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Abstract

This chapter reviews recent trends and variability in river flows to the North Sea. The main contributors are the River Elbe and the River Rhine. In addition to these large rivers many smaller rivers also discharge into the North Sea. However, by far the biggest contributor is the Baltic Sea outflow. Observation records for the major rivers draining into the North Sea are relatively long, while records for the smaller rivers are typically much shorter. Variability in flow is dependent on variations in weather—mainly precipitation and temperature—from year to year, but also on a wide range of direct and indirect human interventions in the North Sea basin. Rivers draining into the North Sea show considerable interannual and decadal variability in annual discharge. In northern areas this is closely associated with variation in the North Atlantic Oscillation, particularly in winter. Discharge to the North Sea in winter appears to be increasing, but there is little evidence of a widespread trend in summer inflow. Higher winter temperatures appear to have led to higher winter flows, as winter precipitation increasingly falls as rain rather than snow. To date, no significant trends in response to climate change are apparent for most of the individual rivers discharging into the North Sea.

4.1 Introduction

The waters flowing into the North Sea from the surrounding land masses add 296–354 km³ of fresh water to the North Sea each year. The main contributors are the River Elbe and the River Rhine. In addition to these large rivers a great

number of smaller rivers also discharge into the North Sea (Table 4.1). However, by far the biggest contributor to the North Sea is the Baltic Sea. Discharging about 470 km³ year⁻¹ this fresh water inflow exceeds the total contribution from the entire North Sea catchment area.

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Table 4.1 Main sources of fresh water inflow to the North Sea (adapted from OSPAR 2000)

	Discharge (km ³ year ⁻¹)	Catchment area (km ²)
Norwegian North Sea coast	58–70	45,500
Skagerrak and Kattegat coasts	58–70	102,200
Danish and German coasts (Elbe)	32	219,900
Dutch and Belgian coasts (Rhine, Meuse and Scheldt)	91–97	221,400
English and French Channel coasts (including Seine)	9–37	137,000
English east coast (including Tyne, Tees, Humber, Thames)	32	74,500
Scottish coast (including Forth)	16	41,000
Total North Sea region (excluding the Baltic Sea)	296–354	841,500
Baltic Sea	470	1,650,000

Climate change is expected to affect the hydrological cycle and so will alter fresh water inflow to the North Sea (see Chaps. 5 and 7). In northern Europe, a trend has been observed towards more intense winter precipitation (EEA 2008, 2012). More inflow to the North Sea in winter is therefore expected.

Change in annual discharge is the usual variable assessed in relation to freshwater flow, but because rivers also transport vast quantities of sediment, nutrients and contaminants, climate change impacts in coastal areas will also result from changes in river regime and in the magnitude and timing of high and low flows. Short periods of high river flow can transport large sediment, nutrient and contaminant loads to the North Sea. This may affect coastal water quality and thus the functioning of coastal ecosystems (see Chap. 7). Although the total loads carried into the North Sea during periods of low flow may be small, nutrient and contaminant concentrations can be high. Meanwhile saline water can penetrate estuaries much further upstream as the river flow is less able to restrict its ingress. As a result, this chapter addresses observed changes in average annual flow as well as in high and low flows. As the rivers Rhine and Elbe and the Baltic Sea outflow contribute most of the fresh water, the focus is on observed changes in these inputs.

4.2 Detecting and Attributing Trends

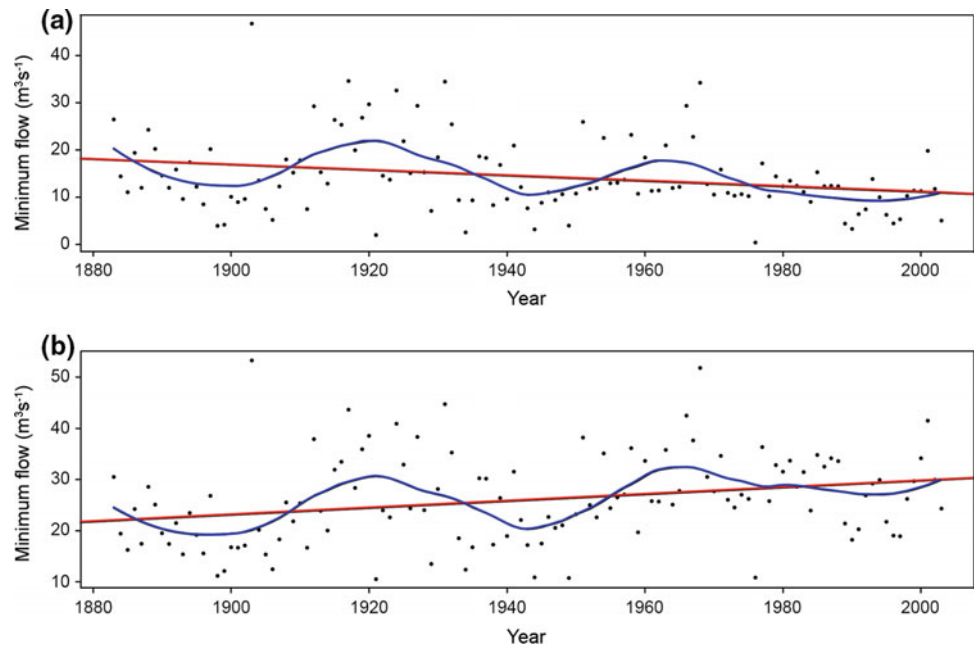
Detecting and attributing temporal and spatial trends in river flow needs long records. Flow measurements based on water level gauges started in the 18th century in Europe, while more extensive monitoring networks of the European rivers were established only towards the end of the 19th century (Brazdil et al. 2006). Historical documentary sources such as newspapers, diaries, economic records, and log books may be used to reconstruct change occurring before the start of the instrumental record as these often report the occurrence and date of extreme events (Buisman 1996, 1998, 2000, 2006; Pfister 1999). Change occurring prior to the historical period must be reconstructed from the geological record.

According to Glaser and Stangl (2003) the frequency of floods has changed considerably over the past 700 years in central Europe. They concluded that flood frequency has higher natural variability than would be expected from present-day observations.

The records of discharge measurements for many of the major rivers draining into the North Sea are long—spanning several decades—while river flow records in smaller catchments are relatively short, and the longest records are clustered in specific regions (Hannaford et al. 2013). As changes over time in flow regimes are often a complex function of different trends and patterns of variability in the many parts of a catchment it is therefore difficult to characterise and understand reasons for interannual variability in river flow from observations alone. It is possible to ‘fill in the gaps’ using river flow simulated by a global or regional hydrological model driven by gridded climate input data (e.g. Jones et al. 2006). Stahl et al. (2012) used an ensemble of gridded hydrological models to simulate past variations in river flow across Europe. They demonstrated that although there were differences between models, they did reproduce the observed trends in the areas where there were data, and therefore that the broad spatial patterns of variability simulated by the models were robust. Stahl et al. (2012) noted, however, that the models tended to perform less well in those parts of Europe affected by snowfall and snowmelt. Also, that the models did not take account of human intervention within the catchment areas, which has substantially affected flow regimes in many of the rivers draining into the North Sea. As a result, Stahl et al. (2012) concluded that models should only be used to simulate ‘natural’ patterns of variability over time.

The large interannual variations in average, low and high river flow make it difficult to establish trends in hydrological data series (e.g. Wilby 2006; Conway 2013; Hannaford et al. 2013). Even in the well-instrumented basins of the rivers Elbe and Rhine, where records are available for 100 years or more, trends are easily obscured by the variability (Diernanse et al. 2010; Bormann et al. 2011), and so the length of the observation record can significantly affect the ability to identify trends over time. Attributing observed trends to changes in climate or other factors is even more difficult

Fig. 4.1 Linear trends and the locally-weighted regression (Loess) smoothing curve for the 30-day minimum-flow time series on the River Thames at Kingston in southwest London, contrasting gauged (*upper*) and naturalised (*lower*) flow records (from Hannaford and Marsh 2006, modified)



because climate change effects are complex and changes in catchment conditions including land use and human interventions occur simultaneously. Some opposing effects of climate change—such as increasing precipitation and increasing evaporation—may cancel each other out, while other effects may have major consequences for river discharge. For example, in the case of the River Rhine where increasing precipitation may have led to higher peak flows, and where canalisation and a reduction in floodplain areas have steepened the peak flows (e.g. Engel 1997, 1999; CHR/KHR 1993; Ebel and Engel 1994). The effect of changes in land use on peak flow magnitude and frequency is another issue of fierce debate (e.g. O’Connell et al. 2007). According to Pfister et al. (2004), changes in land use, particularly urbanisation, can have significant local effects in small river basins (headwaters) with respect to flooding, especially during heavy local rainstorms. In the larger basins of the rivers Rhine and Meuse, however, there is no evidence that land-use change has had significant effects on peak flow in these rivers (Pfister et al. 2004). Water abstraction can also affect natural trends in flow variability and may even reverse them, as it is indicated in Fig. 4.1 which shows trends in minimum flow for the lower River Thames since the late 19th century (Hannaford and Marsh 2006). The gauged flow indicates a decreasing trend, with the decline in low flow primarily attributable to the seven-fold increase in abstraction upstream of the gauging station, to meet much of London’s water needs. Minimum flow corrected for abstraction (here termed ‘naturalised’ flow) shows the opposite trend, and suggests an almost 40 % increase in low flow since the late 19th century.

The sensitivity of river basins to climate change differs from basin to basin. Lawrence and Hisdal (2011) found climate impact effects on peak flows in Norway to depend on

the size of the catchment and the river regime: sensitivity to climate change reduces as catchment size increases and the contribution of snowmelt and melt from glaciers (relative to rainfall) to flow peaks increases. Coastal catchments in south-western Norway are particularly sensitive to changes in climate.

4.3 Observed Changes in Annual and Seasonal Flow

4.3.1 River Rhine

Compared to the extensive literature on future projections of River Rhine discharge, there are relatively few studies on changes in discharge during the instrumental record. The most recent international study was conducted by the International Commission on the Hydrology of the River Rhine (Belz et al. 2007; Belz 2010). This investigated discharge from the various regions using data from 38 main gauges. Each gauge measured daily mean discharge in a sub-catchment of the River Rhine. The longest time series covered the period 1901–2007 and the shortest started in 1951. On the basis of data from the Lobith gauging station near the German-Dutch border (Rhine-km 862.2), Belz et al. (2007) concluded that the observations show a clear increase in average discharge in winter (December to February) over the last century. At the Lobith gauging station over the period 1901–2000 this increase in winter amounts about 12 %, from an average of 2300–2600 m³ s⁻¹. In fact, the same trend of increasing winter discharge appears in nearly

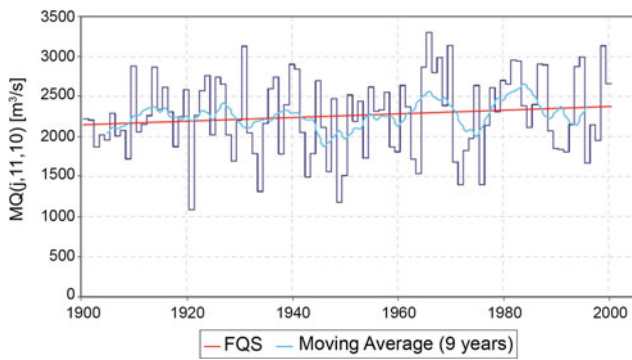


Fig. 4.2 Annual mean river discharges over the 20th century, nine-year moving average and trend (using the sum of errors method—FQS—significant at a 80 %-level Mann-Kendall-test) for the lower Rhine at the Rees gauge (adapted from Belz 2010)

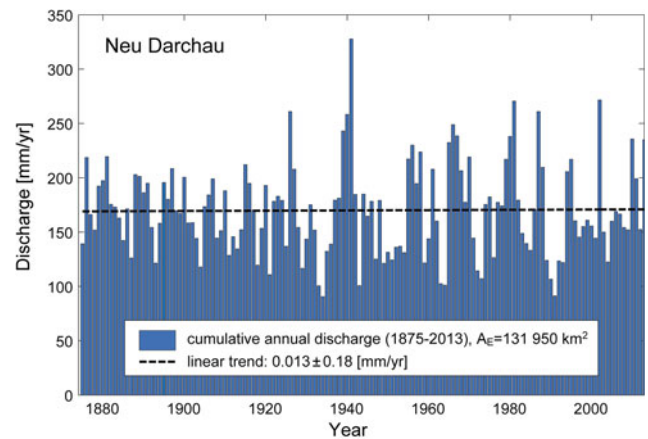


Fig. 4.4 Total annual discharge at the Neu Darchau gauging station on the River Elbe (Elbe-km 536) for the period 1875–2013 (Mudersbach et al. 2013)

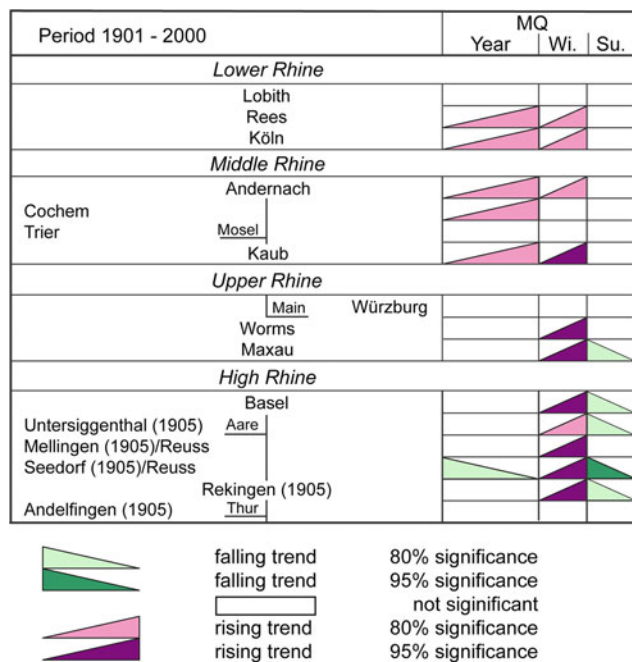


Fig. 4.3 Changes in average annual discharge for the Rhine basin through the 20th century (translated from Belz et al. 2007)

all sections of the River Rhine (Belz et al. 2007). There appears to be a slight increasing trend in annual discharge for the Rees gauge in the lower Rhine which is shown in Fig. 4.2. This trend is significant at the 80 % level for a Mann-Kendall test (Belz et al. 2007). In summer a few gauges in the upper Rhine section show significant (at the 80 % level for a Mann-Kendall test) declining trends (Belz et al. 2007). Belz et al. (2007) attributed the changes in winter discharge to an increase in the amount of winter precipitation. An increase in winter precipitation in the Rhine catchment has been reported by many studies (Caspary and Bardossy 1995; Blochliger and Neidhofer 1998; Konnen 1999; Uhlenbrook et al. 2001). Higher temperatures

leading to more precipitation falling as rain rather than snow have also led to an increase in winter discharge. The findings of Belz et al. (2007) are summarised schematically in Fig. 4.3.

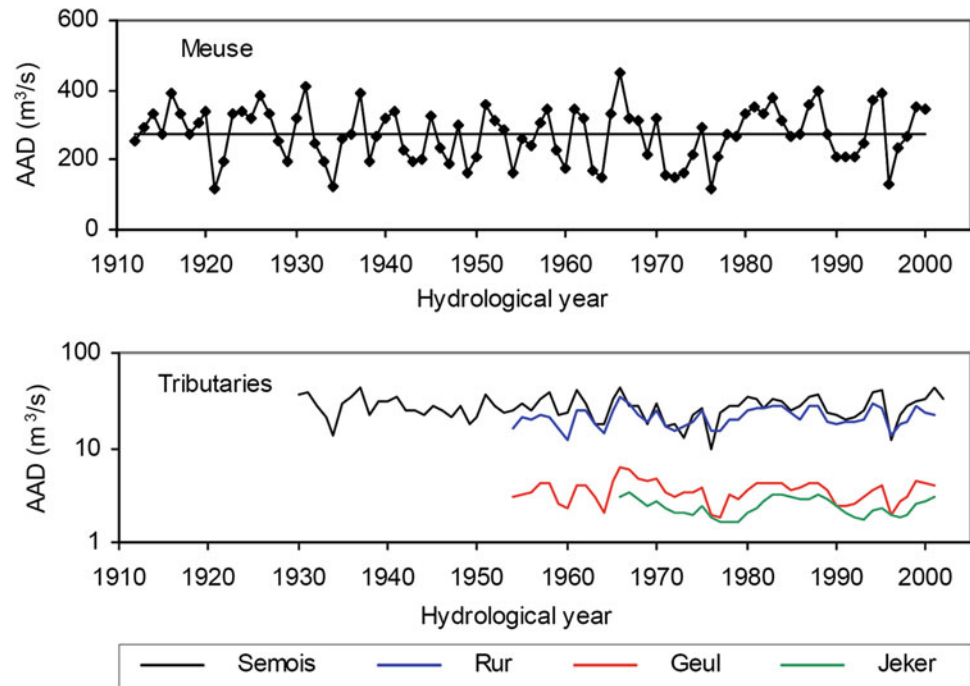
4.3.2 River Elbe

Mudersbach et al. (2013) calculated the cumulative annual discharge at the Neu Darchau gauging station on the River Elbe (Elbe-km 536), about 75 km southeast of Hamburg for the period 1875–2013 (Fig. 4.4). They found no significant long-term trend, but did find strong decadal variability. This long-term variability was also reported by Ionita et al. (2011), who analysed annual mean discharge at the Neu Darchau station based on mean monthly discharge data for the period 1902–2002. They found strong decadal variability with a dominant period of 20 years. Analysing different River Elbe discharge data series from the Dresden gauge downstream to the Neu Darchau gauge, Markovic and Koch (2006) identified statistically significant low frequency oscillations with periods of 7.1 years and 10–14 years occurring in addition to the seasonal cycle, indicating the occurrence of extended dry and wet periods.

4.3.3 River Meuse

Min (2006) analysed the reconstructed discharge series at the Monsin gauging station on the River Meuse, Belgium, for the period 1912–2002, investigating both a long-term (1912–2002) and shorter term period (1950–2002). Average discharge over the long-term was $270 \text{ m}^3 \text{ s}^{-1}$ (de Wit et al. 2001). For the average annual discharge (see Fig. 4.5), neither a change-point nor a trend was found in either record

Fig. 4.5 Annual average discharge in the River Meuse near Monsin (Meuse-km 586) for 1912–2000 and selected tributaries. *Note* a logarithmic scale is used for the tributaries (adapted from Min 2006)



(de Wit et al. 2001; Min 2006). However, a slight increase in average spring discharge was seen between 1978 and 1989 (mainly March), and a decrease in average autumn discharge from 1933 onwards. The increase in average spring discharge could be attributed to an increase in precipitation, and thus to climate variability rather than to land-use change or climate change (Min 2006).

Ward (2009) suggested that discharge in the Meuse basin was higher during the 20th century than in previous centuries, identifying a 2.5 % difference between average annual discharge in the 19th and 20th centuries and an even greater difference relative to earlier centuries. Ward (2009) attributed the difference in annual average discharge between the 19th and 20th centuries to climate change, since there was little change in land use over this period.

4.3.4 UK Rivers

Hannaford and Marsh (2006) and Hannaford and Buys (2012) applied trend tests to time series of discharge and measures of low flow in UK rivers. They reported little variability in discharge and low flow since the early 1960s. However, an increasing trend in annual discharge was apparent for some catchments in Scotland.

Figure 4.6 shows seasonal discharge (summer, winter) for six 'large' UK rivers discharging into the North Sea. Although there are no clear long-term trends, considerable decadal variability is apparent. Table 4.2 shows the coefficient of variation in seasonal discharge from the six rivers

(calculated over the common period 1970–2011). Variability is lowest in northern rivers and highest in the rivers draining southern England. In the northern rivers variability is greatest in summer, while in the southern rivers variability is greatest in autumn. Interannual variability in winter discharge in Scotland (River Tay) is strongly related to the NAO, but the correlations are less strong further south.

4.3.5 Scandinavian Rivers

In Scandinavia, both the seasonal river discharge and the ice regime are strongly influenced by large-scale atmospheric circulation processes over the North Atlantic that are closely correlated with the NAO index (HELCOM 2013). Reported changes in average annual flow from the Norwegian and Kattegat coasts are small. A slight increase in discharge was reported by Hellström and Lindström (2008) which they attributed to a slight increase in annual precipitation. However, higher temperatures lead to less snowfall, earlier snow melt and thus to shifts in river regime where flow in winter tends to increase.

4.3.6 Inflow from the Baltic Sea

Long-term data series on the inflow of water from the Baltic Sea to the North Sea are lacking as measurements of this inflow are not made. Overall, it may be assumed that the total river discharge into the Baltic Sea is a good

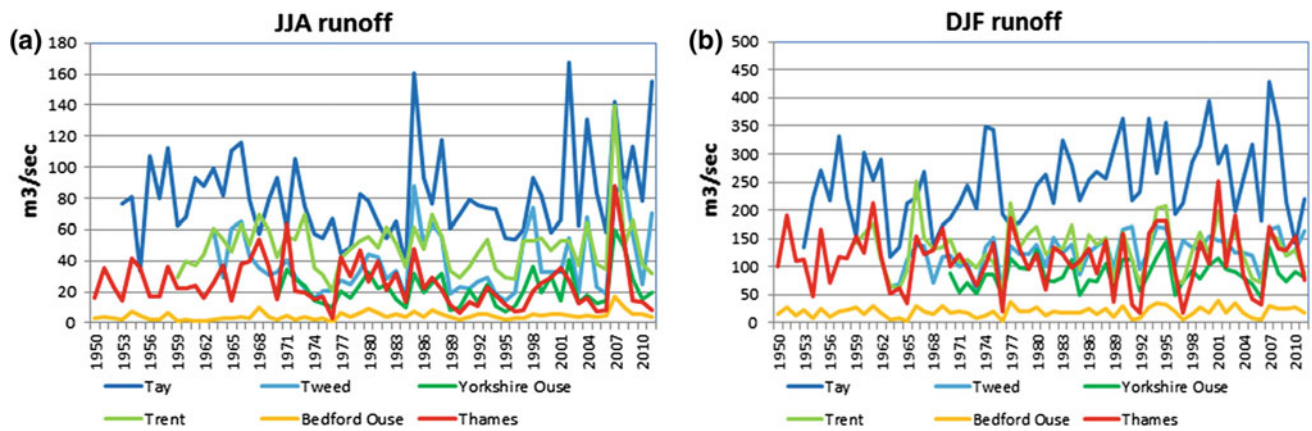


Fig. 4.6 Mean discharge in summer (*left*) and winter (*right*) for selected UK rivers draining into the North Sea. Data from the UK National River Flows Archive (www.ceh.ac.uk/data/nrfa)

Table 4.2 Coefficient of variation in seasonal flows for six UK rivers that discharge into the North Sea (1970–2011) and the correlation between winter flow and the strength of the winter North Atlantic Oscillation (NAO) index

River (north to south)	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)	Annual	Correlation between winter flow and the NAO index
Tay at Ballathie	0.26	0.27	0.39	0.30	0.16	0.71
Tweed at Norham	0.23	0.29	0.56	0.41	0.21	0.20
Yorkshire Ouse at Skelton	0.28	0.39	0.52	0.46	0.22	0.24
Trent at Colwick	0.30	0.35	0.39	0.46	0.22	0.11
Bedford Ouse at Bedford	0.44	0.51	0.54	0.79	0.33	-0.02
Thames at Kingston	0.48	0.47	0.72	0.77	0.36	0.01

Data from the UK National River Flows Archive (www.ceh.ac.uk/data/nrfa)

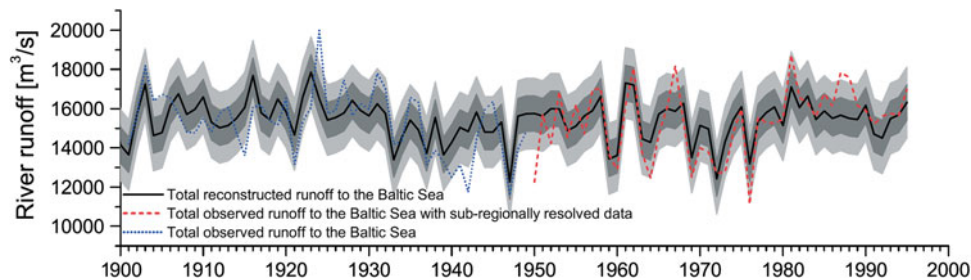


Fig. 4.7 Observed (*blue and red lines*) and reconstructed (*black line*) total river discharge to the Baltic Sea over the 20th century (adapted from Hansson et al. 2011)

approximation for the lower bound of water inflow into the North Sea since precipitation over the Baltic Proper is on average higher than evaporation (typically between 10 and 25 %; see study summaries by Omstedt et al. 2000, 2004; Hennemuth et al. 2003; Leppäranta and Myrberg 2009). Mean annual river discharge into the Baltic Sea is reported by different observational studies as between 470 and 485 km³ year⁻¹ for the past century (Cyberski and Wróblewski 2000; Hansson et al. 2011). According to Omstedt et al. (2004) net outflow to the North Sea, excluding the

Kattegat and Belt Sea water budget, is around 15,500 m³ s⁻¹ (corresponding to 488 km³ year⁻¹) with an interannual variability of ± 5000 m³ s⁻¹.

Figure 4.7 shows observed and reconstructed annual total river discharge to the Baltic Sea during the 20th century. Decadal and regional variability is large, but no *significant* long-term change has been detected in total river discharge to the Baltic Sea during the last 500 years (Hansson et al. 2011).

Owing to climate change in the Baltic Sea basin, Störmer (2011) expected an increase in water temperature, a decrease in salinity and a decrease in summer river discharge. Analysis of discharge sensitivity to temperature indicates that the southern Baltic Sea basin may become drier with rising air temperature (Omstedt et al. 2014). Based on reconstructions, Hansson et al. (2011) concluded that total annual river discharge to the Baltic Sea has decreased by 3 % for each 1 °C rise in air temperature over the past 500 years (see also Omstedt et al. 2014). HELCOM (2013) reported that this increase is not due to the large decadal and regional variability in discharge. HELCOM (2013) also reported increasing trends in annual, winter and spring stream flow, but found no trend for autumn. The shift in discharge towards the winter period was attributed to rising temperature.

Changes (trends and variability) in inflow from the Baltic Sea largely depend on changes in river discharge. Wilson et al. (2010) analysed a dataset of 151 streamflow records from the Nordic countries and found an increase in streamflow over the periods 1920–2005, 1941–2005 and 1961–2000 in the annual data and the winter and spring data. Trends identified in summer flows differed between the three periods, whereas no trend was found for autumn. In all three periods, a signal towards earlier snowmelt-driven high flows was clear, as was the tendency towards more severe low flows in summer in southern and eastern Norway. These trends in streamflow result from changes in both temperature and precipitation, although the temperature-related signal is stronger than the influence of precipitation. Changes in the observed annual and seasonal discharge from rivers in the Baltic Sea catchment were discussed by Käyhkö et al. (2015). They concluded that statistically significant increasing trends were apparent in annual river discharge and winter discharge due to the rise in air temperature and subsequent snowmelt, while spring discharge had decreased due to less snow available.

4.4 Observed Changes in Peak Flow and Low Flow

Owing to the increased attention to flood risk more studies are now investigating trends in the frequency and magnitude of peak flows than in changes in average or low flows.

4.4.1 River Rhine

Toonen (2013) examined the lower Rhine flooding regime between 1350 and 2011 and found no permanent change over this period, but did mention the non-stationarity of the series. There appeared to be more frequent minor floods during the Little Ice Age (AD 1550–1850). Devastating

floods in this period were associated with ice jams, but events of extreme discharge were not recorded (Toonen 2013).

Several authors have reported a noticeable increase in flow peak frequency in the Rhine basin over the past 100 years (Pfister et al. 2004; Pinter et al. 2006; Belz et al. 2007; Diermanse et al. 2010). Pinter et al. (2006) found a statistically significant increase in the frequency of flow peaks ranging from >5000 to 7500 m³ s⁻¹ at nine gauges in Germany. These gauges have records of 50 years of nearly continuous daily water level and discharge observations. Increase in frequency for the very large peak flows (>8000 m³ s⁻¹) is difficult to detect with high (>90 %) confidence because of the relatively small number of these extreme events during the last century. Diermanse et al. (2010) found the increase in annual maximum discharge for the Lobith gauge (running from 1901 to 2003) to be 8 m³ s⁻¹ per year over the observation period (or 13 % of the average annual maximum), but this trend was not statistically significant for four different tests (Pearson t-test, Spearman's rank correlation test, Mann-Kendall test and Wilcoxon-Mann-Whitney test). The significance levels of the tests were between 15 and 32 %.

This recent increase in peak flow is attributed to the increase in winter precipitation and increased snow melt in winter (Pfister et al. 2004; Belz et al. 2007) and to an increase in westerly atmospheric circulation types (Pfister et al. 2004).

4.4.2 River Elbe

Mudelsee et al. (2003) investigated discharge data sets for the past 80–150 years in the rivers Elbe and Odra basin. For the River Elbe (Dresden gauge), they found a decreasing trend in winter peak flows which they attributed to fewer ice damming events. Summer peak flows do not show any significant trend. Mudelsee et al. (2003) analysed floods in the rivers Elbe and Odra over the past 500 years focusing on relations with large-scale atmospheric circulation over Europe. They found significantly decreasing trends in winter peak flows in both rivers but no significant trends in summer peak flows during the 20th century.

In a study based on data from 78 gauges across Germany, Bormann et al. (2011) found no significant trends in different flood parameters. They found trends of different sign along the Elbe and emphasised the strong dependence of the trend on the underlying record length.

Analysing discharge for the period 1875–2011 at the Neu Darchau gauge, Mudersbach et al. (2013) found some evidence of an increase in the number of years with high annual flows over the past few decades. This study included trend analysis of six different flood indicators: annual maximum

floods, annual winter and summer maximum flows, the two-largest flow peaks per year and two peak-over-threshold time series. They found a downward trend in frequency of winter peak discharges and no trend in frequency of summer peak discharges. However, with the exception of one peak-over-threshold time series, none of the trends were significant at the 95 % confidence level.

Changes in low flows have received less attention than changes in peak flows. Belz et al. (2007) reported a redistribution of summer discharge to winter in the Alpine region of the River Rhine but that this disappeared further downstream. For the River Elbe, IKSE (2012) conducted a trend analysis over the period 1961–2005 using different gauging stations. They found different trends at different stations and the trends could not be attributed to the slightly increasing trend in precipitation. They concluded that other human influences such as the operation of large storage reservoirs, especially those of the Moldau cascade were probably responsible for the changes in river flow.

4.4.3 River Meuse

Peak discharges have also increased in magnitude and frequency over the last century in the River Meuse (de Wit et al. 2001; Min 2006; Ward 2009; Diermanse et al. 2010). Diermanse et al. (2010) found an increasing trend in annual maximum discharge for the Borgharen gauge (running from 1911 to 2003) of $3.4 \text{ m}^3 \text{ s}^{-1}$ per year over the observation period (or 23 %). The significance levels of the tests were between 10 and 22 %. Min (2006) and Ward (2009) studied the period after 1984, analysing maximum winter discharges using a peak-over-threshold method, and found a statistically significant increase for this period.

4.4.4 UK Rivers

Hannaford and Marsh (2006) and Hannaford and Buys (2012) found no significant trends for low flow in UK rivers. They did find significant increasing trends for low flows over the period 1973–2002 but these were influenced by a sequence of notably dry years at the start of the study period and were not observed over the most recent 40-year period analysed. Jones et al. (2006) concluded that for the period 1885–2002, there were relatively few low flow periods in UK rivers between 1980 and 2002. There are some indications of an increasing frequency of peak flows in many catchments (Hannaford and Buys 2012), especially in upland areas, but there is considerable year-to-year

variability and the strength of trends is very dependent on the length of record used.

4.4.5 Scandinavian Rivers

With respect to the Scandinavian region, peak flow frequency and intensity differ over time (Lindström and Bergström 2004; Thodsen 2007). Some studies suggest a slight increase in flood discharge but according to overview studies covering many rivers there is no statistically significant trend over the last century (Forland et al. 2000 for Norway; Hyvarinen 2003 for Finland; Lindström and Bergström 2004 for Sweden; Bering Ovesen et al. 2000; Thodsen 2007 for Denmark).

4.5 Conclusions

This chapter reviews the main trends and variations in river flows to the North Sea based on observations from the many gauges throughout the catchments draining into the North Sea. Most of the inflows are from a small number of large river basins, and the overall trends and variability in discharge from these large rivers are the combined effects of much variability in the different parts of the basin. Variability in river flow over time is dependent on variations in the weather—mainly precipitation and temperature—from year to year, as well as on a wide range of direct and indirect human interventions within the basin. Direct interventions include the construction of reservoirs along the river network and the abstraction and return of water for domestic, industrial and, to a much lesser extent, agricultural purposes. Indirect interventions include changes in land use. Although data records for the major rivers draining into the North Sea are relatively long, records for the smaller rivers are typically much shorter.

Analyses of observed flow records lead to three broad conclusions. First, there is considerable interannual and decadal variability in river flow in all areas draining into the North Sea. In northern areas this is closely associated with variation in the strength and direction of the NAO index, particularly in winter. Second, there are some indications of increasing discharge to the North Sea in winter, but little evidence of a widespread trend in summer; the magnitude of the trend, however, appears to depend on the length of record used and the technique used to estimate trends. Third, there is evidence that higher winter temperatures have led to increased winter river flow particularly to the Baltic Sea, as winter precipitation increasingly falls as rain rather than snow.

To date, no significant climate-related trends have been shown for most of the rivers discharging into the North Sea.

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