high level, indicated by the permanganate index. In 2003 and 2015, the strong decreased pollution of the river with easily oxidisable organic matter prevented a drop of the oxygen concentration to a critical level.

Due to lack of WWTP, permanganate index increased during the months with extreme low flow in the time period from 1904 to 1964 in the Elbe at Magdeburg, but the highest permanganate index of the year was often in line with the sugar beets processing period (second half of September to December / January). In regard to the measured TOC / DOC concentrations in 2003 and 2015, no general effects of low flow were observed. During droughts, increasing organic carbon concentrations are described for lakes and reservoirs (Mosley 2015), Zielinski et al. (2009) stated significant decreases of DOC concentrations in small lowland rivers while Worrall and Burt (2008) found no common effects on DOC in rivers. After Gerlach and Gimbel (1996) during low flow a large part of the DOC in the Elbe originates from point sources. Probably, the extensive modern wastewater treatment in the 21st century with high efficiency of WWTP especially during dry periods prevented an increase of DOC in August 2003 and 2015 (Tab. 4). The TOC concentration in the Middle Elbe depends mainly on the content of phytoplankton particularly in summer drought periods, which was smaller during the 2015 low flow than in 2003 (Hübner and Schwandt 2016). The high phytoplankton density at Schnackenburg in August 2003 explains the high TOC concentration at this site.

Increasing chloride and other major ion concentrations in rivers during low flow have been described in many studies (Mosley 2015), in Central Europe for example by Zwolsman and Bokhoven (2007); Vliet and Zwolsman (2008); Hellwig et al. (2017). Our results underline these findings for chloride concentration and hardness. As postulated by Mirsch (1967), the background load of the Saale at Rosenburg during extreme low flow (30 m³/s) is 225 mg/l Cl^- and 4.8 mmol/l hardness, and in the Elbe at Tangermünde (150 m³/s) 133 mg/l Cl^- and 3.3 mmol/l hardness. For the low flow event from 20 July to 5 October 2015, the corresponding average values for Rosenburg/Saale were 49.0 m³/s; 972 mg/l Cl^-; 10.6 mmol/l hardness and for Tangermünde/Elbe 198 m³/s; 277 mg/l Cl^-; 4.1 mmol/l hardness, reflecting high anthropogenic pollution.

The heterogeneous water chemistry of the Elbe after the confluence with the Saale is described by many authors (e.g. Weigold and Baborowski 2009). At Tangermünde, around 100 river km after the confluence the mixing is fairly complete (e.g. Mirsch 1967). In the Middle Elbe during the low flows in 2003 and 2015, high concentrations of chloride (see also Hübner and Schwandt 2016) and high hardness were observed although the pollution level of chloride was lower than in 1964. These results and the increasing Ca^{2+}/Mg^{2+} ratio at the left side of the Elbe at Magdeburg can easily be explained by the influence of the Saale (Fig. 6).

The natural Ca^{2+}/Mg^{2+} ratio of a river depends mainly on the geochemistry of the corresponding groundwater bodies. As reported by Potasznik and Szymczyk (2015), a decrease of the mineral content of water results in a larger Ca^{2+}/Mg^{2+} ratio, which ranges between 4:1 and 2:1 in water with low mineralisation level. Worrall et al. (2012) found an approximately constant Ca^{2+}/Mg^{2+} ratio of 11.5 (mass ratio 18.9) of the river Thames at Teddington with groundwater supplies mainly from Cretaceous Chalk during the period 1974 to 2003. For the German Rivers Fulda and Werra, which like the Saale comprise partly of Zechstein (Upper Permian formation) in their catchment areas, a Ca^{2+}/Mg^{2+} ratio of about 5:1 is reported by the Hessian State Office for Environment and Geology (HLUG) (2008) for uncontaminated river sections.

5 Conclusions

Judged by the investigated water quality parameters, pollution level of the Elbe during the 1904 low flow was relatively low (regardless of the lowest discharge): low permanganate index, stable oxygen regime, elevated chloride concentration, and relatively low hardness. In contrast, pollution load was highest in 1952 and 1964: extraordinarily high permanganate index, periods of complete oxygen depletion, very high chloride concentration and high hardness. The water quality of the Elbe during the 2015 low flow was best comparable with the situation in 2003. In 2015, 2003, and 1904 the oxygen regime of the River was sufficiently stable. Because the Saale is the major source for water hardness and chloride concentration of the Elbe, concentrations in the Saale and its discharge proportion of the Elbe determine the saline pollution level downstream the confluence.

Low flow exacerbates water pollution problems. Depending on the load of emissions from industries and municipalities during the examined low flow periods, extreme low flow months mark unusual low oxygen concentrations (mostly the lowest value of the year) and unusual high chloride concentrations and hardness (often the highest value of the year). During extreme low flow, sampling should be more frequent to increase the chance of covering the period with the most affected water quality. A special monitoring programme like the MPE is recommended. Such special monitoring programme can also help in the assessment of measures to improve the water quality.

The long-term view on the low flow events of the same river helps to differentiate between event specific influences (e.g. proportion of tributaries on the total discharge) and common influences (e.g. accumulation of substances due to lacking dilution). Thereby a foundation for the characterisation and classification of former and present low flow events according to water quality is laid.

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