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Assessment of Hydrologic Alterations in Elbe and Rhine Rivers, Germany

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Abstract: In light of recent anthropogenic-induced climate change, a burning question at present is how these changes influence the water regime of rivers, which are of vital importance for humans as well as for biota. In this study, we investigate the changes in the hydrologic regime of two major German rivers, Elbe and Rhine, after the middle of the 20th century. Here, we use the widely adopted Range of Variability Approach (RVA) method on daily streamflow data from five (Elbe) and seven (Rhine) hydrological stations to determine the variability and spatial pattern of hydrologic alterations. We discuss the potential effect of climate change on the water regime of these two rivers, as well as other potential causes. For both rivers, we find that some hydrologic parameters are highly altered, especially the number of reversals, indicating higher variability. The highest impact is found at Ems hydrological station on Rhine River. The order of affected hydrological stations follows mostly the downstream course of both rivers. Our study indicates that the hydrological behavior of Elbe and Rhine Rivers has altered since the middle of the 20th century, a probable consequence of climate change. These hydrologic alterations can lead to undesirable ecological effects on local biota.

Keywords: hydrologic alteration; range of variability approach; indicators of hydrologic alteration; climate change; Elbe River; Rhine River

1. Introduction

One important question at present is how environmental changes affect hydrologic regimes, which in turn have a high impact on humans as well as on biota. Many studies have shown that the climate has significantly changed in the last decades on a global as well as regional scale [1]. Such changes were also observed in Germany, and it was already shown that climate change has an impact on some major German rivers [2]. Natural flow regime of rivers is extremely important for sustaining the surrounding environment and for the state, functionality, and availability of aquatic, riparian, and wetland ecosystems [3–10], while flow alteration is considered to be a serious threat to such ecosystems [6,11,12]. The flow regime is relevant to the structure of the riverine ecosystem and to the distribution, composition, and diversity of lotic biota, by controlling many physical and ecological aspects of rivers [8,13]. These processes include, for example, sediment transport and nutrient exchange, which influence habitat factors like flow depth, velocity, and habitat volume [4,14,15].

Intensive human activities, such as dam construction, irrigation, and land use change, have strongly modified global hydrologic regimes [16–19]. Dams built for hydroelectric generation or flood control can alter the downstream hydrologic regime by altering the total streamflow quantity, water quality, and duration of extreme flow [20]. In many regions of the world, hydrologic alterations are observed, as a consequence of climate change. For example, the frequency of floods as well as droughts has increased, causing huge human and property damage, and the extremes intensified [21,22]. For instance, significant trends in flood intensity were observed for Rhine River [23–25]. Belz et al. [26]

showed that the runoff regime of Rhine River has changed as a consequence of climate change and anthropogenic impacts, such as land use change and dam construction. Wechsung et al. [27] suggest that changes in low flow conditions in Elbe River can be related to climate change, reservoir operation, and mining activities. Any alteration to the hydrologic regime may have undesirable effects on the distribution and availability of riverine habitat conditions and on the structure and persistence of aquatic communities [4,28–32]. It has been shown that even minor climate changes may trigger a drastic alteration in the hydrologic regime [33]. Changing climate can affect the water balance of river catchments, via changes in precipitation (which affect the river runoff) and via increased temperatures which lead to increased evapotranspiration, as well as melting of the glaciers and changes in the timing and amount of snow fall and snow melt. According to the IPCC climate scenarios (e.g., [34,35]), the winter runoff is expected to increase while the summer runoff will decrease, as a consequence of regional climate change in Germany.

Richter et al. [29] developed the Indicators of Hydrologic Alteration (IHA), based on either hydrologic data or on model-generated data, in order to assess the degree to which human-induced disturbance affects hydrologic regimes within an ecosystem. However, this method has been also applied for understanding the changes in flow induced by climate change [36–38]. Richter et al. [5] proposed the range of variability approach (RVA), with the aim of setting streamflow-based river management eco-targets, by considering the natural hydrologic variability of rivers. With this method, 33 hydrologic parameters are used in order to assess hydrologic alterations in terms of streamflow magnitude, timing, frequency, duration, and rate of change [29,39,40]. The range of variability approach is an effective tool for assessing hydrologic alterations [17,41,42]. It has been used in many studies that focus on determining hydrologic alterations caused by dam constructions [18,19,31,43–46].

There are an increasing number of studies on the changes in runoff characteristics caused by climate change [2,33,47] or human intervention [16–19,48–56]. Here, we offer the first study on the hydrologic alterations of two main German rivers, Elbe and Rhine, based on the widely adopted RVA method, applied on daily streamflow data from several hydrological stations along the two rivers, by comparing the hydrologic regime from post-impact to the pre-impact period. Our study aims at quantifying and characterizing the alteration of natural water regimes on Elbe and Rhine rivers after middle of the 20th century, and assessing the spatial pattern of these alterations. As such, we discuss the possible causes leading to alterations of the flow regime and the potential ecological implications induced by these changes.

2. Materials and Methods

2.1. Study Regions and Data

The Elbe River (Figure 1) is one of the major rivers of Europe. It originates from the Giant Mountains in the northern Czech Republic at an elevation of 1383 m and flows into the North Sea at Cuxhaven (Germany), with a mean annual discharge at the mouth of about 861 m^3/s [57]. From a total length of 1094 km, 367 km are located in the Czech Republic and 727 km in Germany, while much smaller parts lie in Austria and Poland [57]. The mean annual discharge at the border between Czech Republic and Germany is about 311 m^3/s. The Elbe basin has a catchment area of 148,268 km^2, which makes it the fourth largest in Europe. It covers different geographical regions from middle mountain ranges in the west and south to large lowlands in the central, northern, and eastern parts. The river has six major tributaries: Vltava, Saale, Havel, Mulde, Ohre, and Schwarze Elster. The basin is inhabited by 24.5 million people. The Elbe River is located in a transition zone between the maritime and the continental climate, where the temperature indicates strong intra-annual variability, thus influencing the evaporation. It is the driest river in Germany due to low precipitation levels, with an average of about 659 mm/year. The precipitation ranges from less than 450 mm/year in the central part to 1600 mm/year in the mountains (Figure 2a).

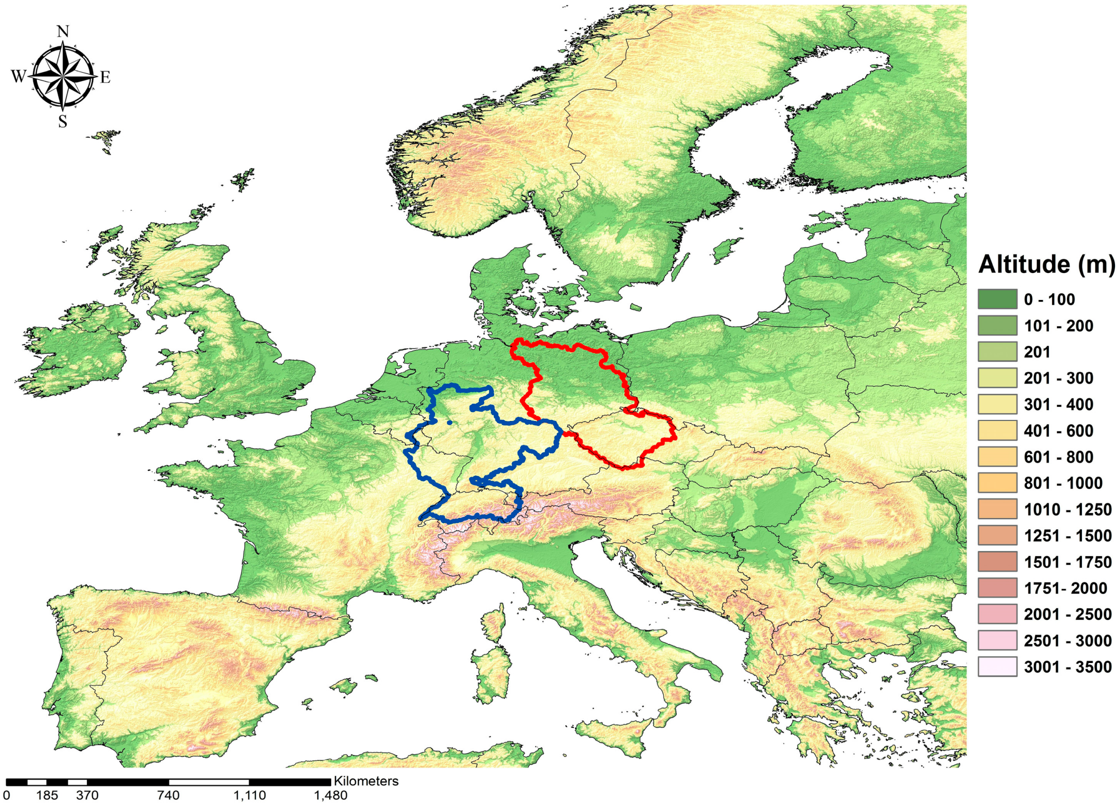

Figure 1. Location and elevation of the two analyzed catchment areas: red, Elbe River; blue, Rhine River.

The Rhine River (Figure 1) is one of the largest and most important rivers in Europe. It originates from the southeastern Swiss Alps at an elevation of 2345 m, and it flows through Liechtenstein, Austria, Germany, and France, before draining into the North Sea in The Netherlands. It has a mean discharge of about 2300 m^3/s and a total length of 1230 km [58]. The river basin covers an area of about 185,260 km^2, being inhabited by about 58 million people. It covers different geographical regions from alpine area upstream to lowlands downstream. The Rhine River is supplied by several large tributaries, such as Moselle, Main, Aare, Saar, and Neckar. The precipitation ranges from less than 200 mm/year in the central part to 3500 mm/year in the mountains (Figure 2b). The Rhine River has been intensively modified by humans during history. The Lower Rhine was channelized during the latter half of the 19th century and through the 20th century [59]. The study by Pinter et al. [24] indicates that the regulation of the basin has little or no effect on Rhine streamflow, while the land-use and climate change over the past 100 years lead to an increase in the magnitude and frequencies of floods.

The daily streamflow data were provided by the German Federal Institute of Hydrology (BfG) in Koblenz, Germany. The five hydrological stations along the Elbe River are: Barby, Dresden, Neu Darchau, and Wittenberge (located in Germany), and Decin (located in the Czech Republic). The streamflow measurements at these stations cover periods ranging from 1806–1900 to 2014–2015 (Table 1). The seven hydrological stations along the Rhine River are: Basel-Rheinhalle, Ems, Kaub, Köln, Lobith, Neuhausen, and Reckingen, with streamflow measurements covering periods ranging from 1817–1931 to 2014–2015 (Table 1). The locations of the hydrological stations along the Elbe and Rhine Rivers are shown in Figure 2. There are no time gaps in the streamflow data used in this study.

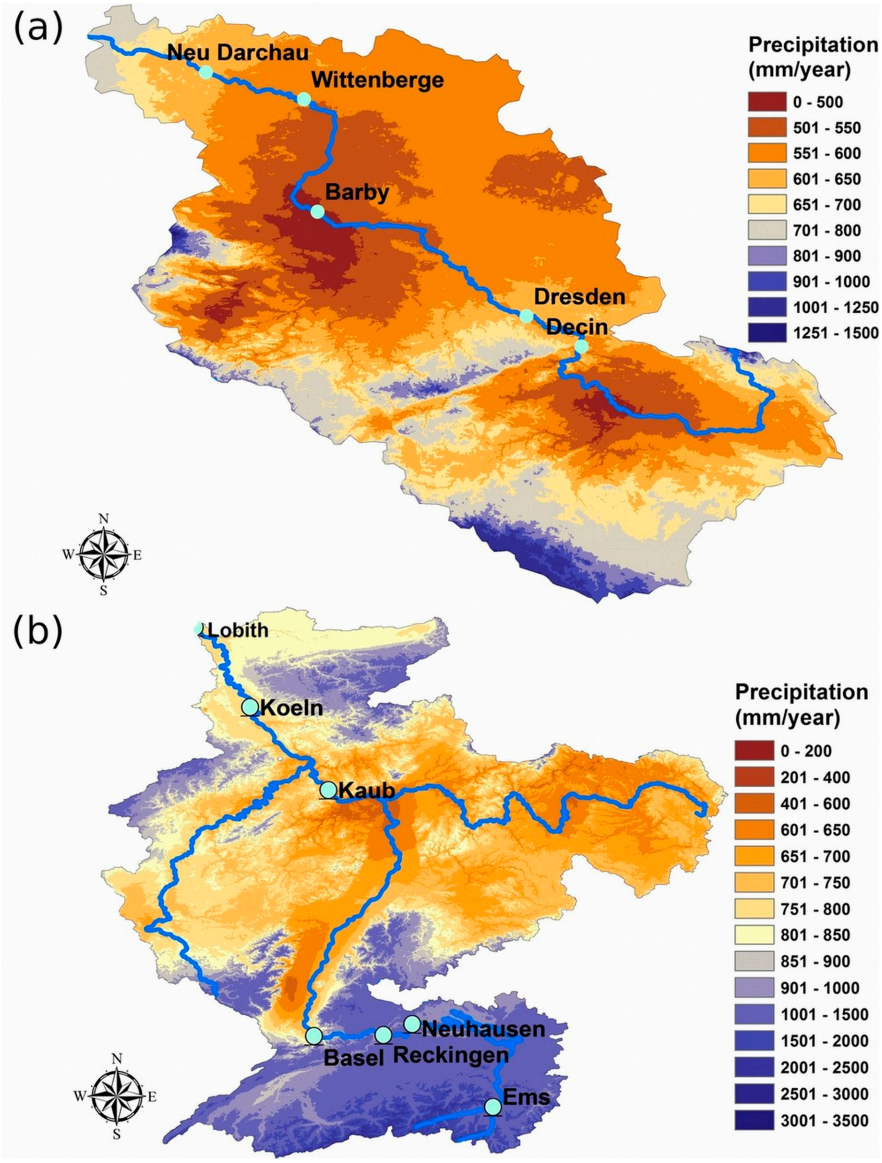

Figure 2. Precipitation over the basins of: (**a**) Elbe River; and (**b**) Rhine River. The circles indicate the location of the hydrological stations considered in this study.

Table 1. Information on the hydrological stations located on Elbe River and Rhine River.

Station Name	Location		River	Sequence Length
Barby	11.88° E	51.99° N	Elbe	1900–2015
Decin	14.23° E	50.79° N	Elbe	1888–2014
Dresden	13.74° E	51.06° N	Elbe	1806–2015
Neu Darchau	10.89° E	53.23° N	Elbe	1875–2015
Wittenberge	11.76° E	52.99° N	Elbe	1900–2015
Basel-Rheinhalle	7.62° E	47.56° N	Rhine	1869–2014
Ems	9.46° E	46.84° N	Rhine	1910–2014
Kaub	7.76° E	50.09° N	Rhine	1931–2015
Köln	6.96° E	50.94° N	Rhine	1817–2015
Lobith	6.11° E	51.84° N	Rhine	1901–2013
Neuhausen	8.63° E	47.68° N	Rhine	1904–2014
Reckingen	8.33° E	47.57° N	Rhine	1904–2014

2.2. Indicators of Hydrologic Alteration

The hydrologic alterations (*HA*) at the gauging stations along the two German rivers were calculated using the Indicators of Hydrologic Alteration (IHA) software developed by Richter et al. [29]. The IHA software determines how affected hydrologic regimes are by human-induced disturbances. Richter et al. [5] proposed the range of variability approach (RVA), which uses the pre-impact natural variation of IHA parameter values as a reference for determining the degree of alteration of natural flow regimes. Richter et al. [5] suggest that the distribution of annual values of the IHA parameters should be kept by the water managers as close to the pre-impact distributions as possible. All the analyzed data follow a normal distribution [60].

There are 33 IHA parameters that can be analyzed using RVA, which are divided in five groups based on magnitude, timing, frequency, duration, and change rate. One IHA parameter was not included in this study, namely the number of zero-flow days, as no such days were observed at the considered hydrological stations during the given periods. The five groups are defined as follows:

1. Group 1 comprises the twelve monthly median flows describing the normal flow conditions. These parameters represent a measure of the availability or suitability of a habitat [61].
2. The parameters of Group 2 present the magnitude and duration of annual extreme flows: one-, three-, seven-, 30-, and 90-day annual minima and maxima, and the base flow index calculated as the seven-day minimum flow/annual mean flow. These parameters are relevant in modulating the structure and function of rivers and floodplains [61].
3. Group 3 contains the Julian dates for one-day annual maximum and minimum, indicating the timing of the annual extreme flows. Changes in these parameters influence the life-cycle of organisms and the degree of stress associated with extreme water conditions [61].
4. In Group 4, the parameters indicate the frequency and duration of high and low pulses, defined as the annual periods when the daily flows are above (below) the 75th (25th) percentile daily flow of the pre-impact period. They influence the reproduction or mortality rates of different species and the population dynamics [61].
5. In Group 5, the parameters indicate the numbers and rates of positive and negative changes in flow between two consecutive days: fall rate, rise rate, and number of reversals. Such changes can lead to drought stress on plants or entrapment of organisms along the edge of the water or nearby ponded depressions [61].

In this study, we use the non-parametric RVA analysis [29], due to its robustness, and define the median (50th percentile) as the central tendency and the category boundaries 17 percentiles from the median. Thus, the low and high boundaries of the RVA target range are established by the 34th and 67th percentile values calculated from the pre-impact values.

The *HA* of each parameter is calculated as follows:

$$HA(\%) = \frac{observed\,frequency - expected\,frequency}{expected\,frequency} \times 100 \tag{1}$$

where the *observed frequency* is the number of years in which the observed parameter value fell within the target range, while *expected frequency* represents the number of years in which the value is expected to fall within the target range. The degree to which the RVA target ranges are not attained is accepted as a measure of hydrologic alteration. A positive (negative) *HA* value indicates that the respective parameter values fell within the target range more (less) often than expected. A hydrologic alteration is zero when the observed frequency of post-impact annual values that fall within the RVA target range equals the expected frequency [61]. Richter et al. [41] proposes the degrees of *HA* to be classified in minimal alteration (0–33%, L), moderate alteration (34–67%, M), and high alteration (68–100%, H).

In our study, we are interested in the effects of climate change on the water regimes. Therefore, the pre- and post-impact periods are separated by year 1950, which we chose as the impact year. In the last decades, the changing climate has affected the water regimes of German rivers. Bormann [2] determined the hydrologic alteration of German rivers caused by climate change since middle of the 20th century and showed that climate change has an impact on the hydrological behavior of rivers and their mean seasonal variability.

According to Richter et al. [5] and Günther and Matthäus [62], at least 20 years should be used for the pre-impact period in order to account for natural climate variability. All the streamflow sequences used in our study start before 1930, except for the sequence recorded at Kaub station, which starts in 1931 and thus only 19 years are used for the pre-impact period.

To assess the spatial extent of hydrologic alteration along a river, the overall degree of *HA* needs to be determined. For this, the IHA factors with statistically significant contributions are selected. The mean of absolute values of each IHA factor for the five (Elbe) and seven (Rhine) hydrological stations is calculated. These means are ranked, and the percentile values calculated. The IHA factors for which the mean exceeds the 67th percentile are statistically significant and considered in the calculation of the overall degrees of *HA*. Then, for each hydrological station the mean of the absolute values of the selected *HA* factors are calculated, thus determining the spatial assessment of *HA*. This method has been described by [41] and used in other studies focusing on the spatial extent of hydrologic alterations along a river [18,19].

3. Results

3.1. Hydrologic Alteration of Elbe River

Table 2 gives the *HA* values for Elbe River at the five hydrological stations. Moderate and low alterations are observed for most parameters. In general, during late spring, early summer (April, May, June, and July) and October, the monthly flow is lower in the post-impact period, while during the late summer, early autumn (August and September) and winter, the flow is higher than in the pre-impact period. The post-impact values in the annual minima flows are in general higher compared to the pre-impact values. By contrast, the annual maxima flows decreased in the post-impact period. The base flow index presents greater post-impact values at all considered hydrological stations. On average, the most affected IHA parameter is the number of reversals, with negative *HA* values for all five stations, indicating that the post-impact values fell in the targeted range less often than expected (Table 2). In contrast, the Julian date of one-day minimum discharge fell in the targeted range more often than expected in the case of all hydrological stations (Table 2).

Table 2. Hydrologic alteration (in percent) of 32 indicators of hydrologic alteration (IHA) for five hydrological stations on Elbe River. L = Low alteration (0–33%); M = Medium alteration (34–67%) marked with light grey; H = High alteration (68–100%) marked with dark grey. The means are based on the absolute values of each hydrologic alteration.

IHA Factor	Barby	Decin	Dresden	Neu Darchau	Wittenberge	Mean
Group 1						
January	22 (L)	−9 (L)	−26 (L)	31 (L)	39 (M)	25
February	−44 (M)	0 (L)	−13 (L)	−45 (M)	−33 (L)	27
March	39 (M)	43 (M)	35 (M)	14 (L)	−20 (L)	30
April	9 (L)	0 (L)	−6 (L)	−18 (L)	−28 (L)	12
May	−20 (L)	−22 (L)	−10 (L)	−27 (L)	−12 (L)	18
June	5 (L)	17 (L)	−26 (L)	−23 (L)	0 (L)	14
July	52 (M)	26 (L)	3 (L)	9 (L)	−3 (L)	18
August	−24 (L)	4 (L)	−3 (L)	−45 (M)	−16 (L)	19
September	1 (L)	52 (M)	40 (M)	−5 (L)	1 (L)	20
October	−7 (L)	49 (M)	13 (L)	5 (L)	30 (L)	21
November	−3 (L)	34 (M)	−10 (L)	0 (L)	22 (L)	14
December	14 (L)	−21 (L)	24 (L)	14 (L)	22 (L)	19

Table 2. *Cont.*

IHA Factor	Barby	Decin	Dresden	Neu Darchau	Wittenberge	Mean
Group 2						
1-day minimum	−20 (L)	−92 (H)	41 (M)	−32 (L)	−28 (L)	43
3-day minimum	−20 (L)	−91 (H)	44 (M)	−27 (L)	−28 (L)	42
7-day minimum	−20 (L)	−96 (H)	48 (M)	−27 (L)	−28 (L)	44
30-day minimum	−7 (L)	−13 (L)	27 (L)	0 (L)	−16 (L)	13
90-day minimum	1 (L)	34 (M)	18 (L)	−9 (L)	−20 (L)	16
1-day maximum	−20 (L)	−9 (L)	13 (L)	−5 (L)	−8 (L)	11
3-day maximum	−24 (L)	0 (L)	−4 (L)	−5 (L)	−3 (L)	7
7-day maximum	−20 (L)	−26 (L)	−4 (L)	−14 (L)	−7 (L)	14
30-day maximum	1 (L)	−9 (L)	−21 (L)	−5 (L)	−7 (L)	9
90-day maximum	−16 (L)	−31 (L)	9 (L)	−32 (L)	−41 (M)	26
Base flow index	−7 (L)	−57 (M)	35 (M)	−5 (L)	5 (L)	22
Group 3						
Date of minimum	5 (L)	39 (M)	70 (H)	14 (L)	47 (M)	35
Date of maximum	−37 (M)	8 (L)	−12 (L)	−32 (L)	−44 (M)	27
Group 4						
Low pulse count	−12 (L)	−46 (M)	2 (L)	−15 (L)	−20 (L)	19
Low pulse duration	−12 (L)	−43 (M)	−1 (L)	14 (L)	−10 (L)	16
High pulse count	28 (L)	−19 (L)	−15 (L)	6 (L)	17 (L)	17
High pulse duration	−20 (L)	−27 (L)	−10 (L)	−14 (L)	18 (L)	18
Group 5						
Rise rate	−53 (M)	0 (L)	−2 (L)	−23 (L)	−12 (L)	18
Fall rate	−48 (M)	−24 (L)	−28 (L)	−39 (M)	−28 (L)	34
Number of reversals	−4 (L)	−63 (M)	−92 (H)	−51 (M)	−24 (L)	47

High alterations are found at Decin hydrological station, where three IHA parameters from Group 2 indicate alterations higher than 90%, namely the annual one-day minimum discharge (−92%), annual three-day minimum discharge (−91%), and annual seven-day minimum discharge (−96%), with most of the values above the RVA high boundary after middle of the 20th century (Figure 3a). The medians of the annual minimum discharges increase by 59%, 50%, and 49%, respectively, in the post-impact period compared to the pre-impact period. The base flow index parameter is indicating a moderate alteration of −57% at Decin station, with values higher in the post-impact period (Figure 3b). High hydrologic alterations are found also at Dresden hydrological station, for the Julian date of one-day minimum discharge (70%) and number of reversals (−92%), with the median 34% greater than the pre-impact value. The Julian date of one-day minimum discharge falls within the target range more often than expected, indicating a bias towards summer and early autumn in the post-impact period (Figure 3c). The annual number of reversals in the post-impact period presents a significant increase, indicating a larger annual variability (Figure 3d). A systematic increase in the number of reversals is observed until 1940, followed by a short-time decrease (but still outside the targeted range) and an increase since about 1970 (Figure 3d). Barby, Neu Darchau, and Wittenberge hydrological stations present only low or moderate alterations (Table 2).

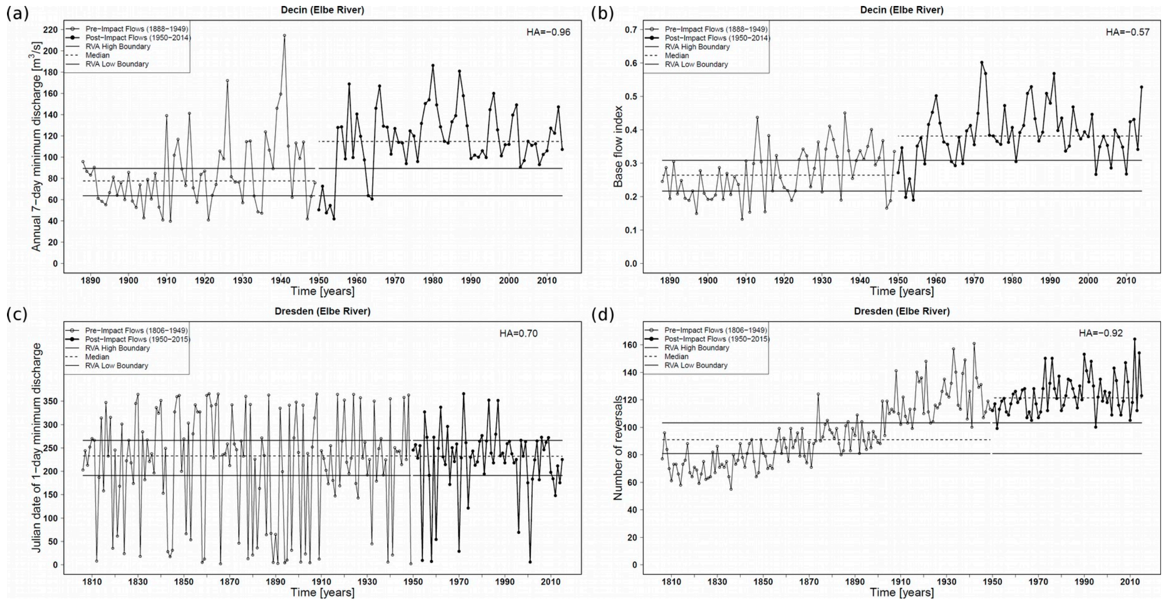

Figure 3. Examples of changes in the hydrologic regime at two hydrological stations on Elbe River: (**a**) annual seven-day minimum discharge at Decin; (**b**) base flow index at Decin; (**c**) Julian date of one-day minimum discharge at Dresden; and (**d**) number of reversals at Dresden.

3.2. Hydrologic Alteration of Rhine River

Table 3 gives the *HA* values for Rhine River at the seven hydrological stations. Moderate and low alterations are observed for most parameters. In general, during summer and early autumn (June, July, August, September, and October), the monthly flow is lower in the post-impact period, while during the months from November to May, the flow is higher than in the pre-impact period. In general, except for the annual 30- and 90-day maximum discharge, Julian dates of one-day minimum and maximum discharge, and low and high pulse duration, all the other remaining parameters indicate higher post-impact values.

High alteration of number of reversals is found also at Basel-Rheinhalle hydrological station (−91%), indicating higher variability in the post-impact period (Figure 4a). However, the most affected hydrological station by far is Ems, which indicates moderate alterations for nine IHA factors and high alterations for 12 IHA factors, namely: monthly flows for January (−74%), February (−78%), and March (−74%), annual three-day minimum discharge (−69%), annual 30-day minimum discharge (−87%), annual 90-day minimum discharge (−74%), base flow index (−74%) (Figure 4b), low pulse count (−81%), low pulse duration (−96%), rise rate (−87%), fall rate (−88%), and the number of reversals (−92%) (Figure 4c). Except for low pulse duration, all other altered IHA factors indicate higher values in the post-impact period compared to the pre-impact period. Starting from 1954, the number of days of low pulse are kept only at values lower than the RVA low boundary, with a decrease in the median from six days in the pre-impact period to one day in the post-impact period, suggesting human intervention. The monthly flow medians for January, February, and March present an increase of 95%, 141%, and 87%, respectively, and larger fluctuations in the post-impact period. For Ems, obvious deviations are actually observed around 1960 (Figure 4b,c). In this particular case, if 1960 would be considered the impact year, IHA parameters such as the rise rate, fall rate, and number of reversals would give *HA* values of −100%, with all values after year 1960 being outside the targeted range. At Ems, lower post-impact monthly flows are found for May to September, while from October to April there is an increase in the flow. The post-impact values in the annual minima flows at Ems are higher, while the annual maxima flows decreased. The base flow index, low and high pulse count, rise rate, fall rate, and number of reversals at Ems present greater post-impact values.

Table 3. Hydrologic alteration (in percent) of 32 indicators of hydrologic alteration (IHA) for seven hydrological stations on Rhine River. L = Low alteration (0–33%); M = Medium alteration (34–67%) marked with light grey; H = High alteration (68–100%) marked with dark grey. The means are based on the absolute values of each hydrologic alteration.

IHA Factor	Basel-Rheinhalle	Ems	Kaub	Köln	Lobith	Neuhausen	Reckingen	Mean
Group 1								
January	2 (L)	−74 (H)	−10 (L)	16 (L)	17 (L)	24 (L)	11 (L)	22
February	15 (L)	−78 (H)	32 (L)	−15 (L)	13 (L)	−17 (L)	2 (L)	24
March	6 (L)	−74 (H)	19 (L)	7 (L)	8 (L)	11 (L)	11 (L)	19
April	−12 (L)	1 (L)	7 (L)	−19 (L)	−23 (L)	19 (L)	−20 (L)	15
May	20 (L)	10 (L)	−5 (L)	1 (L)	−23 (L)	−3 (L)	15 (L)	11
June	−2 (L)	−30 (L)	−26 (L)	−33 (L)	−28 (L)	−47 (M)	−51 (M)	31
July	−29 (L)	−21 (L)	32 (L)	11 (L)	13 (L)	−25 (L)	−20 (L)	22
August	−15 (L)	−34 (M)	27 (L)	14 (L)	4 (L)	−29 (L)	6 (L)	19
September	34 (M)	−52 (M)	32 (L)	16 (L)	35 (M)	15 (L)	33 (L)	31
October	−3 (L)	5 (L)	−1 (L)	−16 (L)	−23 (L)	11 (L)	6 (L)	9
November	20 (L)	−16 (L)	40 (M)	21 (L)	67 (M)	37 (M)	37 (M)	34
December	−31 (L)	−60 (M)	−22 (L)	−28 (L)	8 (L)	−29 (L)	−33 (L)	30
Group 2								
1-day minimum	−20 (L)	−34 (M)	−18 (L)	−8 (L)	−23 (L)	−20 (L)	−34 (M)	22
3-day minimum	−3 (L)	−69 (H)	−22 (L)	3 (L)	−32 (L)	−25 (L)	−25 (L)	26
7-day minimum	−8 (L)	−60 (M)	−5 (L)	−6 (L)	−28 (L)	−16 (L)	−7 (L)	19
30-day minimum	25 (L)	−87 (H)	−18 (L)	−10 (L)	8 (L)	−3 (L)	−7 (L)	23
90-day minimum	−12 (L)	−74 (H)	−1 (L)	−15 (L)	35 (M)	−12 (L)	6 (L)	22
1-day maximum	20 (L)	−30 (L)	−14 (L)	−10 (L)	−5 (L)	−29 (L)	11 (L)	17
3-day maximum	11 (L)	−25 (L)	−26 (L)	−19 (L)	−1 (L)	−29 (L)	19 (L)	19
7-day maximum	20 (L)	−38 (M)	11 (L)	−1 (L)	8 (L)	−29 (L)	−3 (L)	16
30-day maximum	−2 (L)	−43 (M)	−26 (L)	−28 (L)	8 (L)	−43 (M)	−20 (L)	24
90-day maximum	2 (L)	−52 (M)	−18 (L)	−42 (M)	4 (L)	−25 (L)	−29 (L)	24
Base flow index	−40 (M)	−74 (H)	7 (L)	34 (M)	−1 (L)	−38 (M)	−34 (M)	33
Group 3								
Date of minimum	−18 (L)	−25 (L)	55 (M)	71 (H)	58 (M)	−60 (M)	−25 (L)	45
Date of maximum	−26 (L)	−43 (M)	11 (L)	1 (L)	−28 (L)	−20 (L)	−47 (M)	25
Group 4								
Low pulse count	−28 (L)	−81 (H)	2 (L)	−27 (L)	1 (L)	−34 (M)	−20 (L)	28
Low pulse duration	−31 (L)	−96 (H)	−14 (L)	−26 (L)	−23 (L)	−20 (L)	8 (L)	31
High pulse count	38 (M)	−20 (L)	9 (L)	2 (L)	17 (L)	3 (L)	−43 (M)	19
High pulse duration	32 (L)	26 (L)	15 (L)	−24 (L)	−23 (L)	4 (L)	2 (L)	18
Group 5								
Rise rate	−27 (L)	−87 (H)	−10 (L)	−14 (L)	18 (L)	−32 (L)	42 (M)	33
Fall rate	−38 (M)	−88 (H)	−21 (L)	−33 (L)	−27 (L)	−36 (M)	1 (L)	35
Number of reversals	−91 (H)	−92 (H)	−30 (L)	−42 (M)	−23 (L)	−37 (M)	12 (L)	47

At Köln hydrological station, high alteration is found for Julian date of one-day minimum discharge (0.71) (Figure 4d). Kaub, Lobith, Neuhausen, and Reckingen experienced only moderate alterations since the middle of the 20th century. As in the case of Elbe River, the most affected IHA parameter is the number of reversals, with negative *HA* values at all stations, except for Reckingen, indicating that the post-impact values fell within the targeted range less often than expected (Table 3).

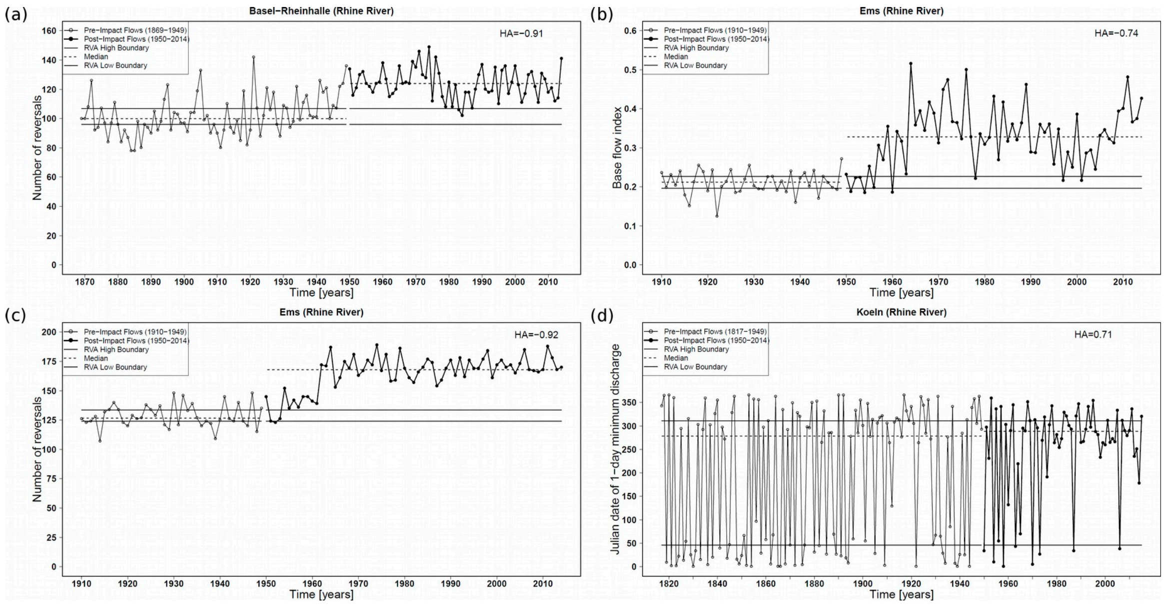

Figure 4. Examples of changes in the hydrologic regime at three hydrological stations on Rhine River: (**a**) number of reversals at Basel-Rheinhalle; (**b**) base flow index at Ems; (**c**) number of reversals at Ems; and (**d**) Julian date of one-day minimum discharge at Köln.

3.3. Spatial Pattern of Hydrologic Alteration along Elbe River

Figure 5 presents the ranked mean of absolute degrees of 32 indicators of hydrologic alteration for the five hydrological stations on Elbe River. The factors for which the mean exceeds the 67th percentile ($\geq$25%) are considered the ones with the highest impact: number of reversals, annual seven-day minimum discharge, annual one-day minimum discharge, annual three-day minimum discharge, Julian date of one-day minimum discharge, fall rate, monthly flow for March, monthly flow for February, Julian date of one-day maximum discharge, annual 90-day maximum discharge, and monthly flow for January. As shown in Table 4, the overall degree of *HA* for the five hydrological stations ranged from 25% (Barby) to 45% (Decin), which indicates low to moderate alterations. These parameters were considered in the calculation of the overall degrees of *HA*, which indicate that the most affected hydrologic regime is found at Decin station in Czech Republic, followed by Dresden, Wittenberge, Neu Darchau, and Barby being the least affected station (Table 4). The order of affected stations follows the downstream course of the Elbe River, except for the Barby station.

Table 4. Overall degrees of hydrologic alteration (in percent) for the 11 most altered indicators of hydrologic alteration (IHA) for five hydrological stations on Elbe River. The means are based on the absolute values of each hydrologic alteration.

IHA Factor	Barby	Decin	Dresden	Neu Darchau	Wittenberge
Number of reversals	−4	−63	−92	−51	−24
7-day minimum	−20	−96	48	−27	−28
1-day minimum	−20	−92	41	−32	−28
3-day minimum	−20	−91	44	−27	−28
Date of minimum	5	39	70	14	47
Fall rate	−48	−24	−28	−39	−28
March	39	43	35	14	−20
February	−44	0	−13	−45	−33
Date of maximum	−37	8	−12	−32	−44
90-day maximum	−16	−31	9	−32	−41
January	22	−9	−26	31	39
Mean absolute value	25	45	38	31	33

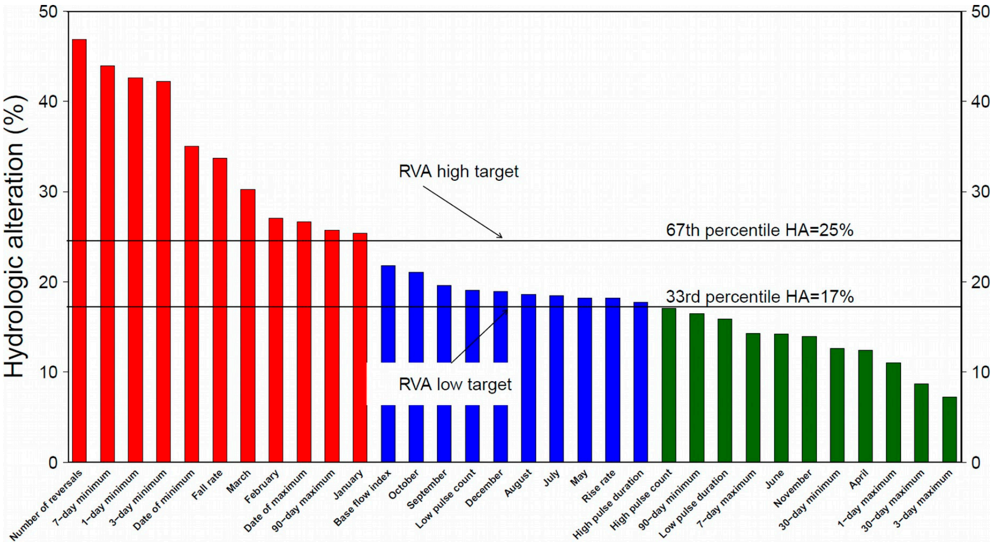

Figure 5. Ranked mean of absolute degrees of 32 indicators of hydrologic alteration for five hydrological stations on Elbe River and the 67th and 33rd percentile values. Red indicates mean hydrologic alterations higher than the 67th percentile, blue indicates mean hydrologic alterations between 33rd and 67th percentiles, and green indicates mean hydrologic alterations lower than 33rd percentile.

3.4. Spatial Pattern of Hydrologic Alteration along Rhine River

Figure 6 shows the ranked mean of absolute degrees of 32 indicators of hydrologic alteration for the seven hydrological stations on Rhine River. The factors for which the means exceed the 67th percentile (≥27%) are considered the factors with the highest impact: number of reversals, Julian date of one-day minimum discharge, fall rate, monthly flow for November, rise rate, base flow index, low pulse duration, monthly flow for June, monthly flow for September, monthly flow for December, and low pulse count. As shown in Table 5, the overall degree of *HA* for the seven hydrological stations ranged from 23% (Kaub) to 64% (Ems), which indicates low to moderate alterations. These parameters were considered in the calculation of the overall degrees of *HA*, which indicate that the most affected hydrologic regime is found at Ems station, followed by Neuhausen, Basel-Rheinhalle, Köln, Reckingen, Lobith, and Kaub being the least affected station (Table 5). The order of affected stations follows the downstream course of the Rhine River, except for the Reckingen and Kaub stations. As shown above, Ems station has the most affected hydrologic regime, with alterations more than twice the value found at the farthest station, Lobith.

Table 5. Overall degrees of hydrologic alteration (in percent) for the 11 most altered indicators of hydrologic alteration (IHA) for seven hydrological stations on Rhine River. The means are based on the absolute values of each hydrologic alteration.

IHA Factor	Basel-Rheinhalle	Ems	Kaub	Köln	Lobith	Neuhausen	Reckingen
Number of reversals	−91	−92	−30	−42	−23	−37	12
Date of minimum	−18	−25	55	71	58	−60	−25
Fall rate	−38	−88	−21	−33	−27	−36	1
November	20	−16	40	21	67	37	37
Rise rate	−27	−87	−10	−14	18	−32	42
Base flow index	−40	−74	7	34	−1	−38	−34
Low pulse duration	−31	−96	−14	−26	−23	−20	8
June	−2	−30	−26	−33	−28	−47	−51
September	34	−52	32	16	35	15	33
December	−31	−60	−22	−28	8	−29	−33
Low pulse count	−28	−81	2	−27	1	−34	−20
Mean absolute value	33	64	23	31	26	35	27

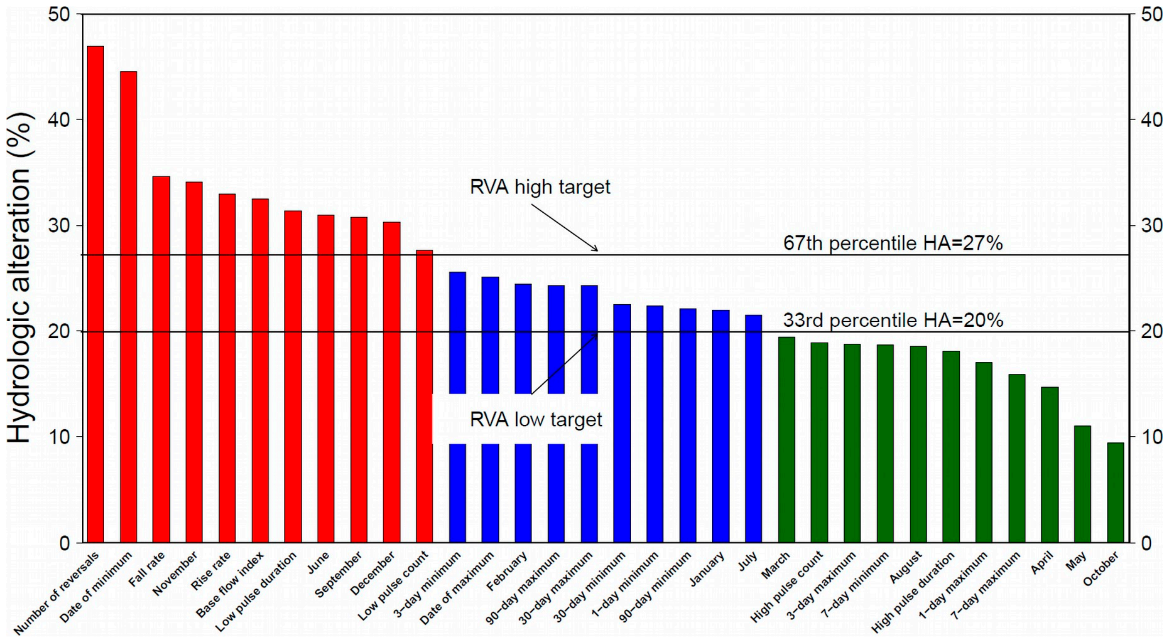

Figure 6. Ranked mean of absolute degrees of 32 indicators of hydrologic alteration for seven hydrological stations on Rhine River and the 67th and 33rd percentile values. Red indicates mean hydrologic alterations higher than the 67th percentile, blue indicates mean hydrologic alterations between 33rd and 67th percentiles, and green indicates mean hydrologic alterations lower than 33rd percentile.

4. Discussion

In the above section, we have shown that the natural flow regimes of the Elbe and Rhine Rivers were significantly altered after the middle of the 20th century, at some hydrological stations. These alterations coincide with the rapid onset of climate change since about 1950. We have shown that the most affected hydrological station on Elbe River is Decin, located in the Czech Republic. The main tributary of Elbe in the Czech Republic is Vltava River, merging with Elbe at Mělník, which is upstream from Decin. On the Vltava River, several dams were built in the 1950s. The Orlík dam is the largest reservoir with respect to the volume, while the Lipno dam is the largest reservoir with respect to the area. The Štěchovice Reservoir was built north of Prague. The Vltava River also features numerous locks and weirs that help adjust its flow from an elevation of 1172 m at its source near the German border to 155 m at its mouth in Mělník. The construction of these water reservoirs on Vltava may partly contribute to the high hydrologic alterations observed at Decin (Table 2, Figure 3a,b). We have also shown that the alteration of the hydrologic regime decreases with the increase in distance from Decin hydrological station (Table 4). However, the least affected station is Barby, which may be related to the fact that a major tributary of Elbe, Saale, is merging with Elbe just above Barby. Furthermore, the waterflow in the Elbe River varies considerably with the amount of precipitation and thawing in its drainage basin. Barby is located in a region with smallest precipitation averages of up to 500 mm/year (Figure 2a). Although dams were built on the Elbe in the Czech Republic, as well as on its major tributaries Vltava and Saale, these are not sufficient to control the water level of the Elbe, indicating that other causes might have altered the water regime on Elbe.

We have shown that Rhine River is only moderately altered since the middle of the 20th century, except for Ems hydrological station, which is significantly affected. The Ems station is located in Domat/Ems, Switzerland, where a run-of-the-river power station is operated. The Reichenau power plant was built between 1959 and 1962 in the Alpenrhein. It is located at Domat/Ems only a few kilometers below the confluence of Vorderrhein and Hinterrhein near Reichenau. The Rhine River is dammed up above Domat/Ems and the water is led into a channel about 1 km long, which partly runs underground. At the end of this canal lies the power plant, after which the water flows back into the natural riverbed. As shown above, drastic changes in the hydrologic regime at Ems are observed after about 1960, coinciding with the time when the Reichenau power plant was built. Another possible explanation for the observed alterations in the flow regime at Ems may be an increase in the percentage of rainfall in winter instead of snow, which would result in higher discharge and less snow storage [62,63]. The smaller snow pack would lead to lower runoff in summer because snow melt occurs earlier due to rising temperature [2]. Bormann [2], who assessed the effects of climate change on several German rivers runoff, found a decrease in the summer Pardé coefficients, consistent with a decrease in precipitation, inducing less runoff, while winter Pardé coefficients present an increase, consistent with an increase in precipitation, generating more runoff.

As in the case of Elbe River, the hydrological stations on Rhine River indicate that alterations decrease with the increase in distance from Ems, except for Kaub and Reckingen. One cause for the water regime at Kaub station being less affected may be because one major tributary, namely Main River, merges with Rhine above Kaub, reducing the effects found upstream. Furthermore, as mentioned above, for Kaub station, the streamflow sequence before the impact year has a length of only 19 years, when at least 20 years are needed for the pre-impact period in order for the natural variability to be properly represented [5,64]. Moreover, similar to the Elbe River case, we found the least affected station to be the one located in the area with the smallest amount of yearly precipitation, which is Kaub in the case of Rhine River (Figure 2b). The second most affected water regime is found at Neuhausen hydrological station (Table 5). Although Neuhausen is the closest station to Ems, the hydrologic alteration is a little more than half the alteration found at Ems, and only moderate alterations occurred since 1950. One cause may be that Neuhausen is located shortly after Rhine River flows out of Lake Constance, the lake mitigating the effects seen at Ems.

For both rivers, the number of reversals is the most affected IHA parameter, while the base flow index is considerably altered for Rhine River. The start of these alterations on Rhine River is observed around 1960 (Figure 4b,c), which coincides with the construction of the run-of-the-river Reichenau power station. The most affected hydrological stations with respect to these parameters are those close to the power plant, namely Ems, Basel, Neuhausen, and Reckingen. A high number of reversals indicates higher frequency in alternating periods between positive and negative flows. This would suggest that human intervention has modulated the flows via the power station, leading to an increased streamflow variability. However, in the case of Elbe River, the high alterations in the number of reversals cannot be easily explained by human intervention. The most altered number of reversals parameter is found at Dresden hydrological station (Table 2), indicating a clear increasing trend between 1830 and 1940, followed by a decrease (Figure 3d). Such long-term changes would suggest that other processes may have played a role in modulating the number of reversals at Dresden hydrological station.

In a previous study [19], the RVA method has been applied on streamflow data from the Yangtze River in order to determine the impact of a dam operating since 2009. It has been found that the dam strongly affects the water regime on the Yangtze River and that, as in our study, the hydrologic alterations decrease with the increase in distance between the hydrological stations and the dam. We find similar results for both rivers, the order of affected stations following the downstream course of the rivers. The most affected IHA parameter in the previous study [19] is the seven-day minimum. In our study, this parameter is the second most altered IHA parameter after the number of reversals, for the Elbe River. High alterations in the number of reversals are also found in another study [18] by applying the RVA method on the streamflow data to determine the influence of several dams constructed along the Yellow River, China.

Changes in the natural flow of a river may lead to undesirable effects on local biodiversity. A change in the timing of extreme flows interferes with the life cycle requirements of fish, for example the spawning season [61]. In general, an increase in the low pulse count affects strongly the aquatic communities by influencing the diversity and number of organisms that live in a river [51]. Alterations in the rate and frequency of water condition changes can cause drought stress on plants, entrapment of organisms on islands and floodplains, and desiccation stress on low-mobility streamedge organisms [61]. An increase in waterflow discharge during winter may lead to higher water velocities, changing the river morphology, and causing displacement of small organisms, changes in photosynthesis due to increased turbidity, disturbing the functioning of the riparian ecosystem [37]. On the other hand, reduced flow rates during summer may lead to higher water temperature and growing levels of dissolved nutrients and pollutants, changing the physical, chemical, and biological characteristics relevant to the biota [37].

Other causes, such as land use can have an impact on the runoff as well. However, Bronstert et al. [65] show that land use change can have a significant effect on the local scale only, while the river catchments are only slightly affected. Belz et al. [66] also show that anthropogenic influences have an effect on small spatio-temporal scale, only, while Finke et al. [67] suggest that direct anthropogenic impacts on the water cycle are small compared to the climate change impact. There are still many uncertainties that shall be considered in the assessment of hydrological changes, which should be further quantified and addressed in future research. Furthermore, the application of the RVA method in the case of climate change has its limitations, as the exact date of the climate change is not known, thus complicating the analysis.

5. Summary and Conclusions

In our study, we aimed at estimating the impact of climate change on the hydrologic regime (and its spatial pattern) of two major German rivers, Elbe and Rhine, using the RVA method on daily flow data. The main findings can be summarized as follows:

(1) For Elbe River, the natural hydrologic regime has changed since the middle of the 20th century at Decin and Dresden hydrological stations. The annual one-, three-, and seven-day minimum discharges have significantly increased at Decin, while the annual variability at Dresden has also significantly increased. These high alterations at Decin may possibly be related additionally to the dams constructed on Vltava tributary. At Wittenberge, Neu Darchau, and Barby, we find only moderate and low alterations. The order of affected stations follows the downstream course of the Elbe River, except for Barby station.

(2) In the case of Rhine River, we find large alterations at Ems hydrological station where 12 IHA factors are highly altered since around 1960, which can be possibly related, in addition to the effects of climate change, to the effects caused by the run-of-the-river power station. Higher intra-annual variability is found at Basel-Rheinhalle, while at Köln the Julian date of one-day minimum discharge is highly altered. At Neuhausen, Reckingen, Lobith, and Kaub, we find only moderate and low alterations. However, the order of affected stations follows the downstream course of the Rhine River, except for the Reckingen and Kaub stations.

(3) This study shows that the hydrological behavior of Elbe and Rhine Rivers has altered since the middle of the 20th century, a probable consequence of climate change. The results presented here characterize the hydrologic effects of climate change and/or human intervention on two major German rivers. However, determining the exact contribution of each of these factors to hydrologic alterations is not straightforward and more studies on quantifying these effects are necessary.

The IHA model can help identify which hydrologic parameters are affected as a result of climate change and can help scientists and managers to consider the ecologically important parameters. As important drivers of ecosystems, these hydrologic parameters may indicate present or expected effects on biodiversity, and thus should be monitored and maintained in an appropriate range. Management strategies to keep the future flow regimes as close to the pre-impact natural flow as possible are necessary.

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