Article

Low-Flow Similarities between the Transboundary Lauter River and Rhine River at Maxau from 1956 to 2022 (France/Germany)

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Abstract: Climate change is increasing air temperatures and altering the precipitation and hydrological regime on a global scale. Challenges arise when assessing the impacts of climate change on the local scale for water resource management purposes, especially for low-mountain headwater catchments that not only serve as important water towers for local communities but also have distinct hydrological characteristics. Until now, no low-flow or hydrological drought studies had been carried out on the Lauter River. This study is unique in that it compares the Lauter River, a transboundary Rhine tributary, with a nearby station on the Rhine River just below its confluence at the French–German border. The Lauter catchment is a mostly natural, forested catchment; however, its water course has been influenced by past and present cultural activities. Climate change disturbances cascade through the hydrologic regime down to the local scale. As we are expecting more low-flow events, the decrease in water availability could cause conflicts between different water user groups in the Lauter catchment. However, the choice among different methods for identifying low-flow periods may cause confusion for local water resource managers. Using flow-rate time series of the Lauter River between 1956 and 2022, we compare for the first time three low-flow identification methods: the variable-threshold method (VT), the fixed-threshold method (FT), and the Standardized Streamflow Index (SSI). Similar analyses are applied and compared to the adjacent Maxau station on the Rhine River for the same time period. This study aims at (1) interpreting the differences amongst the various low-flow identification methods and (2) revealing the differences in low-flow characteristics of the Lauter catchment compared to that of the Rhine River. It appears that FT reacts faster to direct climate or anthropogenic impacts, whereas VT is more sensitive to indirect factors such as decreasing subsurface flow, which is typical for small headwater catchments such as the Lauter where flow dynamics react faster to flow disturbances. Abnormally low flow during the early spring in tributaries such as the Lauter can help predict low-flow conditions in the Rhine River during the following half-year and especially the summer. The results could facilitate early warning of hydrological droughts and drought management for water users in the Lauter catchment and further downstream along some of the Rhine.

Keywords: low flow; hydrological drought identification; low-mountain catchment

1. Introduction

Climate change with rising temperature alters the interannual behavior of key hydrological components, such as precipitation, evapotranspiration, and snowpack, hence fundamentally modifying the global water cycle [1]. There have been many studies in Europe focusing on evaluating the impacts of future climate scenarios on water resources on a continental scale [2–4]. However, studies on smaller, low-mountain, forested catchments are scarcer [5]. In this study, the Lauter catchment bordering France and Germany was chosen since it is a rural, sparsely populated catchment and pioneering example for transboundary water resource management under climate change and biodiversity protection within a new Interreg project, RiverDiv. Despite the uncertainties introduced by

different downscaling methods and hydrological models from large-scale approaches, they all suggest high hydrological vulnerability in the region surrounding the Lauter River catchment. Hagemann et al. compiled runoff predictions generated from three global climate models (GCMs) regarding the A2 emissions scenario. Central, Eastern, and Southern Europe will face a significant decrease in water resources, with more than a 10% decrease for the period 2071–2100 based on 1971–2000 [2]. Donnelly et al. further performed a sensitivity analysis on the hydrologic impacts of temperature increase and found out that the runoff signal was more sensitive to a 1.5-degree mean global warming scenario than a temperature increase of 2 to 3 degrees [3]. Nevertheless, the hydrological regime changes not only according to the magnitude of the annual average temperature but also according to seasonal temperature fluctuations, which influences the timing of the peak flow and the frequency of drought events. Schneider et al. indicated that the European temperate oceanic zone will face higher precipitation in winter and lower precipitation in summer and will expect a shift in flow regime with higher runoff towards winter and lower flow in summer [4]. Challenges in Central Europe for water resource management are well summarized by Stagl et al. in terms of three aspects: (1) changes in seasonality, (2) changes in evapotranspiration and soil moisture, and (3) changes in rain–snow distribution [6]. As we focus on the Rhine basin, studies show similar predictions of changes in the flow regime. The Rhine River is expected to have a significant modification in runoff in the far future (2071–2100) [7] with a 42% decrease in summer flow and a 14% increase in winter flow [8]. Fluctuations in evapotranspiration and soil moisture will result in more "flash-drought" events in Rhineland-Palatinate [9] characterized by rapid drought onset and severe desiccation thus placing local water resource management at higher risk, particularly in the agricultural sector.

River runoff is important for the domestic water supply, agricultural irrigation, industrial usage, ecological services, navigation, and recreational uses. Being menaced by decreasing runoff in summer, water agencies need wise and accurate water resources planning strategies to secure the demand for each water use section. Hence, defining hydrological drought periods is a crucial step for setting up catchment-wide water resource management plans. Regarding different uses, there are generally four types of drought definition: meteorological drought, hydrological (including hydrogeological) drought, agricultural drought, and socio-economic drought. Many studies have been focusing on the linkage and propagation between these different drought types [10,11]. However, in the first step, we only focus on low-flow identification of the Lauter catchment in this study, as the stream runoff is the most direct factor effecting local water resource management. In a second step, we compare low-flow events in the Lauter, a confluent of the Rhine with an adjacent station on the River Rhine at a larger scale.

Numerous low-flow indices are used by hydrologists in determining low-flow events. Defining drought events with a predefined threshold was first introduced by Yevjevich in 1967 [12] and Zelenhasić et al. in 1987 [13]. These studies defined the structure of the low-flow hydrograph and its key components, which are drought duration, severity as cumulative flow deficit, and probability and recurrence analysis [12,13]. Recent studies have shown a paradigm shift by including anomalies into drought period identification, such as the variable-threshold method and the Standardized Streamflow Index (SSI) [14]. Yet different water use sectors have different practical definitions for drought. For instance, hydroelectric power stations require targeted water yield volumes with a fixed threshold, whereas ecologic services require the identification of seasonally abnormally low flow. Recent studies have also called for comprehensive comparison amongst different low-flow indices [14]. Hence, the objective of this paper are as follows: (1) to compare different threshold approaches (i.e., fixed threshold and variable threshold) and a statistical approach (i.e., SSI) for identifying drought events; and (2) to assess and recommend the most appropriate approach for the highly dynamic local-scale Lauter River basin and for the adjacent downstream station on the Rhine River representing a regional scale river basin. Despite the Upper Rhine basin being much larger and more complex than the Lauter

catchment, we assume that droughts are large-scale, persevering phenomena that can be extracted and compared at different spatial scales.

This study is novel since it is the first time that a low-flow analysis has been performed on the Lauter River catchment and furthermore the first time that it has been compared to the Rhine River. In addition, this is the first study that puts the extreme drought year 2022 into a long-term time perspective. We hope that this research can serve as an example for low-flow analysis of small-scale stream catchments and provide a fundamental base for local water resource management.

2. Study Area

The Lauter River flows through the Upper Rhine valley [15] and is a confluence of the Rhine river. Its sources are two headwater streams, the Wieslauter and the Salzbach, which join to form the Wieslauter. It flows through the Palatinate Forest in Germany, continues as the Lauter on the French–German border, and ultimately flows into the Rhine River. The highest altitude in the catchment is the Weissenberg at 609.3 m and the lowest point is 115 m at the confluence of the Lauter with the Rhine. The geology of the Upper Lauter (Wieslauter) catchment is dominated by Buntsandstein sandstones from the Trias and sedimentary layers of Zechstein from the Late Permian whilst the Lower Lauter is dominated by Pleistocene–Quaternary and alluvial sediments of the Rhine. The information was retrieved from the State Office for Geology and Mining of Rheinland-Pfalz, https://mapclient.lgb-rlp.de//?app=lgb&view_id=4 (accessed on 10 January 2024). The Lauter catchment contains large groundwater reservoirs. From a geomorphological perspective, it has highly incised low mountains with characteristic rock pinnacles and rock terraces and soils are mainly sandy. Forest dominates the catchment and is part of the Palatinate Forest which belongs to one of the largest, continuous forest areas in Mid-Europe. The climate is temperate, with annual average temperature of 10.7 °C based on the Deutscher Wetterdienst climate data of the Bad Bergzabern station between 1950–2022. The mean annual total rainfall is 950–1050 mm for the Upper Lauter and 700–800 mm for the Lower Lauter between 1951–2020 [16]. The catchment has a dense network of sources and streams, and the average discharge of the Lauter at different gauging stations are presented in Table 1.

Table 1. Summary of the basic characteristics of each station (Data provided by the State Office for the Environment of Rheinland-Pfalz).

Station	Altitude (m)	Catchment Area (km^2)	Distance to Rhine (km)	Study Period	Average Discharge (m^3/s)
Bobenthal (Lauter)	173	253	37.2	1 January 1956–15 June 2023	2.31
Salmbacher Passage (Lauter)	127	345	15.6	1 January 1961–31 December 2021	3.27
Maxau (Rhine)	98	50,196	-	1 January 1950–31 December 2022	1250.98

Even though the Lauter catchment is a sparsely populated, natural, forested catchment, the Lauter River is highly influenced by past and present human activities, especially by an ancient, semi-natural wood-rafting pond system. The northern part of the headwater area is designated as a drinking water protection zone, and the western part belongs to the Palatinate Forest–North Vosges Biosphere Reserve. Small urban areas are clustered along the river valley and tributaries and the main villages and towns from upstream to downstream are Hinterweidenthal, Dahn, Bundenthal, Wissembourg, and Lauterbourg. Upstream urban area modifications to the natural hydrological regime include river channelization, bank stabilization, small hydroelectric stations, and surface water and groundwater extractions for drinking water and industrial uses. As the Lauter River exits the mountain area of the Palatinate Forest downstream of Wissembourg, the flatter downstream part is largely occu-

pied by agricultural land. Natural water courses have been strongly modified over time for irrigation. Surface water and groundwater pumping for agricultural usages also alter the local natural hydrological regime. The catchment location and hydro-morphological characteristics are presented in Figure 1 and Table 2.
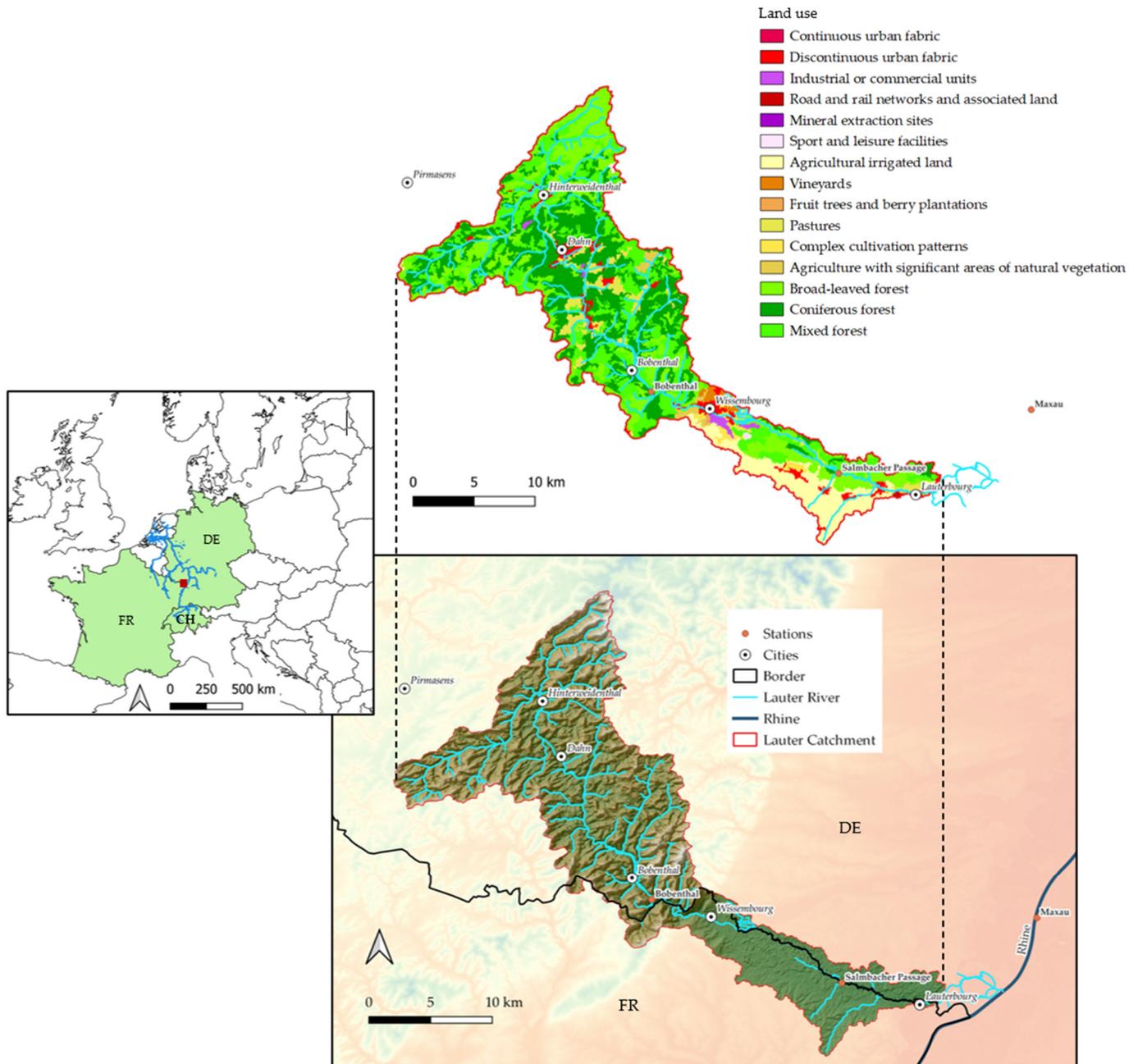

Figure 1. Map of the study area (marked in red in the image on the left hand side) with a land-use map obtained from the CORINE Land Cover inventory [17] and the streamflow stations (FR: France; DE: Germany; CH: Switzerland).

The Upper Rhine is influenced by a glacio-nival regime and was highly modified during the 19th and 20th centuries, mainly by rectification and the introduction of sluices and hydroelectric dams, which has profoundly changed its natural regime. However, the Maxau station analyzed in this study only reflects the navigable part of the Rhine whose regime is no longer controlled by dams. Furthermore, its regime is not yet influenced by major tributaries, since it is still upstream of the Moselle and Main.

Table 2. Characteristics of the Lauter catchment (the elevation data were retrieved from the State Office for Surveying and Geo-Basic Information of Rheinland-Pfalz, the geomorphology data were obtained from the Harmonized World Soil Database [18], and the rest of the data were derived from the NASA SRTM Digital Elevation map [19]).

Parameter	Unit	Value
Area	(km^2)	375.8
Elevation	(m)	285 (107–609.3)
Average slope	(%)	11.8
Length of the mainstream	(km)	74.6
Slope of the mainstream	(%)	0.25
Geomorphology	(-)	Sandy

This study uses streamflow data from the only two available discharge gauging stations on the Lauter River: the Bobenthal station and the Salmbacher Passage station in Germany. For the Rhine River, we use the discharge data from the Maxau station which is the closest station just downstream of the Lauter catchment with long-term monitoring results. The locations of the stations are showed in Figure 1. The Bobenthal station is located at the border of the Pfälzerwald, where the Lauter River drains from the mountains to the plain. The Salmbacher Passage station is located further downstream after the Lauter has passed through an intensively used agricultural region. Hence, the streamflow differences between these two stations could demonstrate both how anthropogenic factors and the geological setting can alter the hydrological regime, especially when considering different drought identification approaches. Data sources and time-series duration are presented in Table 1. All the data used within this study are extracted from public open-source materials.

3. Methodology

Here, we present the methodology and the parameter and distribution functions we chose to apply in this study. The study period as presented in Table 1 is from 1956 to 2022.

3.1. Variable- and Fixed-Threshold Methods

The threshold approach is commonly employed for defining low-flow periods in hydrological analyses. Common thresholds approaches include the daily threshold and monthly threshold [20]. In contrast to the fixed threshold, which considers desired water yield required by water users, the variable threshold takes seasonality into account and reveals any abnormalities of the flow regime [21].

Gamma, Pearson type III, Weibull, and log-normal distributions are commonly used for hydrological parameter analyses [22]. We chose to use two-parameter gamma distribution for this study as it has been proven to fit well with streamflow time series of the Rhine basin [23]. Since there were no zero values within the streamflow time series, we do not need to consider the zero-flow case. Hence, the gamma distribution function for each streamflow time series, denoted as $g(x)$, and the corresponding cumulative probability $G(x)$ are presented below:

$$g(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{\frac{-x}{\beta}} \tag{1}$$

$$G(x) = \frac{1}{\Gamma(\alpha)} \int_0^x t^{\alpha-1} e^{-t} dt \tag{2}$$

where α and β are the shape and scale parameters.

For perennial streams, the exceedance rate is normally set within the range of 75% to 90% [24]. In particular, the French Water Law from 1992 (La loi sur l'eau de 1992) defines the threshold "QMNA (annual minimum monthly flow)" for different return periods. The QMNA 5, which denotes the minimum monthly flow with a 5-year return period, is widely used in the Rhine–Meuse basin (SDAGE 2022–2027, Rhine–Meuse) [25]. Hence, we employed an exceedance rate of 80% for both the variable and fixed thresholds in this study.

We then used a 30-day and a 3-month moving average to smooth the daily and monthly thresholds correspondingly.

The challenge was to define the complete drought period in situations with several minor drought periods of mutual dependence or a significant extended drought period with several inferior, spiky flow disturbances. For this we employed the pooling criteria "inter-event time" t_i and "inter-event ratio" p_i for defining the drought events based on variable-threshold methods by Zelenhasić and Salvai in 1987 [13]. Figure 2 presents the pooling process. We tested different pooling scenarios and defined the pooling-criterion combination of $t = 20$ days and $p = 0.25$ as the pooling criteria for this study. For a detailed comparison, see the Supplementary Information.
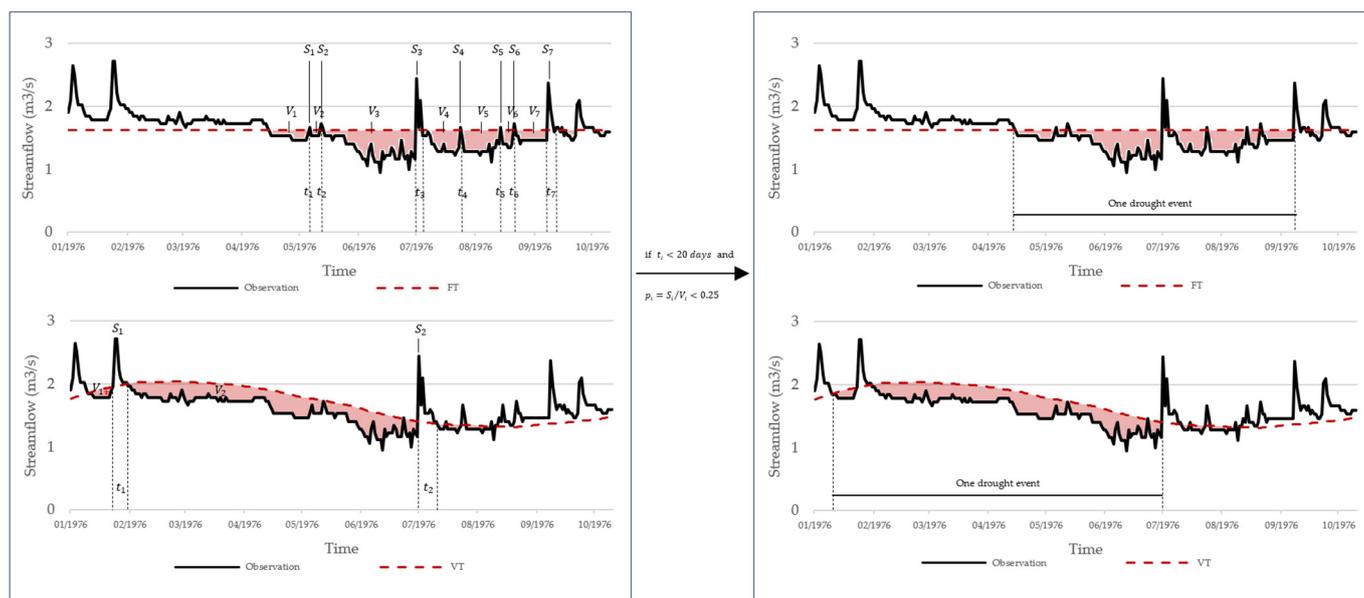

Figure 2. Schematic demonstration of the pooling criteria, where $t_i = inter-event\ time$, $V_i = interval\ deficit\ volume$, and $S_i = interval\ excess\ volume$. The inter-event ratio is defined as, $p_i = S_i/V_i$.

Nevertheless, minor droughts could cause significant noise in the final result. In order to screen out the disturbance from minor droughts, we excluded drought events with flow deficit value of less than 0.5% of the maximum deficit value [26].

3.2. The Standardized Streamflow Index (SSI)

The Standardized Streamflow Index (SSI) identifies streamflow drought events with the same calculation steps as for meteorological drought events using the standardized Precipitation Index (SPI). SSI analyses streamflow series using a hydro-meteorological approach. This is the only index recommended by the WMO for streamflow drought analysis [27]. In recent years, an increasing number of studies are using SSI to analyze catchment drought patterns [28–30]. Whereas hydrologists tend to study the streamflow character based on a finer spatial and temporal resolution, the meteorological approach using SSI prefers to interpret environmental signals on a monthly or yearly scale. However, for catchments such as the Lauter catchment with a relatively small contributing area and high streamflow variations, there have been few studies investigating the ability of the SSI to recognize drought events.

Many researchers have been focusing on assessing the accuracy of SSI from a statistical approach [22,31]. However, few studies compare the SSI with fixed- or variable-threshold methods for identifying drought events and their characteristics. As more and more researchers are integrating SSI into their streamflow analysis, especially for drought prediction with machine learning [29,32], this paper will use the Lauter catchment to demonstrate

the similarities and differences between SSI and FTM and VTM considering that they are all based on monthly time series analysis. The same analysis will be performed for the Rhine close to its confluence downstream of the Lauter and compared to the Lauter.

We used the Standardized Drought Analysis Toolbox (SDAT) of MATLAB to conduct the SSI analysis in this study. The toolbox can be accessed via https://www.mathworks.com/matlabcentral/fileexchange/51081-standardized-drought-analysis-toolbox-sdat (accessed on 17 August 2023) [33]. It calculates the SSI based on a non-parametric approach using the empirical Gringorten plotting position rather than fitting with parametric functions [31].

The empirical probability equation used in this study is as follows [31]:

$$p(x_i) = \frac{i - 0.44}{n + 0.12}, \ \ i \in (1, \ n) \tag{3}$$

where x_i is the streamflow series ranked from low to high, n is the total number of observations, and i denotes the ranking order.

The severity categories based on SSI values are presented in Table 3. Here we follow the categories used by the Global Integrated Drought Monitoring and Prediction System (GIDMaPS) of the University of California, Irvine [34].

Table 3. Categories of drought events based on SSI values.

SSI	−0.50 to −0.79	−0.80 to −1.29	−1.30 to −1.59	−1.60 to −1.99	−2.0 or less
Category	Abnormally dry	Moderate drought	Severe drought	Extreme drought	Exceptional drought

4. Results

The low flows identified by the three methods are compared in this section. The total event count, duration, and deficit volume patterns are presented for each approach.

4.1. Threshold Approaches

The streamflow series of the Bobenthal, Salmbacher Passage, and Maxau stations are studied using both variable- and fixed-threshold approaches. The total number and general characteristics of drought events identified by each analysis are shown in Tables 4 and 5. Since monthly resolution thresholds analyze the deficit based on a monthly scale, the deficit volume presented below is calculated by multiplying the difference between the monthly average streamflow value and the threshold with the number of the days of the corresponding month in order to compare it with the daily resolution thresholds.

Table 4. Summary of the VTD and VTM results.

Station		Total Events (Counts)	Average Duration	Max Deficit (m^3)	Min Deficit (m^3)	Avg Deficit (m^3)
Bobenthal (Lauter)	VTD	96	56.2 d	131.73	0.66	9.81
	VTM	47	3.8 m	170.07	0.88	23.97
Salmbacher Passage (Lauter)	VTD	130	35.8 d	110.59	0.56	8.67
	VTM	53	2.7 m	195.77	0.98	28.76
Maxau (Rhine)	VTD	146	35.7 d	41,429.96	220.68	2866.19
	VTM	75	2.4 m	49,563.14	416.35	10,467.23

Both VTM and FTM identify fewer drought events than VTD and FTD, respectively, due to their coarse temporal resolution. Sutanto et al. also found that VTD identified almost double the amount of drought events compared to VTM in their pan-European streamflow analysis [20]. As shown in Table 4, drought events defined by VTM are 2.1 times longer and have 1.4 times the maximum deficit volume of VTD. Moreover, concerning the fixed-threshold approaches in Table 5, FTM identifies an average drought duration that is

1.7 times longer with a maximum deficit volume that is 0.8 times that of FTD. However, at the monthly scale, both the variable and fixed thresholds produce average flow deficit volumes that are about 2.5 times higher than at the daily scale. Regarding the detection limit (i.e., minimum deficit volume), all methods were capable of detecting droughts with low deficits of similar scale.

Table 5. Summary of the FTD and FTM results.

Station		Total Events (Counts)	Average Duration	Max Deficit (m³)	Min Deficit (m³)	Avg Deficit (m³)
Bobenthal (Lauter)	FTD	72	84.1 d	131.26	0.70	15.20
	FTM	43	3.8 m	80.46	0.69	24.83
Salmbacher Passage (Lauter)	FTD	138	43.0 d	142.97	0.73	12.54
	FTM	49	3.2 m	141.74	0.72	29.90
Maxau (Rhine)	FTD	185	45.1 d	65,880.90	339.23	7255.28
	FTM	76	2.3 m	61,978.08	337.16	10,893.43

Both the monthly threshold and variable threshold of each approach extended over similar time periods even though the number of identified drought events were different. The gap between the events number was mainly caused by the shorter droughts which could only be detected via a daily resolution. Regarding VTD, the Rhine station at Maxau had 12% more low-flow events than the Lauter station at Salmbacher Passage but with the same relative low-flow duration and 52% more low-flow events than the Bobenthal station but of 36% shorter duration. For FTD, the Rhine station had 34% more low-flow occurrences than the Salmbacher station with again the same relative duration but 157% more low-flow events than the Bobenthal station and of 46% shorter low-flow duration time. As for the hydrograph behavior, the peak deficit volume was always concomitant between daily and monthly resolution for each approach and the rising and falling limbs followed similar trends. Please see the Supplementary Document for further information.

4.2. The Standardized Streamflow Index (SSI)

There is no actual climate station available within the Lauter catchment. Here, we present the average annual precipitation and temperature values provided by the Deutscher Wetterdienst of the Bad Bergzabern station which is closest to the three stations with long-term climate records. As shown in Figure 3, there are rising trends in both winter and summer temperatures.
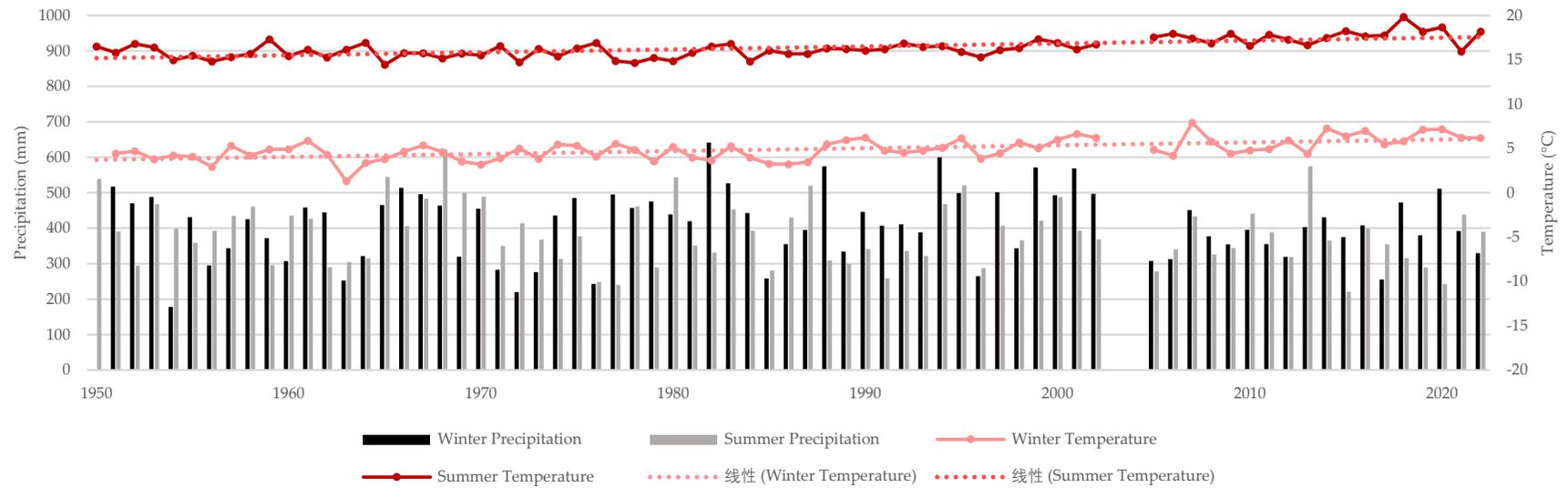
Figure 3. Precipitation and temperature time series of the Bad Bergzabern station between 1950 and 2022, with seasons separated into the preceding year's October to March as the winter/spring half-year and April to September as summer/fall half-year; the dotted lines show the temperature trends.

The Standardized Streamflow Index values for 1 month, 6 months and 12 months are calculated for each of the three stations. The percentage of each drought category for low flow identified by SSI-1, SSI-6, and SSI-12 of the study period are presented in Table 6. As the calculation time scale augmented from 1 month to 12 months, the Bobenthal and Salmbacher Passage stations on the Lauter River increasingly resembled the Maxau station on the Rhine River. All the stations revealed decreasing weighting for abnormal and moderate droughts and increasing weighting for extreme and exceptional droughts. We further plotted out the SSI results in Figure 4. Zalokar et al. suggested that an appropriate time scale should be chosen to better represent catchment drought characteristics [28]. We could not detect any significant percentage change (above 0.1%) in the extreme or exceptional drought class when increasing the accumulation period from 1 month to 12 months, either for the Rhine River or for the Lauter River. Hence, we decided to use SSI-12, which identified the drought severity more comprehensively with regard to the antecedent conditions for further comparisons with FTM and VTM.

Table 6. The percentage of each drought category for low flow based on the Standardized Streamflow Index (SSI) analysis in the Lauter and Rhine.

Station		Abnormal	Moderate	Severe	Extreme	Exceptional
Bobenthal (Lauter)	SSI-1	10.4%	11.1%	3.7%	4.4%	1.5%
	SSI-6	10.4%	11.8%	3.1%	4.5%	1.5%
	SSI-12	9.9%	12.0%	3.0%	4.5%	1.5%
Salmbacher Passage (Lauter)	SSI-1	9.8%	11.5%	4.9%	3.3%	1.6%
	SSI-6	9.2%	11.6%	5.0%	3.3%	1.7%
	SSI-12	8.5%	11.7%	5.0%	3.3%	1.7%
Maxau (Rhine)	SSI-1	11.0%	11.0%	4.1%	2.7%	2.7%
	SSI-6	10.4%	11.0%	4.1%	2.8%	2.8%
	SSI-12	9.8%	11.1%	4.2%	2.8%	2.8%

(**a**) Bobenthal (since 1956)
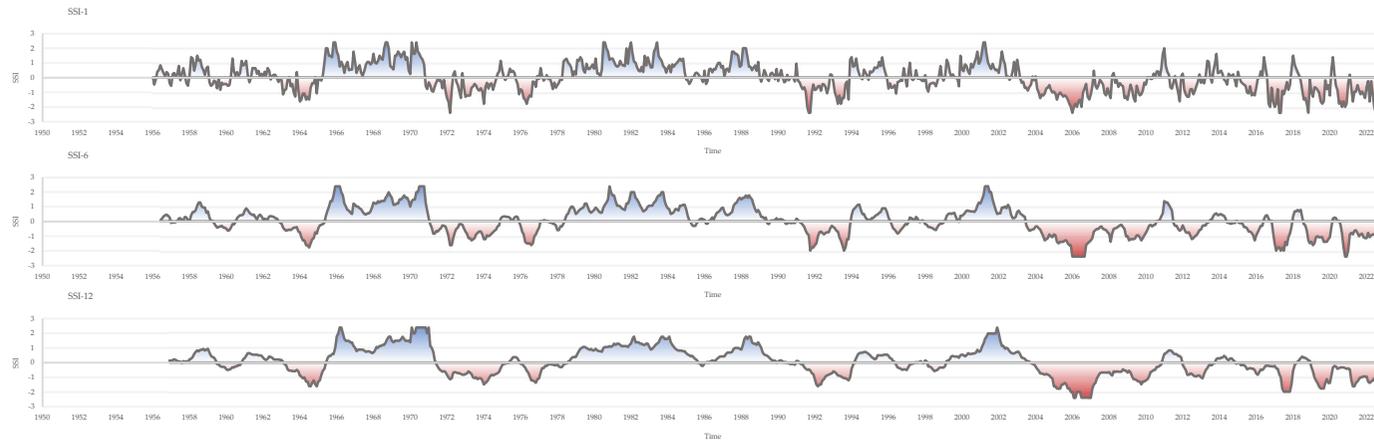
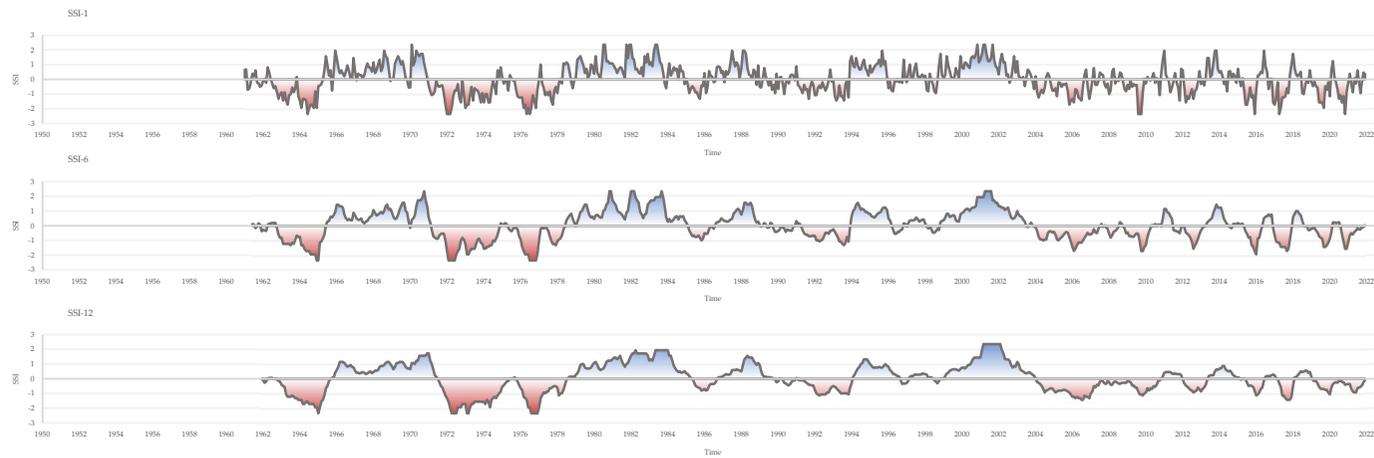(**b**) Salmbacher Passage (since 1961)

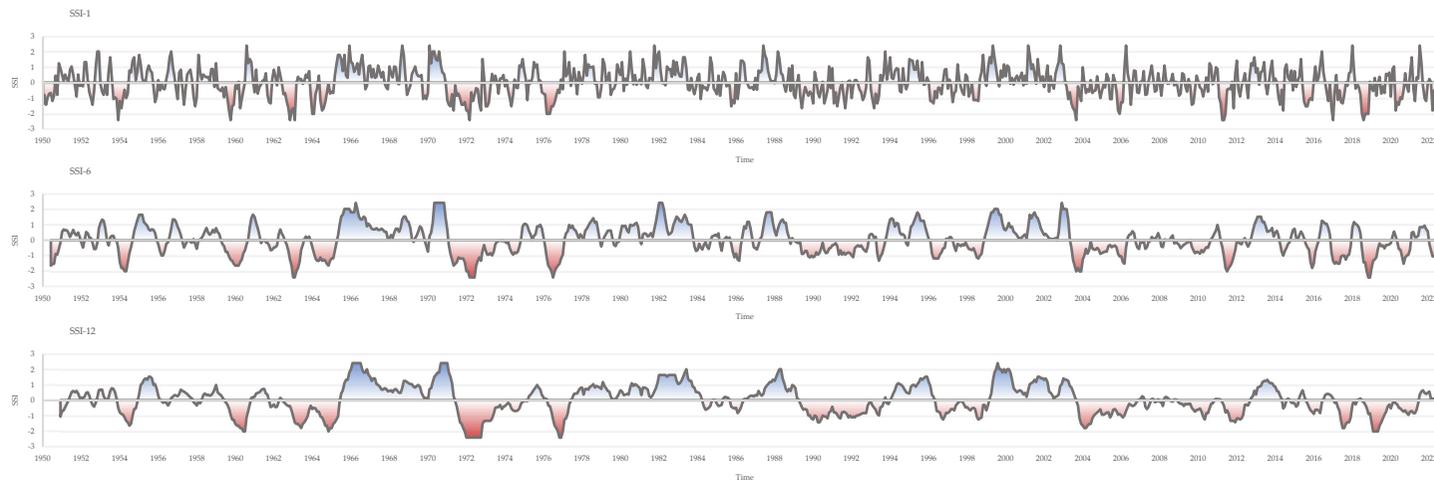**Figure 4.** *Cont.*

(**c**) Maxau (since 1950)

Figure 4. The Standardized Streamflow Index (SSI) between 1950 and 2022 for the Bobenthal and Salmbacher stations on the Lauter and Maxau on the Rhine River. Red designates low-flow period, and blue designates high-flow period.

It is noticeable that the Lauter River has a relatively higher percentage of 0.5% to 1.7% for the extreme class but around 1% less for the exceptional class compared with the Rhine. In Figure 4 we noticed that the difference occurred mainly within the time period from 1971 to 1978. The streamflow of the Lauter River was around 1 m³/s during this time period. We think this statistical bias is due to limitations in measuring capacity during very low flow under drought events of the last century.

The SSI-12 in Figure 4 recognized similar streamflow trends for the variable- and fixed-threshold methods. As for the time period 1950–1980, severe to exceptional droughts were observed in 1963–1964, 1971–1974, and the year 1976 for the Lauter River. The Rhine River showed seasonal fluctuations with the most significant drought period identified in the years 1954, 1960, 1963, and 1965. Nevertheless, the SSI-12 was relatively stable, with no significant drought signals from 1981 to 2000 and a notable downward trend for each station since the beginning of this century.

5. Discussion

The identification of low flow by the variable-threshold, fixed-threshold, and SSI methods are discussed according to the differences in approaches used and according to the variations caused by the characteristics of each station. The implications of the results with respect to past climate change and their current and future applicability and predictability are also discussed.

5.1. Differences amongst Drought Identification Methods

Low-flow events observed at daily resolution were mostly clustered in three different time periods: 1950–1980, 1981–2000, and 2001 to present. During the first period, low-flow events in the Lauter and Rhine were more severe and of much longer duration, followed by the second period with relatively fewer severe low-flow events of lower frequency. Since the beginning of this millennium, low-flow events seem to have become more erratic and scattered all over the year. Compared to the 1950–1980 period, the annual occurrence of low-flow events in the Rhine at Maxau has increased 1.6-fold since 2000, whereas the average deficit volume has decreased to about half its annual discharge. The SSI-12 showed an 20% increase in low-flow periods. The Lauter River showed similar trends. Rapidly onsetting "flash droughts" are rarely long-lived, since they are frequently interrupted by rather insignificant, spiky floods to form "drought–flood" cascading events. Climate change has thus introduced higher variations to streamflow both in small-scale catchments such as the Lauter and in large-scale catchments such as the Rhine. In their historical hydrological drought analysis of the Upper Rhine valley over the last 450 years until 2006 Pfister et al. also obtained a clear increase in low flow values (7-day annual mean) after the 1980s [35].

The FT, VT, and SSI approaches were all highly coherent in defining low-flow periods over time. However, individual variances still occurred amongst different indicators. As a daily indicator, the FTD systematically produced longer average duration and higher average flow deficit volumes than the VTD and extracted more accurate detection limits within our study area. It is noticeable that such a pattern is not universal. Study of snowmelt- and rainfall-driven catchments in both Canada and China appear to have both longer drought duration and higher severity when using VT than FT [10]. On the other hand, studies in America in minimally disturbed catchments report a longer duration with FT and higher deficit with VT [36]. We argue that the climate regime has a dominant influence on low-flow behavior for each index. Therefore, we recommend that a thorough comparison among different low-flow indices should be performed before giving recommendations for local water resource regulations.

We also noticed differences in the total event count and maximum deficit volume for FTD and VTD linked to the characteristics of each station. The variable-threshold approach is more robust in detecting low-flow signals for the Bobenthal station due to the buffering effect of the forest and sandstone geology of the upper Lauter catchment

(Wieslauter) on low flow. As such, both the variable- and fixed-threshold approaches attain nearly the same maximum flow deficit volumes. However, at Salmbacher Passage, the fixed-threshold approach is a better indicator of water scarcity reflecting human water abstraction from the town of Wissembourg and the surrounding irrigated agricultural area. As for Bobenthal, the two threshold methods produce very similar maximum flow deficit volumes but Salmbacher Passage had higher maximum flow deficit volumes identified by fixed thresholds than variable thresholds. Interestingly, low-flow characteristics of the Rhine at Maxau are very comparable to Salmbacher Passage, with similar high interannual low-flow variability in terms of duration and severity and a similar gap between the two threshold approaches. Overall, Rhine low flows are relatively shorter and attain less severe relative deficit volumes than at Bobenthal over the entire study period. Caution should be taken when applying the fixed- and variable-threshold methods in smaller catchments such as that of the Lauter, since they can produce very contrasting results even if the streamflow stations lie in geographic proximity and within the same climatic zone. It seems that human influences such as small dams with ponds and irrigation can significantly alter the natural hydrological regime thereby increasing streamflow variations and causing a gap between the fixed- and variable-threshold results.

For both rivers, most low-flow events begin in early winter around December (Figure 5). It is interesting to note that the months in which low flows most commonly develop depend on station location and threshold approach. Although low-flow starting dates are particularly discordant for the two stations on the Lauter there is strong concordance between the Upper Lauter (Wieslauter) and the Rhine station. For the Bobenthal station, low flows mostly begin in December. However, there is a larger spread in low-flow starting dates over the whole winter and spring season produced by the VT (i.e., from December to April). Salmbacher Passage shows a similar seasonal spread of low-flow initiation identified by VT, whilst the seasonally less sensitive FT produces opposite staring dates in the summer months around July. This is because FT applies only one single value for the whole year, making it difficult for FT to predict an early low-flow signal during a drought winter with a precipitation deficit. At the Rhine station, low-flow events also predominantly begin in December. However, as for the Lauter, there is a larger monthly spread from the variable-threshold approach. The month when low flow is least likely to begin in the Lauter is June at Bobenthal and April at Salmacher Passage, respectively; in the Rhine, low flow is least likely to begin in July.
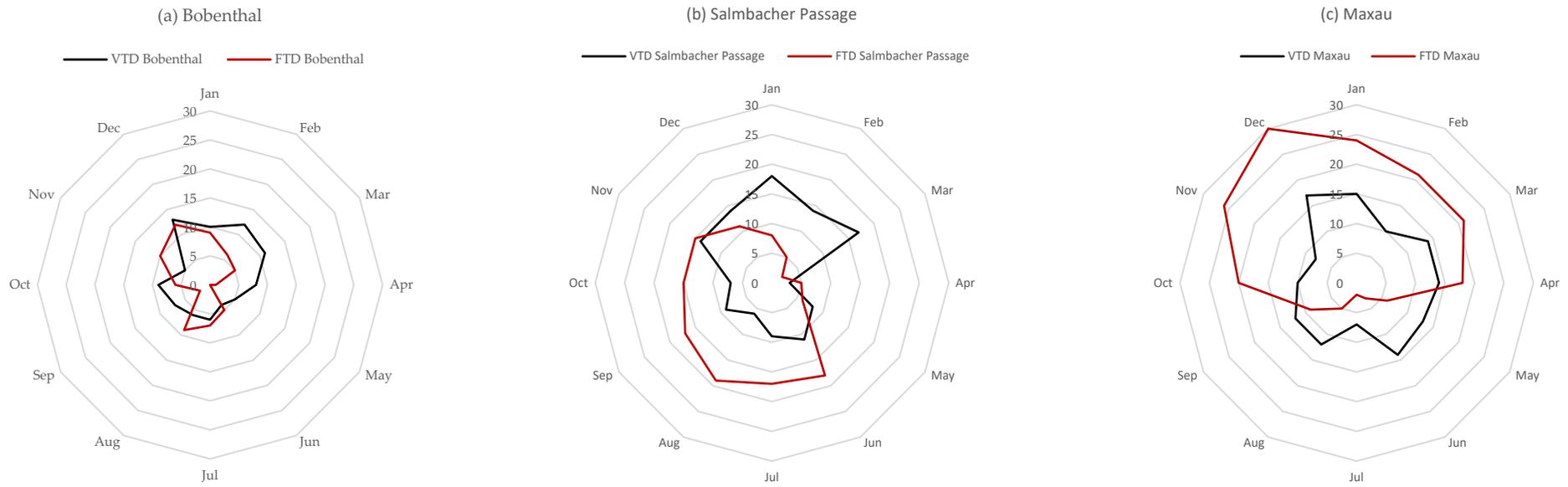
(a) Bobenthal

(b) Salmbacher Passage

(c) Maxau

Figure 5. Radar maps with the total count of low-flow starting dates for each event for each specific month in the Lauter and Rhine Rivers based on the variable daily threshold (VTD) and fixed daily threshold (FTD) over the time period from 1950 to 2022.
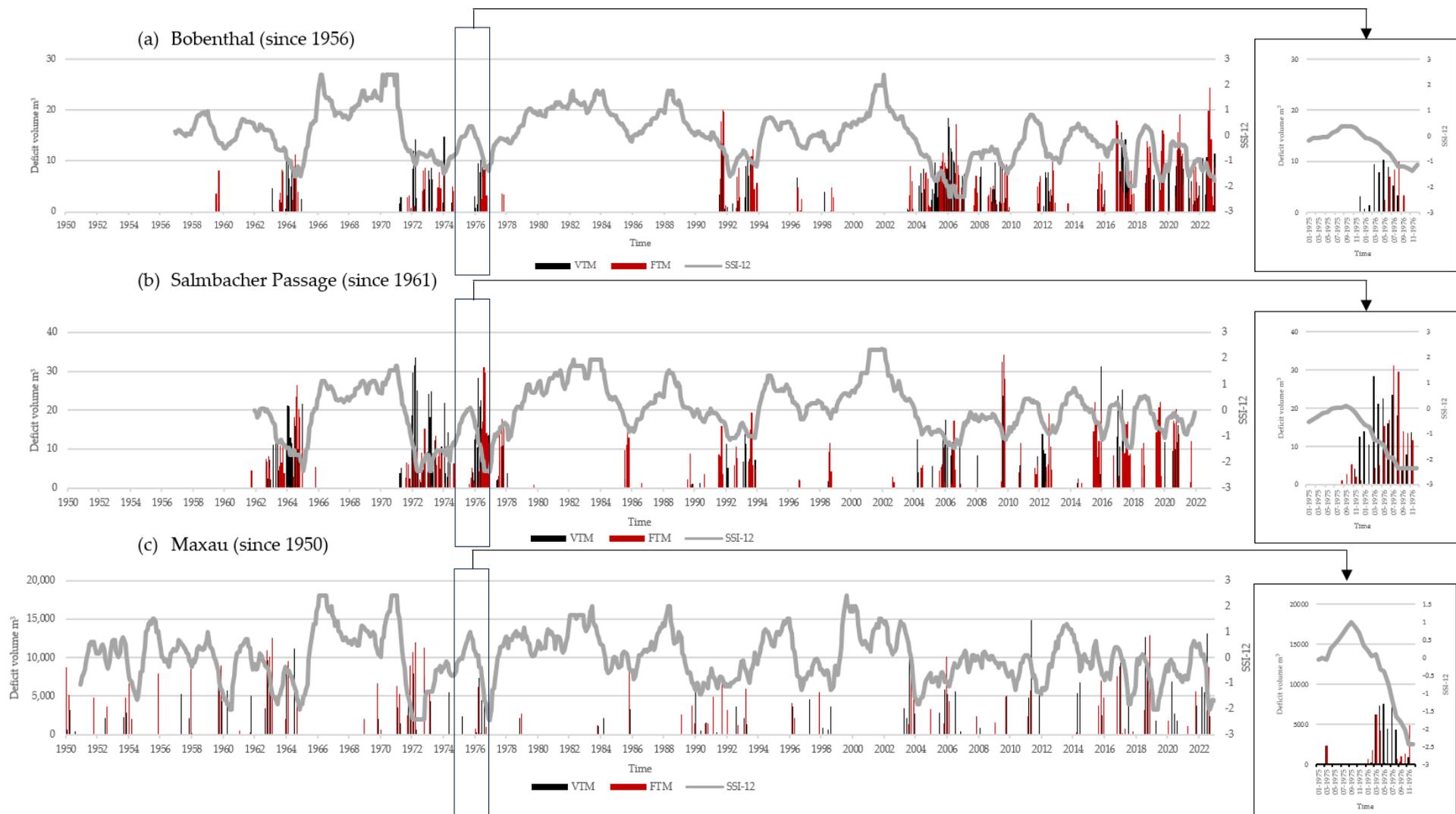
Figure 6. Comparison of variable monthly threshold (VTM), fixed monthly threshold (FTM), and Standardized Streamflow Index (SSI)-12 for each station along the Lauter River and Rhine River between 1950 and 2022.

It also seems that low-flow signals are more scattered since the beginning of this millennium due to more abrupt disturbances created by "flash droughts" and "drought–flood" cascading events, thus qualifying VT over FT (Figure 6). An increase in annual low-flow events, as shown in the downward trends of the SSI-12 index corresponds well with the deficit volumes identified by the threshold approaches for the Lauter as well as the Rhine in Figure 6. However, as SSI-12 calculates the index based on the cumulative streamflow of the previous 12 months, SSI-12 always reaches the lowest minimum value after the threshold method reaches the highest deficit volume peak. Its resolution is therefore far too coarse for water management purposes. Application of the SSI-12 index as the only indicator would be inappropriate for designing water resource management plans, as it incorrectly identifies and predicts the beginnings and ends of low flows. However, SSI-12 is efficient in categorizing the drought severity situation by including antecedent conditions, which is not possible when using the threshold approach. Hence, we suggest combining the SSI-12 index with the threshold identification methods for low-flow diagnosis, as threshold methods are very sensitive to streamflow anomalies, and the SSI-12 index delivers a comprehensive drought severity classification. For major drought events in the last century, it is noticeable that VTM can predict significant low-flow events during the previous winter/spring half-year from low-flow signals before the onset of major streamflow deficit. This was the case for the drought periods of 1963–1964, 1971–1972, and 1975–1976 at the Bobenthal station and 1971–1974 at the Salmbacher Passage station. However, there were no early low-flow signs from VTM at the Maxau station during this time period mostly because the Rhine River is less dynamic and has less streamflow variations than the Lauter River at this location.

Furthermore, we took an intensive look at the 1976 drought year in Figure 6. The drought period started at the Salmbacher Passage station in September 1975, followed by the Bobenthal station in December 1975, and was only picked up in January 1976 at the Maxau station on the Rhine River, which has a much larger, more complex, glaciated catchment. Studies have revealed that the 1976 drought was caused by high temperatures and amplified by excessive evapotranspiration, which lead to decreased subsurface storage [37,38]. The Salmbacher Passage station, located downstream of the Bobenthal station on the Rhine plain, picked up the low-flow signal from the fixed-threshold approach three months earlier. This is because Salmbacher Passage is more vulnerable to droughts and low flows as a result of anthropogenic influences such as water abstraction from irrigation and household consumption. In contrast, Bobenthal benefits from the drought-buffering role of its undulating, forested catchment and the sponge effect of its sandstone geology, possibly enhanced by the water-retention role of its multiple valley stream ponds. The mountain headwater characteristics thus gave it a lead into the winter before the onset of low flow.

We also argue that the fixed threshold reacts faster to direct climatic or artificial impacts such as water abstraction, whereas the variable threshold reacts more strongly to more complex signals issued from indirect factors such as decreasing subsurface flow. This is typical for small headwater catchments that are more sensitive to flow disturbances. Other research based on European catchments agrees that the VT approach is more flexible when dealing with anomalies in low-flow conditions [39,40]. However, in our two rivers the earlier warning ability of VT over FT was only true for identification low-flow clusters between 1958 and 1980. In the third period (after 2000) VT substantially lost its predictive ability over FT (Figure 6). Being more sensitive to flow abnormalities, VT reacts earlier than FT to low flows beginning in the winter/spring half-year, such as in March 2004 at both the Bobenthal station and the Salmbacher Passage station. However, FT starts around the same time as the VT for low flows in the summer season, such as August 2007, July 2008, July 2015, and June 2020 at the Bobenthal station and August 2005, July 2009, and June 2015 at Salmbacher Passage station. In contrast, the Maxau station did not follow this pattern, due to much more complex antecedent conditions and influences of a large alpine catchment as well as significant artificial influences by sluices and dams that dominate over the natural regime. For the Maxau station, drought events defined by FT were constantly interrupted

by high peak flow events in contrast to the VT approach. Therefore, even though the FT is useful for navigation purposes in terms of accurately differentiating high and low flows, the VT is more appropriate for accurately defining the beginning and end of an integral drought period in view of ecosystem services and water resource management.

5.2. Differences between the Lauter Tributary and the Rhine River

We analyzed several significant drought events to understand the differences between the Lauter and the Rhine River. Despite the Rhine catchment being a much larger catchment than that of the Lauter, this study shows that the network of low-flow monitoring stations on the Lauter are strong early indicators for the Maxau station on the Rhine. This can be very helpful for drought prediction and water management in the Rhine. Our hydrological analyses of all the main tributaries bordering the Rhine in Alsace (France) and Baden Württemberg (Germany) show that low-flow events have extremely similar behavior over the past 20 years. This is because droughts are large-scale, long-lasting phenomena that have a direct influence on the streams, whether draining the Vosges or the Black Forest [41]. Similarly, a study on the large-scale spatial coherence of European drought showed that the highest regional pairwise correlation of low-flow phenomena in Europe covered our study area between northeastern France and southwestern Germany [42].

For the drought period of 1962–1964, which was caused by an extremely cold winter and prolonged snow storage [35], drought events were also diagnosed at the Maxau station between September 1962 and February 1963, between December 1963 and February 1964, and the following summer between June 1964 and October 1964. The Salmbacher Passage station on the Lauter River showed similar behavior whereas the upstream Bobenthal station only generated low-flow signals from February 1963 onwards but lasting over the whole year of 1964. Low flow increased as indicated by the SSI-12 index of the Bobenthal station from March 1963 onwards, the Salmbacher Passage station from August 1962 onwards, and the Maxau station from July 1962 onwards. It appears that the hydrological regime at the Maxau station on the Rhine River was much more dominated by the snow and glacier melt from the Alps. Hence, the Lauter catchment, with a relatively low elevation, has less predictive capacity over the adjacent Rhine River for this drought type.

The situation is different for the 1970s, where prolonged dry spells [43] resulted in exceptional droughts in the Rhine and Lauter Rivers, but only extreme droughts at Bobenthal. The Bobenthal and Salmbacher Passage stations started revealing flow deficit starting in March 1971 and at Maxau starting in January 1971. However, during the following years until the next extreme drought year in 1976, the two stations on the Lauter River were constantly exposed to streamflow deficit in contrast to the Rhine River station that only generated some separate drought signals. For the 1976 drought year in the Lauter, the Salmbacher Passage station started experiencing flow deficit from August 1975 onwards followed by the Bobenthal station in December 1975, whereas the Rhine River station at Maxau only reacted at the beginning of 1976. Moreover, the low-flow event terminated in September 1976 for Bobenthal but only three months later in December 1976 for Salmbacher and the Rhine respectively. This was at a time when urban development was not yet very intensive upstream of Bobenthal and irrigation had not yet been introduced around Salmbacher Passage. It appears that small tributaries such as the Lauter River generate more reliable drought period indications than the Rhine River itself. The recovery or not of Rhine tributaries such as the Lauter from low-flow impacts can provide early warning for drought termination or potential drought beginning for the Rhine River.

Brunner et al. concluded that the rainfall-deficit drought type dominates more drought events over the lower elevation Alps region since 1994 [44]. The Bobenthal station, representing the most upstream flow station in the headwater catchment, showed the most significant decreasing trend in SSI-12 and increasing drought periods since the beginning of this century. As mentioned above, drought periods are now perturbated more frequently by high flow peaks caused by short floods thereby interrupting the continuity of low-flow events. Recently the Maxau station has developed a tendency towards separate low-flow

signals during dry years, usually one in the early spring and another one later in the same year, such as in April 2017 and June–July 2017, in April 2021 and October–November 2021, and in March 2022 and May–September 2022.

The 2018 hydrological drought had particularly disastrous impacts on the Rhine, bringing navigation to a temporarily halt. According to our analyses and in contrast to the previous period from 1980 to 2000, low flows started nearly simultaneously in July at all three stations following a spring and summer rainfall deficit [45]. Again, the Rhine at Maxau imitated the Lauter at Bobenthal well but experienced a less severe relative low-flow deficit. Regarding the year 2022, it is interesting to note that the characteristics of the 2022 low-flow event were different to the 1976 event. The Rhine River flow deficit between April and September 2022 was amplified by the lack in recharge during the 2021/2022 winter but started later and finished much earlier than in 1976. The Bobenthal station already signaled low flow as early as April 2021 which indicates inadequate winter water storage in the headwater catchment, primarily due to a lack of snow. Similarly, the Rhine at Maxau signaled low flow in April 2021. No data is available for Salmbacher passage for 2022.

Since the beginning of this century, the Rhine at Maxau is experiencing more frequent interruption of low-flow events by high flow peaks. More interestingly, the two stations on the tributary Lauter River are acting as a kind of early warning system for low-flow conditions in the Rhine. They can indicate the potential recurrence of low-flow events on the Rhine during flood-drought cascading events. Hence, observing the tributaries' streamflow behavior, especially during the early spring, helps in predicting the drought conditions of the Rhine River for the following half-year. This has major potential for hydrological drought risk assessment and for implementing different water level saving policies at the beginning of the year.

6. Conclusions

In this study, we studied the flow-rate time series of the Lauter River from 1956 until mid-2023 and compared it with the closest station on the Rhine River. We employed the fixed-threshold method, variable-threshold method, and Standardized Streamflow Index to identify low flows for two streamflow stations on the Lauter River, which are the Bobenthal station and the Salmbacher Passage station, and one on the Rhine River, the Maxau station, in order to evaluate the differences between these approaches and their applicability to both a small headwater catchment and a large-scale catchment. Drought events defined by the monthly variable threshold are 2.1 times longer and aggregate 1.4 times the maximum deficit volume of the daily variable threshold. FTM identifies an average drought duration that is 1.7 times longer with a maximum deficit volume that is 0.8 times that of FTD. However, at the monthly scale, both the variable and fixed thresholds produce average flow deficit volumes that are about 2.5 times higher than at the daily scale. In spite of these differences, they were all capable of identifying low flows for each station with good consistency. VTD had the ability of predicting low-flow events during the winter/spring half-year well before VTM detected the onset of major deficit volumes in the summer. However, such patterns no longer prevailed after the year 2000. Compared to the 1950–1980 period, the annual occurrence of low-flow events in the Rhine at Maxau since 2000 has increased 1.6-fold, whereas the average deficit volume has decreased to about half its annual discharge. The SSI-12 showed an 20% increase in low-flow periods. The Lauter River followed similar trends to the Rhine River. The FTD did not achieve such significant predictive ability over FTM. Since "flash droughts" and "flood–drought cascading events" are disturbing the flow rate time series due to climate change [46], VT is more robust than FT in defining the beginning and the end of low-flow periods. Furthermore, we found that the FT reacts faster to direct climate or artificial impacts such as irrigation or dams whereas VT reacts to indirect factors such as decreasing subsurface flow and higher evapotranspiration, especially for small headwater catchments with higher flow dynamic reactions to flow disturbances. The standardized streamflow and threshold approaches were consistent and an increase in low-flow events was evident in both the Lauter and Rhine Rivers since

2000. We suggest that local water resources managers should combine the 12-month SSI with the threshold approaches for better low-flow identification and severity evaluation. It is noteworthy that, as rainfall-deficit droughts are starting to dominate more low-flow events in this century, we find that abnormally low flow during the early spring time in Rhine tributaries such as the Lauter can help predict low-flow conditions of the Rhine River during the following summer and autumn. Water managers will need to adapt to more frequent, seasonally much earlier but shorter low-flow events on both the Rhine and tributaries such as the Lauter as a result of lacking precipitation storage (mainly snow) and higher temperatures. They will also need to adjust to the dwindling seasonal buffering role of low-mountain water towers for droughts and low flows since the beginning of this millennium. Despite differences in the scale of catchments, situations can occur (such as in 2018) where the beginning of low-flow events is no longer temporally offset in the Lauter tributary and Rhine but instead starts simultaneously. This means a lack of several months of buffering flow from headwater catchments during low flows further downstream. Hence, we suggest that further studies could focus on integrating more streamflow time series analysis from low-mountain Rhine tributaries into seasonal low-flow early warning systems for the Upper Rhine Valley.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16111584/s1, Figure S1: Sensitivity analysis of relative mean duration for different pooling-criterion combinations of t_i between 5 and 30 days and p_i between 0 and 0.3; Figure S2: Drought identification comparisons between variable daily threshold (VTD) and variable monthly threshold (VTM) for low flows in the Lauter and Rhine Rivers; Figure S3: Drought identification comparisons between the fixed daily threshold (FTD) and fixed monthly threshold (FTM) for low flows in the Lauter and Rhine Rivers. Refs. [26,47] is cited in Supplementary Materials.

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Data Availability Statement: All data used in the article are open-source data. The streamflow data for the Bobenthal station and the Salmbacher Passage station are available from the State Office for the Environment of Rheinland-Pfalz (https://wasserportal.rlp-umwelt.de/geoexplorer, accessed on 7 August 2023), and the streamflow data for the Maxau station are available from the GRDC portal (https://portal.grdc.bafg.de/applications/public.html?publicuser=PublicUser#dataDownload/Home, accessed on 7 August 2023).

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