Inventory of the low water conditions on the Rhine

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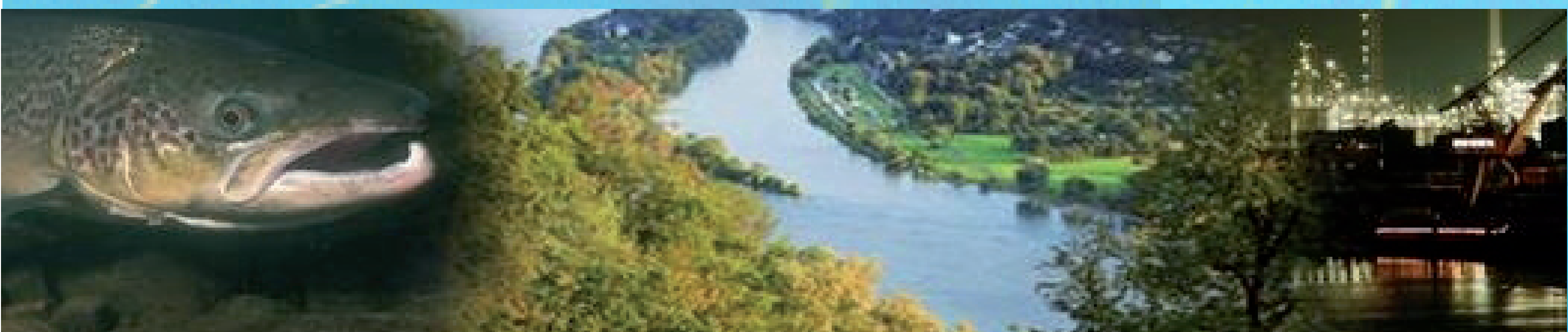

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Inventory of the low water conditions on the Rhine

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Report of the EG LW
"Inventory of the low water conditions on the Rhine"

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1. Summary

The low water event in the extreme summer of 2003 with ecological adverse effects on the Rhine as well as further subsequent more moderate events have pushed the low water problem into the public perception once again after a period with fewer low water events since the beginning of the 1980s. The effects of climate change can also change the genesis and extent of low water events. In the 15th Conference of Rhine Ministers in 2013, this topic was adopted and anchored in the ICPR Working Programme for 2016-2021.

To work out a common understanding of low water situations for the states adjacent to the Rhine, and in particular their cross-border effects, as well as to develop cooperation possibilities, the Expert Group Low Water was commissioned to take stock of and analyse existing knowledge on low water events in the Rhine area. The focus is on the low-water discharges on the Rhine, whose genesis and characteristics are naturally determined by the hydro-meteorological conditions in the catchment area.

What the various definitions of the term "Low Water" (or “low flows”) have in common is that the water level or discharge falls below a certain threshold. Accordingly, for this comparative inventory, discharges were analysed whose statistical low-water parameters are to be considered in relation to related discharge thresholds for a number of gauging stations along the Rhine. The most widely used characteristic was the NM7Q, the lowest arithmetic mean discharge of 7 consecutive days of a reference period (year), and corresponding parameters for longer periods. To arrive at comparable threshold values along the Rhine, these parameters were evaluated with extreme value statistics at 10 examination gauges from Diepoldsau above Lake Constance up to and including Lobith at the German-Dutch border and threshold values regarding their respective occurrence probability (T = 2, 5, ... up to 100-year) were derived. The low water event duration aspect was taken into account by analysing the number of contiguous days with discharges below these thresholds.

The quantitative proportions from different sub-basins of the Rhine are significant for the natural low-water discharge. The gauge-related measured value evaluations along the Rhine also illustrate the significance of the discharge proportion from the Alps and Alpine foothills, including in the low water range, which accounts for around half of the average low water discharge even in the Netherlands. In addition, the changing discharge regime with a winter minimum in the nival area (to Basle) and summer minimum in the pluvial area (below Worms) creates a certain resilience against extreme low water events for the entire Rhine.

The low water run-offs on the Rhine is influenced by abstractions and diversions of water as well as by the storage management. Significant water transfers take place from the Inn to the Rhine area (7.8 m³/s) and from the Danube to the Main/Rhine area (up to 16 m³/s). Abstractions from the Rhine area benefit the Ticino area at around 2 m³/s and the Rhône area at around 3 m³/s. Direct withdrawals from the Rhine can be quantified on the northern Upper Rhine with up to 1.5 m³/s for groundwater infiltration and about 5 m³/s for agricultural irrigation. As a result of the above measures, the Rhine is gaining with regard to total discharges. An even more significant positive influence on the low water discharges on the Rhine can be seen in the management of storage areas for energy generation in the Alps and Alpine foothills. More than 1.8 billion m³ of storage space are used there to retain accumulating water in the summer and to generate energy during the low water period that prevails on the Rhine in winter. The low water discharges of the Rhine in winter are thereby increased by an order of magnitude of up to 100 - 120 m³/s.

Low water has direct effects on water quality and ecology, and impacts caused by use relate to shipping, power generation, industry, agriculture, tourism and leisure, as well as infrastructure safety.

No serious long-lasting negative effects on the water quality of the Rhine have been found for the main stream of the Rhine during low water events. This is particularly attributable to the enormous efforts in wastewater treatment over the past decades. Ecological problems occur especially when there are summer low water events, combined with elevated water temperatures and the associated low oxygen levels (fish and mussels

dying in 2003). As part of the preparation of the report, there was coordination with the ICPR Working Groups "Ecology" (WG B) and "Water Quality/Emissions" (WG S).

Inland waterway transport and the persons and businesses that depend on it show a cross-border impact at low water levels, with associated negative economic consequences and supply bottlenecks for energy and raw materials. For the water supply in the Netherlands, salinisation of the surface water can occur at low water due to the ingress of seawater, and this can lead to the cessation of drinking water abstraction or a restriction of abstraction for the agricultural water supply. Energy production is affected, on the one hand, by reduced production at hydropower plants and, on the other hand, by restrictions in the abstraction of cooling water or in the discharge of waste heat. This can also lead to restrictions for industry and commerce. At low water, some instabilities may occur in peat dykes in the Netherlands.

According to the analysis of historical discharge series, low water levels on the Rhine were much more pronounced in the first half of the last century and occurred with lower discharges and longer shortfall periods than in the last 50 years. With regard to the low water discharges, a significantly increasing trend can be determined for the Rhine from Diepoldsau to Andernach for the entire period from 1901 to 2010. This trend is not homogeneous for the last approximately 100 years, but is based on a break point around the period of 1960-1970, which is mainly attributed to the influence of storage management in the Alpine region, which has caused a change in low-water discharge from 1960-1970. The increasing trend of annual precipitation in the 20th century for the Rhine catchment area may also be contributing to the observed trend. No significant trends can be detected for the low-water discharges for the period from 1961 to 2010. The current perception of low water events is influenced on the one hand by the long absence of significant low water events and on the other by increased vulnerability.

The low-water discharge developments due to climate change in existing discharge projections for the period 2021-2050 for the Rhine range from decreases of 10% to increases of 10% and show no clear development. For the remote future (2071-2100), the discharge projections for the hydrological summer half-year consistently show significant low water discharge reductions.

For a pessimistic scenario with low water decreases of 5 to 10% of the MNM7Q (long-term mean low water discharge on 7 consecutive days) for the period 2021-2050, there are greater decreases from 7 to 14% for 2 to 50-year low water discharges on an increasingly annual basis. The decrease in the discharge is accompanied by a significant extension of the low water duration.

In the future, low water events in the summer months on the Rhine could have increasingly negative ecological effects. With low discharges, water temperatures can increase more in summer. An example of this is the low water events in 2003 and 2006. According to research by the ICPR Expert Group STEMP, summer water temperatures on the Rhine are expected to rise by 1.5 °C in the near future and over 3 °C in the remote future. For the near future (2021-2050), this means, among other things, a doubling of the days with water temperatures above 25 °C (ecologically critical threshold) in the Rhine.

It makes sense to set up a low-water monitoring system for the Rhine for uniform monitoring of these phenomena across the entire river. Current events can be classified by direct comparison and possible changes in the low-water discharge can be determined.

Based on a detailed analysis of the historical discharge series, discharge-related threshold values for the classification of the low water situation into five characteristic states from "normal" to "extremely rare low water" were derived for the Rhine in coordination with the International Commissions for the Protection of the Moselle and the Saar (ICPMS). The suitability of this classification, which provides a differentiated classification of low water events, has been validated by applying it to historical discharge time series. Extreme events can be clearly distinguished from smaller events, with sufficient sensitivity to minor low water events.

The key message is that although the low water events on the Rhine have not worsened in the last 100 years, today they have a greater impact on numerous uses (shipping, industry, agriculture, energy production, etc.). The demand for water and the socio-economic influences could increase in the Rhine catchment area. In addition, low water events can have a negative impact on aquatic ecosystems, especially if they occur at the same time as higher water temperatures. Some climate projections forecast more frequent low water events in summer with increased water temperature in the future. All these points are reasons to continue monitoring developments on the Rhine.

2. Reason and problem

2.1 Reason and problem

At the 15th Conference of Rhine Ministers in 2013, the missions for the ICPR were formulated for the coming years. These missions have been prepared and specified in the ICPR work programme 2016-2021. The issue of low water was included in the topic of "Climate change and adaptation". It was noted in that regard that the topic of low water needs to be made more concrete. In the first step, the low water events are to be analysed in more detail. Both hydrological and qualitative aspects (temperature and chemistry) are relevant to low water.
The WG H (Floods) was asked to record and analyse in detail the hydrological aspects of low water events. The WG S and WG B are reviewing the qualitative aspects of low water.
To this end, the WG H has set up a new Expert Group Low Water (EG LW), which met for the first time on 17 January 2017.

Problem

Currently, the Rhine states do not have a consistent perception of low water events, even though (extreme) low water situations occur regularly. Also, there is no common understanding of the relevance of cross-border effects of low water or of the possibilities for cross-border cooperation in dealing with bottlenecks caused by low water.
The establishment of the EG LW serves as a prelude to this with the achievement of a common overview of low water in the Rhine.
The EG LW has the mission of taking stock of the existing knowledge about low water events in the entire Rhine catchment area, analysing it and monitoring the possible corresponding developments at the level of the Rhine catchment area. Possible effects of climate change are thereby taken into account.
It is also the task of the EG LW to actively share the resulting knowledge with other Working Groups (in particular S and B) in order to be able to assess/evaluate the impact of low water events on the ecological function and the use of water systems by humans.

2.2 Mandate of the Low Water Expert Group

The Expert Group Low Water (EG LW) is mandated to carry out the following tasks. This report documents the implementation of activities for the realisation of these tasks. At the same time, this report is one of the planned products developed by the EG LW in accordance with its mandate.

1. **Inventory of knowledge about low water in the Rhine IRBD**
    - Analysis of the low water situation by means of the gauge-related evaluation of measured data (long-term);
    - Analysis and description of selected extreme low water events;
    - Compilation of influences on and concerns caused by low water;
    - Reflections on the effects of climate change on low water through the use of the results of the EG KLIMA/ CHR-Rheinblick2050 and transfer of the change factors determined there;
    - Exchange of information on national low water monitoring, on aspects of low water management including cross-border aspects

2. **Establishment of low water monitoring (measuring network and monitoring parameters)**
3. **Exchange of information with the other Working Groups** WG S and WG B and, if applicable, further uses regarding the respective specific concern.
4. **Preparation of a contribution** (report) for WG H's reply to the mandate of the 2013 Conference of the Rhine Ministers (and in the run-up to the next Conference of the Rhine Ministers). **Preparation of a contribution** for the recommendation by WG H on the work results, the state of knowledge and on the issue of the relevance/necessity of an ICPR low water management plan

3. Existing investigations in the Rhine area, subcatchment areas and other river basins

Due to the importance of the Rhine as one of the largest rivers in Europe, studies on the discharge conditions are of great interest. A basic and comprehensive compilation of the discharge conditions on the Rhine and its main tributaries as well as the conditions in the Rhine catchment area was presented by way of an example in the so-called "Rhine monograph" ("Rheinmonographie")(CHR, 1978) with maps, texts and tables. This already contains information on the extremely low water year 1947 as well as "Reflections on the low water periods of 1959 and 1964" (Betrachtungen über die Niedrigwasserperioden von 1959 und 1964).

Buck et al. (1993) summarises the effects of human activity on the discharge events on the Rhine. This influence on the low water events is illustrated in particular by the development of dam expansion with a total storage volume above Basle of more than 1.8 billion cubic meters (moderation of discharge). An analysis of the discharge conditions on the Rhine and its tributaries for the entire 20th century was presented by Belz et al. (CHR, 2007). For the first time, the quantitative-hydrological developmental dynamic for the entire Rhine basin was analysed and documented over this kind of long uniform period. In addition to developments in the discharge regime and the medium and high-water conditions, developments in low water conditions in the 20th century were also examined. The summary of the results for low water describes this development and comes to a clear conclusion:

"The observed low water extremes have become more moderate during the 20th century in the Rhine area. This applies particularly to the Rhine itself and its large tributaries; there are stronger regional differentiations in the catchment areas of downstream, smaller tributaries. In light of the interrelationships described above, it is understandable that this moderation is taking place more intensively where the winter season represents the actual low water season, that is, in the southern, nival Rhine area. In contrast, in the pluvial low mountain regions and lowland regions, where the low water season is usually in late summer and autumn, the trend towards moderation is absent, as there is little change in precipitation in these months. Only other influences, as shown by the example of transfer gains on the Main, justify exceptions to this configuration. "(Belz et al., 2007)

The KLIWAS project investigated the effects of climate change on waterways and shipping in Germany (BMVBS, 2009). KLIWAS comes to the following conclusion*: "With regard to the low water extremes, this means a significant increase in discharge and thus moderation for the southern Rhine area, where the winter months are usually the time with the lowest water supply for surface waters. North of the Main, on the other hand, the months with the lowest water levels are in late summer and autumn - here there is an undirected, sometimes even slightly decreasing trend in the low water extremes. However, this slight intensification of the low-water extremes in the northern Rhine basin is so weak that it cannot be statistically substantiated as being significant"* (BMVBS, 2009).

In the project "Rheinblick 2050" (Görgen et al., 2010), a comprehensive ensemble of climate projections for the 21st century was used to model the future discharge conditions in the Rhine basin that are influenced by climate change. The summary comes to the following conclusion on the subject of low water*: "With respect to low flow we see no strong development in the near future; while most ensemble members show no clear* *tendency in summer (ranging from +/-10%), winter low flow is even projected to be alleviated (0% to +15%). For the remote future, the change signal is stronger in summer, with a tendency towards decreased low flow discharges (-25% to 0%), while for winter no clear signal is discernible (bandwidths are mainly from -5% to +20% depending on discharge diagnostic and gauging station)"* (Görgen et al. 2010).

In the projects "Abflussregime des Rheins" [Discharge regime of the Rhine] (Belz et al., 2007) and "Rheinblick2050" (Görgen et al., 2010) it became clear that there was a lack of reliable quantification of snow and glacier melt ratios in the total discharge of the Rhine. This gap was closed by the CHR project "Abflussanteile aus Schnee- und Gletscherschmelze im Rhein und seinen Zuflüssen vor dem Hintergrund des Klimawandels" [The snow and glacier melt components of the streamflow of the River Rhine and its tributaries considering the influence of climate change] (Stahl et al., 2016). The daily discharge portions attributable to snow and glacier melt for different gauges throughout the Rhine for the period 1901 - 2006 are analysed and presented. As a result, the extent of these effects can also be quantified for the low-water discharge.

In particular, the results from Görgen et al. (2010) were taken into account in a scenario study by the EG KLIMA of the ICPR for the discharge regime of the Rhine (ICPR, 2011).

On the basis of the air temperature and discharge developments determined in the scenario study for the discharge regime of the Rhine (ICPR, 2011), the ICPR (STEMP Expert Group) first published a report in 2014 on the estimation of the effects of climate change on the development of Rhine water temperatures in the near future (2021-2050) and the remote future (2071-2100) (ICPR, 2014). This report supplements the ICPR publications on the long-term development of the Rhine water temperature in the period 1978-2011 (ICPR, 2013a) and the possible effects of these changes on aquatic communities (ICPR, 2013b). The latter shows that in particularly warm summers with very low discharges, the water temperature can rise to such an extent that there can be negative effects on the aquatic ecosystem (ICPR, 2013b).

In addition, the ICPR has published the following reports, which show both effects and measures for past low water events: Report no. 142 "Wärmebelastung der Gewässer im Sommer 2003 Zusammenfassung der nationalen Situationsberichte" [Thermal load on the waterway in summer 2003 - summary of the national situation reports] (ICPR, 2004), Report no. 152 "Maßnahmen bezogen auf die Wärmebelastung des Rheins in extremen Hitze- und Trockenperioden: Überblick und Zusammenstellung der Länderberichte" [Measures related to the thermal load on the Rhine in periods of extreme heat and drought: overview and summary of the national reports] (ICPR, 2006) and Report no. 198 "Niedrigwasserperioden 2011 im Rheineinzugsgebiet" [Low water periods in the Rhine river basin in 2011] (ICPR, 2012).

In the German Working Group KLIWA (climate change and water management) low water conditions and developments were investigated for a variety of gauges in Baden-Württemberg, Bavaria and Rhineland-Palatinate (Working Group KLIWA, 2009). In a collaboration between the KLIWA partners and the state of Hesse, discharge projections with evaluations were also compiled for low water characteristic values for the Rhine (HYDRON, 2015).

In Belz (2005) and on the Undine information platform (www.undine.bafg.de) (BfG, 2016), descriptions of past low-water events in the Rhine basin are compiled.

For the Moselle region, a report on the inventory of low water problems was presented in the ICPMS (International Commissions for the Protection of the Moselle and the Saar) (ICPMS, 2014). In addition, the project FLOW MS 2009 to 2013 (ICPMS, 2009-2013) was dedicated to the topic "Floods and low water management in the Moselle and Saar catchment areas". Operational low water monitoring is currently being carried out by the ICPMS and an updated report on low water is expected to be available in 2018. In addition, there was coordination between the ICPR and the ICSMS as part of the present ICPR study.

A comprehensive compilation of fundamentals up to the low water management and measures in different sectors was compiled for Bavaria, which has a very large share of the Main catchment area (BY-LfU, 2016).

With the support of the Swiss Federal Office for the Environment (FOEN), the ICPR and the Central Commission for the Navigation of the Rhine (CCNR), i.e. the three "Rhine commissions", the CHR held the international symposium "Low flows in the Rhine catchment" on 20 and 21 September 2017 in Basel, with 70 participants. The focus was on the exchange between science and practice and dealing with hydro-climatic processes and parameters and the effects of low water. For instance, the first results from the ICPR and ICPMS Expert Groups on low water and information from the CCNR on the effects of low water on shipping were presented. In addition, examples of monitoring, management and moderating measures were shown.
It also became obvious at this symposium that although the low water events on the Rhine have not worsened in the last 100 years from a hydrological point of view, today they have a greater impact on numerous uses (shipping, industry, agriculture, energy production, etc.). It is assumed that the demand for water and the socio-economic influences are increasing in the Rhine catchment area. It is assumed that in the future there will be more frequent low water events in summer in conjunction with higher water temperatures. The results of the symposium served as input for the work of the three "Rhine Commissions" concerned. More information can be found at www.chr-khr.org (CHR, 2017) and www.iksr.org (under "Events").

From the above-mentioned projects and studies, there are extensive results and methodological approaches, which were also included in the present study.

Although most of the other European river commissions continue to prioritise the topic of "flood", the management plans according to WFD, annual reports and various documents or strategies on the impact of climate change or adaptation to it also mention the issue of low water (or drought). Noteworthy examples include the International Commission for the Protection of the Danube River (ICPDR) with an article on the dry period in 2003 and a detailed report on influences and effects of the 2015 drought on uses (based on a survey of states) or the International Meuse Commission (IMC) with a thematic workshop in November 2003 with the participation of 60 representatives from public authorities, the private sector, stakeholders and universities (result: Introduction of an automatic and permanent information notification system in the event of low water situations). The International Commission for the Protection of the Elbe (ICPER) is devoting the 18th Magdeburg Water Conservation Seminar to the issue of "Low Water and Demands on Water Utilisation in the Elbe River Basin" (18/10 - 19/10/2018 in Prague). In addition, the Hydrology Expert Group of the ICPE recently published a report on the low water situation in 2015 in the catchment area of the Elbe (ICPER, 2017).

At a European level, the issue of water scarcity and drought, which is also relevant with regard to low water, is mainly covered by the Water Framework Directive (WFD) and its requirements for achieving a good water status (surface water and groundwater), including water abstraction. These requirements should be included in the management plans to be set up in accordance with the WFD and related programmes of measures. In 2007 the EU published the communication "Addressing the challenges of water scarcity and droughts in the European Union" (EU Commission, 2007). The "Drought Management Plan Report" (EU Commission, 2008) describes detailed drought management approaches. Here, among other things, compulsory components of a drought management are mentioned: 1) a drought early warning system, 2) drought indicators and limit values for various drought stages, 3) measures to be taken in the various drought stages to achieve specific objectives.
A strategy (EU Commission, 2012), a network of experts on this topic (EU Commission, 2008) and the European Drought Observatory of the Joint Research Centre (JRC) of the EU (JRC, 2017, Cammaleri, 2017) were set up. The European Environment Agency (EEA, 2009) and various research projects (DROUGHT-R & SPI, 2015) are addressing this topic. The European Drought Impact Inventory is an inventory of drought and drought effects across Europe. It also contains information on past low-water events in the Rhine catchment area (see also Section 6.3 and Appendix 2) (DROUGHT-R & SPI, 2015; Kohn, 2017). Some interesting technical reports or guidelines, such as the Drought Management Plan (EU Commission, 2008) and the document "River Basin Management in Climate Change", which also includes information on low water (EU Commission, 2009), have been prepared and published in the context of the Common Implementation Strategy (CIS) to support the implementation of the WFD in the member states.

On a global scale, among others, the Manual on Low-Flow Estimation and Prediction (WMO, 2009) and the Integrated Drought Management Program (IDMP) (WMO - GWP, 2014), which provide valuable information on low water estimation and analysis and integrated drought management, are also worthy of mention. In this context, in 2013, the UN launched the initiative “Capacity development to support national drought management policies” (UN, 2013; BY-LfU, 2016). In December 2017, der UN-ECE “International Workshop on Water Scarcity: Taking action in transboundary basins and reducing health impacts” took place (UN-ECE, 2017). The preliminary results of the EG LW were presented on this occasion.

4. Terminology, definitions and procedures

Low water levels in rivers are the result of overlapping hydrological and meteorological events. The decisive factor for the development of a low water level is a long dry period associated with declining groundwater discharge from the catchment area. The causes of low water are mainly due to below-average or a complete lack of precipitation or a high retention of precipitation in the form of snow and ice.

The German DIN 4049 standard designates "low water" as a "condition in a body of surface water, where the water level or the flow has reached or fallen below a certain value (threshold value)".

This definition allows for differing views of the low water and can lead to very different assessments of an event, depending on whether the water level or the discharge is the variable of interest and depending on where a particular type of use is affected in a certain location. The impact is associated with a "threshold value", which either corresponds to a hydrological classification, or below which a use is either increasingly impaired (e.g. shipping), or must be immediately stopped in terms of a limit value (e.g. water drainage, water abstraction). Significant vulnerabilities with low water on the Rhine have been queried in the states and compiled into an inventory. Significant anthropogenic influences on discharge and low water discharge events were also researched and assigned to the respective sections of the Rhine.

Low water levels can be described by different parameters and their probability of occurrence (see Chapter 5). The occurrence of low water levels or discharges is a first obvious feature of low water, and it is expressed even more strongly as the event continues. These parameters can be determined for different reference periods (e.g. summer season) or measurement series and compared with long-term averages or threshold values.

Consequently, for the present comparative study of low water conditions on the Rhine, discharges were examined, and these are then compared with statistical hydrological low water characteristic values as threshold values. Thus, the extent and development of the occurrence of low water over the entire length of the Rhine can be represented. The discharge threshold values and low water parameters used can basically be converted into water levels via the water level discharge relationship at the gauge. These water levels, however, only apply to the gauge cross section and would have to be transferred to the respective location for the classification of local impairments.

To define low water classes (as threshold values) for monitoring, the available time series were limited following a homogeneity analysis to a 50-year reference period, which is meaningful for the current situation. The approach followed is explained in Chapter 5. In Chapter 7, the low water classes defined were used to retrospectively analyse and illustrate the occurrence of low water in the historical time series.

5. Data Bases and Methods

5.1 Measuring point selection and hydrological data basis

The study in the EG LW focuses on the description and analysis of the low water conditions along the Rhine, taking into account the influences from the catchment areas of the tributaries. For the individual sections of the Rhine between which hydrological changes can then occur due to larger tributaries, the following reference gauges have been determined, whose values are determined by the upstream catchment area and are significant up to the next gauge with the exception of the Diepoldsau gauge (see Fig. 1):

Diepoldsau gauge on the Alpine Rhine upstream of Lake Constance

Rekingen gauge on the Upper Rhine downstream of Lake Constance and the inflow of the Thur

Basle gauge on the Upper Rhine downstream of the inflow of the Aare

Maxau gauge on the Upper Rhine with the inflows from the Black Forest and Vosges

Worms gauge on the Upper Rhine after the inflow of the Neckar

Mainz gauge on the Upper Rhine after the inflow of the Main

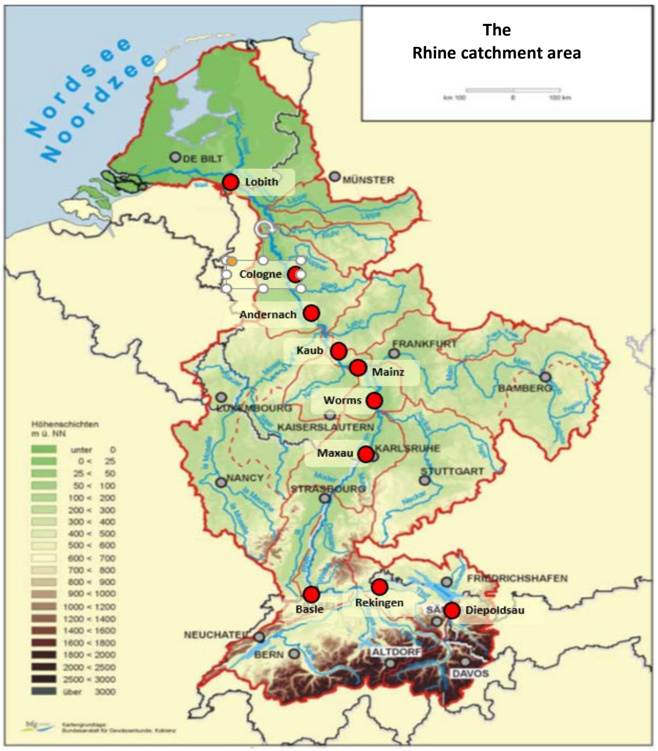
Kaub gauge on the Middle Rhine after the inflow of the Nahe

Andernach gauge on the Middle Rhine after the inflow of the Lahn and Moselle

Cologne gauge on the Lower Rhine after the inflows of the Ahr and Sieg

Lobith gauge on the Lower Rhine after the inflows of the Wupper, Erft, Ruhr and Lippe to the German-Dutch border. Downstream from Lobith the water in the Netherlands is distributed over 3 arms of the Rhine.

These reference gauges are hydrological gauges (gauges with discharge analysis) for which long-term discharge time series (measured discharges or discharges calculated on the basis of the water level) are available. (see fig. 1). Since daily average discharges are usually examined for low-water investigations and these represent a sufficiently high temporal resolution due to the catchment area sizes of the Rhine gauges, a database was compiled of daily average discharges from 1900 to 2015, as far as data were available. Data are available only from 1919 onwards for the Diepoldsau gauge and only from 1931 onwards for the Mainz gauge.



Definition of the investigation gauges

Low water discharge at Rhine gauges:

(1961 -2010)

Lobith	1095 m³/s
Cologne	1028 m³/s
Andernach	998 m³/s
Kaub	851 m³/s
Mainz	850 m³/s
Worms	720 m³/s
Maxau	645 m³/s
Basel	527 m³/s
Rekingen	238 m³/s
Diepoldsau	92 m³/s

Figure 1: Location of the examination gauges on the Rhine including long-term average low-flow discharge on 7 consecutive days (MNM7Q) (changed according to Federal Institute of Hydrology [Bundesanstalt für Gewässerkunde - BfG])

5.2 Low water parameters

The extent of a low water event is comprehensively characterised on the one hand by a low discharge and on the other hand by the length of the duration of the low discharges by means of a discharge hydrograph. Statistical analyses and comparative studies require parameters derived from the discharge hydrographs that describe the low water. Based on the daily average discharges in respective reference periods, the smallest daily average discharge from a period to be considered (1901 to present) (**NNQ**), the lowest daily average discharge from a reference period (**NQ**) or the mean lowest daily average discharge from a number of years (**MNQ**) is used. To limit disturbing effects in the analysis due to influenced individual daily average values or such values afflicted by measurement errors, parameters from several consecutive days are determined. For example, a common value is the lowest arithmetic mean of 7 consecutive days (**NM7Q**) in a reference period (e.g. year). The **MNM7Q** for a long homogeneous period was used as the threshold value was in this analysis (see Figure 1 and Chapter 5.3).

The duration of a low water event is determined by the number of days on which a threshold value Q_S (to be determined) is fallen short of. This threshold value may be dictated by local use or defined for comparative studies by statistical hydrological parameters. For the low water duration parameter, the longest uninterrupted duration of falling short of a threshold value within a time period (**MaxD**) is distinguished from the sum of all durations of falling short of a threshold value within the time period (**SumD**) (DVWK, 1983).

A more complex low water parameter is defined as the discharge deficit (DVWK, 1983). This is understood to be the maximum discharge deficiency between a threshold value Qs and the discharge hydrograph within a time interval (**MaxV** [m^3]) or the sum of all discharge deficiencies between a threshold value and a discharge hydrograph (**SumV** [m^3]).

The "Water Year" from 1 April to 31 March of the following year was used as the reference period for the low water characteristic values, so as not to interrupt the low water events occurring in late autumn or winter and, if applicable, not to take their values into account for two consecutive years when deriving annual series.

With regard to a local impact, low water parameters can also be determined on the basis of water level values instead of discharges, but then they are not comparable with other reference gauges (on rivers).

5.3 Evaluation and analysis methods

The study of low-water conditions was based on classic statistical methods or methods of low-water analysis published in regulations (DVWK, 1983; DVWK 1992). The statistical analyses and the preceding series and serialisation of the characteristic values were carried out with the HyStat programme of the Institute of Applied Water Management and Geoinformatics [Institut für angewandte Wasserwirtschaft und Geoinformatik (IAWG)].

After plausibility checking and if necessary correction of the collated data from all gauge time series, **yearly series** of the low-water characteristic values NMxQ (x = 1, 3, 7, 21, 60) were determined. For this purpose the smallest mean low water discharge of x consecutive days is filtered out for each year. The arithmetic average of the annual characteristic values then results in the low water characteristic values MNMxQ (MNQ, MNM3Q, MNM7Q, MNM21Q and MNM60Q) for the different low water lengths at each gauge (e.g. "**long-term mean low water discharge** on 7 consecutive days" MNM7Q).

With the series of NMxQ values, **jump analyses** were performed to see if there were any changes in the behaviour of the values at any given time in the series. In the Bernier and Pettit methods that were used, a time at which the statistical character of a time series changes is sought. The determined breakpoint divides a time series into two time series sections with significantly different behaviours. Based on the results of the jump analysis and the graphical representation of the time characteristic of the characteristic values, a reference period for the current state (1961-2010) was derived from the total period under investigation (1901-2015).

For the study of the **low water duration**, the series of daily average discharges were used to form series of absolute sums of the days per year and maximum contiguous event days per year, which fall short of a threshold value Q_S. The MNM7Q parameter and the NM7Q values of different probabilities of occurrence of the respective gauge were selected as a threshold value, so that all Rhine gauges can be directly compared with one another with regard to the duration of the low water event.

By means of **trend analyses**, time series were examined for the presence of increasing or decreasing trends in low-flow discharge behaviour. The time series were checked with regard to the significance of a linear trend through the adaptation of a trend line by minimizing the least squares error of the residuals. The significance test (error probability of 5%) was carried out with the (non-parametric) Mann-Kendall test and the t-test of the slope coefficients of the straight line.

To classify the extent of low-water discharges and low-water durations (low-water time spans) in terms of their **probability of occurrence**, the data were subjected to an extreme-value statistical analysis. For the reference period (1961 - 2010), the values of the annual series of low-water characteristic values were adjusted to a theoretical probability distribution, from which the corresponding quantiles for a T-annual event were output (T = 2, 5, 10, 20, 50, 100 years). A **classic probability analysis** was carried out for the low-water parameters NMxQ, for which there is a value for each year. Since individual annual values that don't fall below the threshold value occur for the low-water durations and the value zero occurs for these years, these series cannot be adjusted with the usual hydrological distribution functions. Therefore, the **indirect method** according to the German Association of Water Management and Land Development (DVWK - Deutscher Verband für Wasserwirtschaft und Kulturbau e.V.) (DVWK, 1992) was used. For this purpose, the respective shortfall duration in the individual years is determined for a whole spectrum of threshold values. Thus, for each shortfall duration, a sample of the associated threshold Q_S whose elements are greater than zero can be obtained. After the adjustment of a distribution function, threshold values can initially be determined as a function of the return period T and the shortfall duration D. From this, the magnitude of the shortfall duration D which is of interest as a function of the threshold value Q_S and the return period T can then be determined as an inverse function.

6. Inventory

6.1 Hydrological conditions in the Rhine area

The discharge regime describes the overall behaviour of river discharges with regard to the annual average over many years as well as the characteristic developments of extreme flood and low water situations (Belz et al., 2007). Different discharge regimes overlap one another in the Rhine catchment area (see Fig. 2).

The southern alpine area (Basle gauge) is characterised by the interplay of winter snow cover and summer snowmelt and by relatively high summer precipitation **("snow regime" or nival regime)**. Consequently, **low water events occur mainly in winter** and flood events mainly in summer.

Typical of the waters that drain the low mountain area (Neckar, Main, Nahe, Lahn, Moselle, etc. Trier gauge) is a **"rain regime" (or pluvial regime)**. This is shown by a dominance of winter flood and **summer low water.**

The overlapping of the two regimes results in an **increasingly even distribution of the discharge over the year** downstream of the Rhine **("combined regime", Cologne gauge).**

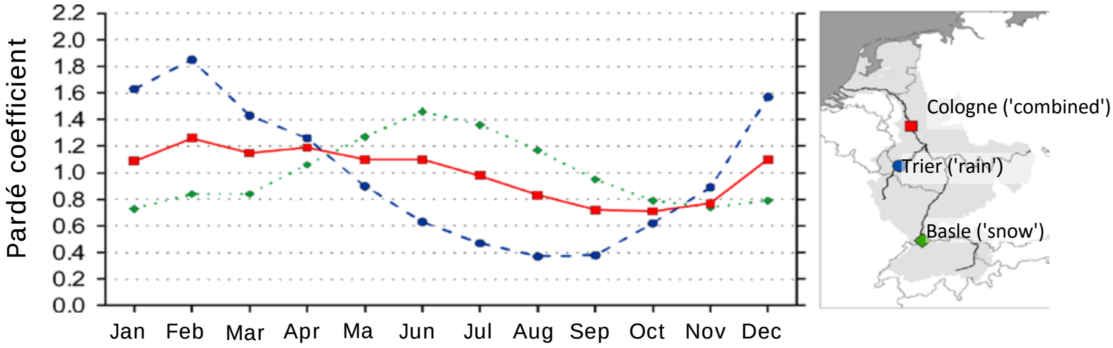


Figure 2: Typical discharge regime in the Rhine catchment area according to Pardé[1]; reference period 1961-1990 (ICPR, 2011)

The quantitative proportions from different sub-basins of the Rhine are significant for the low-water events (see also 7.1). For example, the long-term average low-water discharges from the Alpine and Alpine foothills regions measured at the Basle gauge still provide almost three-quarters of the low-water discharges after the confluence of the Neckar at the Worms gauge. After the confluence of the Main, the low-water characteristic values at the Mainz gauge are still dominated by about two-thirds of the Basle gauge, while at least about half of the low-water discharge at the Lobith gauge is attributable to the Basle gauge. The base load of the mean low-water discharges is thus provided by the Alpine and Alpine foothills regions (in particular by the local discharge regime and the effect of the Alpine marginal lakes). Due to their inflow, the large tributaries increase the low water characteristic values on average by 12% (Neckar) to 18% (Main and Moselle). Thus, pronounced low-water situations occur in the catchment areas with a pluvial regime in the case of decreasing discharges in the Alpine/Alpine foothills region from September/October and dry winters (or very cold winters with predominant precipitation retention in the snow cover).

The variable components from the snow and glacier melt have a non-negligible influence on summer low water events on the Rhine. In addition to the significant portions of the discharge attributable to snow melt, glacial meltwater plays a considerable role in supporting low-water phases on the Central and Lower Rhine during extreme late summer low water phases (Stahl et al., 2016). These portions of glacial ice melt accounted for up to one-third of the discharge in Basle and one-fifth of the discharge in Lobith for maximum daily contributions during the event in 2003. In average conditions, however, the influence of glacier melt in Lobith is low (<2%).

6.2 Inventory of the influence of the discharge conditions (abstractions, water discharges, diversions, water retention and time-delayed water release)

Anthropogenic influences on low water are difficult to distinguish from the natural variations in hydrological parameters. In general, low water changes can be said to occur directly as a result of storage management, abstractions and diversions of water, or can be indirectly caused by changes in use in the catchment area (LAWA, 2007; Belz et al., 2007). This chapter provides an overview of anthropogenic impacts, based on a survey among states as well as reports on past low water episodes and literature reviews (see Figure 3). The present study focuses on direct influences and does not consider the indirect influences (land use, forestry, agriculture, special uses such as mining, etc.) which are difficult to quantify.
Figure 3 shows a schematic view of the main abstractions and diversions of water on the Rhine and in the catchment area (source: Information from the states, ICPR (internal), 2017).

[1]Pardé coefficient = ratio of multi-year monthly discharge to multi-year annual discharge.

Storage management

Storage management, which displays seasonal redistribution and balancing dynamics with water storage during the period of excess water and depletion of storage in the demand period, is a significant anthropogenic factor and contributes significantly to reducing discharge variability despite increasing variability in precipitation. This is particularly the case upstream of Basle with the development of dam expansion (more than 1.8 billion m³ total storage volume) at the beginning of the last century up to the 1960s (see Fig. 3). Outside the Alpine region, storage management is characterised by considerably less uniform storage management objectives and is becoming less significant as an influencing factor for the Rhine. In addition to these effects, reservoirs always mean extensive artificial water surfaces with high evaporation and, in comparison with the former situation, damming of artificial lakes and sewer construction or river damming can also lead to major groundwater recharge (LAWA, 2007; Belz et al. 2007). The storage volumes (i.e. storage space or water retention capacity) of the reservoirs in the Rhine catchment are listed in Table 1. The current control in the Alpine area of the Rhine catchment area is leading to a temporal discharge shift, with the result that in the otherwise rather low-discharge winter season, the discharges and in particular the low water discharges have increased by approx. 120 m³/s (Weingartner, 2017).

Table 1: Storage volumes of the reservoirs in the catchment area of the Rhine (modified according to Wildenhahn & Klaholz, 1996 in Belz et al., 2007)

Rhine section or tributary	**Volumes [millions of m³]**	**Sum of the volumes [millions of m³]**
Anterior Rhine	253.14	253.14
Posterior Rhine	289.36	542.50
Tamina	38.50	581.00
Ill (A)	183.40	764.40
Bregenzerach	8.40	772.80
Lake Constance	1.40	774.20
Thur	0.60	774.80
High Rhine (CH)	7.26	782.06
Aare	496.95	1279.01
Reuss	153.19	1432.20
Limmat	314.86	1747.06
High Rhine (D)	112.85	1859.91
Upper Rhine	27.63	1887.54
Ill (F)	24.29	1911.83
Neckar	37.99	1949.82
Main *(incl. storage system of the Danube-Main transition: since 2000. + 64 million m³)*	180.00	2129.82
Nahe	14.05	2143.87
Lahn	6.63	2150.5
Moselle (F)	103.58	2254.08
Moselle (D; without Sauer)	50.53	2304.61
Sauer (Moselle tributary)	71.40	2376.01
Wied	4.45	2380.46
Ahr	0.73	2381.19
Sieg	123.10	2504.29
Wupper	140.43	2644.72
Erft	51.00	2695.72
Ruhr	496.06	3191.78
Lippe	50.01	3241.79

Abstractions and diversions of water

The anthropogenic measures directly affecting the discharge include direct withdrawal, abstraction and return of used water. This primarily includes the use of water for drinking water, irrigation needs or the cooling of thermal power plants. In addition, by transferring water to other catchment areas, water can be withdrawn from its original area. Such large-scale water transfers exist, for example, on the Neckar (drinking water transfer from Lake Constance) and on the Main (particularly the transfer from the Danube area since the mid-1990s on the Danube-Main-transfer system including the Rhine-Main-Danube Canal for discharge support/ low-water elevation and particularly the Regnitz, which also benefits the Main) (Belz et al., 2007).

The schematic diagram in Figure 3 shows the significant abstractions and diversions of wateron the Rhine and in the catchment area (source: Information from the states, ICPR (internal), 2017/2018). Approximately 2 m³/s are lost to the catchment area through transfers into the area of the Ticino and about 3 m³/s from the Aare area to the Rhône area. By contrast, the Rhine area gains almost 8 m³/s due to transfers from the Inn area. The abstraction from Lake Constance (Lake Constance remote water supply) is predominantly returned to the Rhine after the confluence of the Neckar with the wastewater quantities. Ad hoc and temporary abstractions of up to 6.3 m³/s are used in the northern Upper Rhine plain for irrigation and groundwater infiltration. Up to 15 m³/s from the Danube area (water from Altmühl and Danube, stored floods of the Altmühl) are supplied to the Rhine via the river Main, which serves for the discharge support[2] or low water elevation of the Rednitz, the Regnitz and the Main (see Fig. 4). Furthermore, up to 0.9 m³/s of additional water in the Lech estuary is pumped into the Main catchment area for drinking water. Downstream from Mainz to Lobith there are no significant abstractions and/or diversions of water. The Rhine delta begins downstream of Lobith. The river divides quickly into three arms. On the Kop van Pannerden the Rhine divides into the Waal and the Pannerden Canal. After a few kilometres, the Pannerden Canal passes into the Dutch Lower Rhine, and at Arnhem the IJssel branches off from this river. The Dutch Lower Rhine and the Waal finally flow into the North Sea. The IJssel flows into the IJsselmeer. Excess water from the IJsselmeer is channelled through sluices into the Wadden Sea.

All of the above-mentioned water flows, in particular the abstraction for irrigation and the water transfer from the Danube to the Rhine, do not occur at the same time and evenly, but it can be seen from the compilation that the balance for the Rhine is positive overall. This positive balance still needs to be supplemented by the quantifiably much more significant support of winter low-flow discharge through the storage management in the Alpine region (see above).

[2] Comment: The Danube-Main transfer occurs not only at low water periods, but - with variable discharges - throughout the year. The purpose of the transfer is, among others, to counter possible disadvantages for the economic development in Franconia (sufficient provision of water, thus support for the water quality).

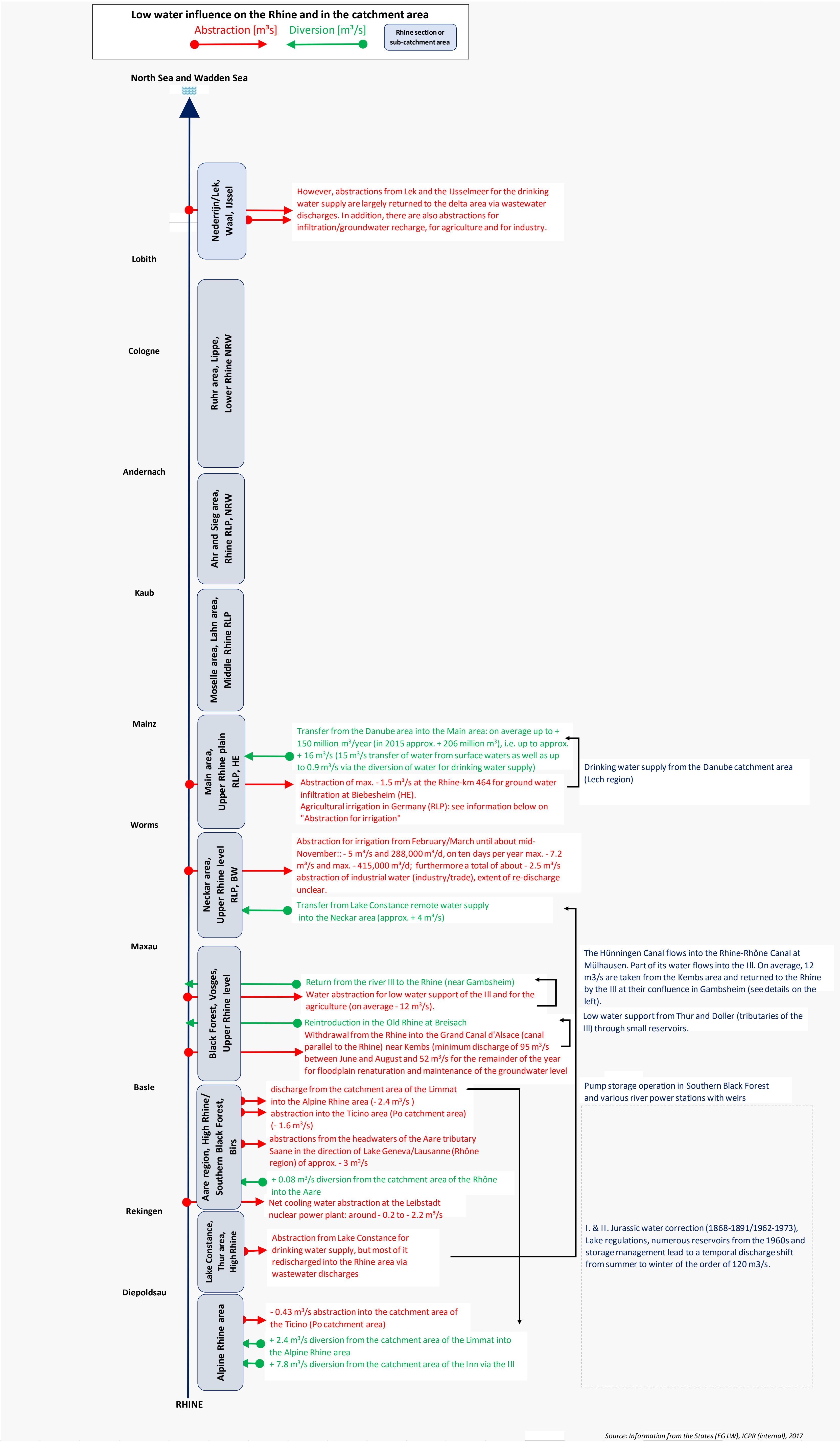


Figure 3: Significant abstractions and diversions of water on the Rhine and in the catchment area

Figure 4: Danube-Main transfer system (StMUV, 2011)

6.3 Inventory of the effects of low water on the Rhine

Like floods, low water levels and discharges are natural events that are unavoidable. If low water is accompanied by a strong warming of the waters, it may cause negative ecosystem impacts due to the reduced oxygen transport (low discharge combined with lower oxygen concentration due to temperature increases).
Low discharges or water levels can severely restrict navigation on the Rhine and the power of hydroelectric power stations. The effects of low water can be differentiated as follows:

- Effects on water quality and ecology
- Usage-related effects

Figure 5 shows a summary of different uses which may be qualitatively or quantitatively influenced or impaired by low water.

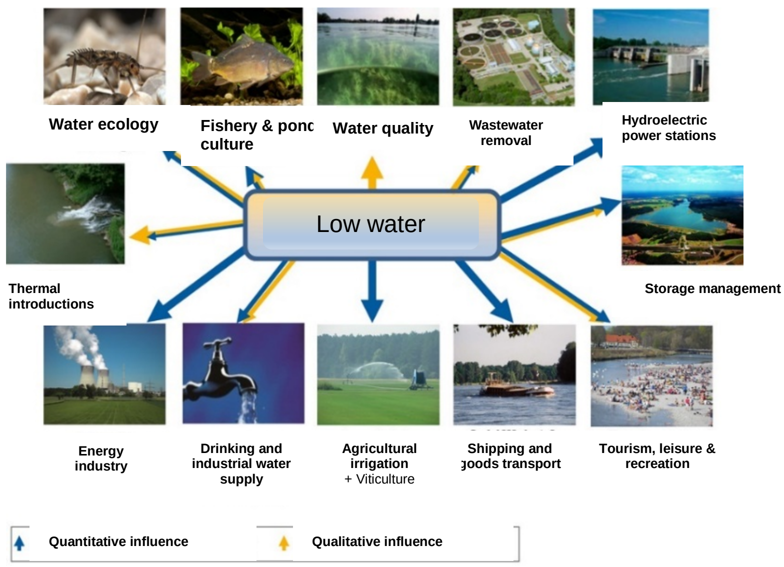


Figure 5: Simplified interactions between low water and water uses (KLIWA Working Group, 2017)

Although the vulnerabilities may differ regionally and seasonally, the ICPR has identified a number of low water impacts (source: Information provided by the states, ICPR (internal), 2017), some of which was also recorded in the information on past low-water events (in particular in 2003 and 2011) (ICPR, 2004, 2006, 2012). The summary from the European Drought Impact Inventory (EDII) of low water impacts in 2003 and 2011 in the Rhine catchment area reflects the information on both events provided by the states as part of the ICPR (extent, effects, vulnerabilities and impacts...) (Kohn, 2017) (see Appendix 1). Among other things, it is noted that during the 2003 event the effects were more pronounced and far-reaching (also in the catchment area) than in 2011, where they were limited to the Rhine (see Appendix 1).

In particular, the agreement on the abstraction of water from Lake Constance for the supply of drinking water and the general consequences of the Rhine discharge for downstream riparian zones, as well as shipping, are relevant on a cross-border/transboundary basis for the Rhine as an international corridor.

6.3.1 Impact on water quality and ecology

Water quality

Various aquatic ecological aspects are relevant for low water in summer. Temperature is an important parameter for water quality: It is decisive for the speed of all chemical and biochemical processes, it influences the solubility of substances and it plays an important role for the chemical-physical balance in water as well as for self-purification processes (ICPR, 2013, 2015).
As the water temperature increases, the oxygen solubility decreases. At the same time, the oxygen demand for chemical and biological processes increases. These two opposing effects can lead to crises during periods of low water.
With lower discharge, the concentrations of (purified) wastewater-borne substances from point sources (biodegradable substances, nutrients and pollutants, as well as salts and pathogens) increase due to the lower dilution. In times of meteorological drought or when precipitation is stored in the solid state, on the other hand, the lack of surface run-offs is expressed in smaller diffuse discharges. No **serious** long-lasting negative effects on the water quality of the Rhine have been found for the main flow after low water events. In general, the impact of substances has been significantly reduced by the rigorous expansion of wastewater treatment in municipalities and industry in recent decades. Critical pollutant or oxygen concentrations were generally not reached. This basically positive balance was also supported, e.g. in 2003, by the fact that, due to the lack of precipitation, neither diffuse surface discharges (erosion and run-off among others) nor inputs from combined waste water plants occurred. In 2003, at least on the Upper Rhine, warming and intense sunlight led to a mass development of algae, the photosynthesis activity of which resulted in oxygen oversaturation and conspicuous lime excretion (biogenic decalcification) - this in addition to effects such as increased concentration caused by lack of dilution.
As a result of the reduced flow velocities, **weir-regulated tributaries** heat up to a greater extent, so that the residual loads from wastewater discharges can lead to strained oxygen ratios. The areas directly downstream of wastewater discharges are primarily at risk. This became apparent in 2003 when, for example, local fish mortality occurred (see below).
During long-lasting low water periods there is a greater risk of salty seawater penetrating from the groundwater into the surface water and of the polders in the west of the Netherlands experiencing subsidence. Salinisation can also be a serious threat to water quality and ecology.

Ecology

Low water, which is perceived by humans as a sensitive disturbance and sometimes as a worrying event, occurs for the most part naturally throughout the year, and is characteristic and important for the ecosystem of river waters. Many species have developed specific strategies for survival and adaptation to it. Nevertheless, less mobile species of small upper reaches can be damaged by dehydration (e.g. river mussel or pearl oyster populations). In the Rhine, ecologically valuable groyne fields and flat areas beyond the fairway can dry out at low tide or the estuarine areas of tributaries can be decoupled. This leads to restrictions in the accessibility of important habitat structures (banks that are shaded or protect against flows) or the ascent of migratory fish species in the tributaries.
However, the water temperature should be seen as having a more relevant ecological impact. In this regard, the reaction possibilities are severely limited. Temperature is one of the most important environmental factors for animals and plants, as it controls reproduction, growth, development and migration among other things. A prolonged or even permanent increase in water temperature has a particular effect on poikilothermal organisms such as fish and macroinvertebrates, which cannot regulate their body temperature themselves, but constantly adapt to their environment (ICPR, 2013, 2015, 2017). At high temperatures they have an increased energy and oxygen demand with simultaneously decreasing O_2 supply in the water. Their metabolism can be so strongly increased that the animals no longer find enough food and begin to consume their fat reserves to provide their bodies with energy. This leads to stress and increased susceptibility to diseases.
Due to increased water temperatures in conjunction with habitat limitations, in 2003 in particular fish and shellfish deaths were reported (the dying of Asian clams that had migrated from the Upper Rhine to North Rhine-Westphalia was observed).
In Switzerland in 2003 there was a mass extinction of the grayling in the Upper Rhine and in Lower Lake Constance. Numerous fishes were resettled from smaller rivers. In Switzerland and Germany eels died to a greater extent in the Rhine (red eel pest). In France, in 2003, despite local fish deaths, no widespread negative effects on fish fauna were noted. In the Netherlands, there was very strong growth of algae (including blue-green algae) and aquatic plants (growth of weeds) as well as botulism (in waterfowl) in the waters. In recent years, a significant change in the communities through immigrant neobiota is increasingly being observed in the Rhine and its tributaries due to anthropogenic use. Higher water temperatures (especially in winter) may facilitate settlement in some species or provide a competitive advantage that may increase the size of the corresponding population. It can be assumed that the increases in these species usually cause a worsening of the ecological status according to the WFD.

However, due to the improved water quality and the resilience of the flora and fauna, there were no massive and permanent ecological effects or damage in the whole of the Rhine basin during past low water events.

6.3.2 Effects on use

The economic damages of the restrictions of use associated with low water events are in part difficult to quantify. Depending on their duration, spatial extent and regional circumstances, however, negative effects on the usage functions and considerable economic damage can be triggered (LAWA, 2007). The Rhine catchment area is used intensively and many stakeholders and functions are affected by pronounced low water, including water supply, shipping, power generation, industry, agriculture, recreation and security.

Water supply

Locally, drought periods can cause consumption restrictions and supply bottlenecks in the drinking water supply. This is particularly the case where the water supply is mainly from rivers, or superficial and/or sensitive groundwater resources. In some areas, depending on the nature of the low water situation, there may be temporary restrictions on the abstraction of surface and groundwater. Restrictions apply among others to the irrigation of gardens and parks as well as in agriculture and the abstractions and discharges of certain power plants and industrial plants. In the Netherlands, salinisation of surface water occurs due to the ingress of seawater, which can lead to cessation of drinking water abstraction or abstraction for the agricultural water supply. The freshwater discharge of the water body usually acts as a natural barrier against the ingress of saltwater. During low water periods the amount of fresh water is not always enough to prevent this ingress of salt water, so the salt water penetrates farther east and inland. Vulnerable uses such as drinking water abstraction may thereby come under pressure (Beijk, 2017).

Shipping

Shipping (inland navigation on the Rhine and its tributaries) can be considered as one of the main cross-border uses during low water periods. It suffers from severe restrictions at low water levels in free-flowing rivers, for example, due to reduced depths and narrowing of the fairways. To a lesser extent, this also affects the dammed tributaries and canals, which may, for example, make it impossible to fully secure the operation of locks with extremely low discharges. As a result, inland waterway transport is not able to carry as much cargo, which in turn leads to several negative economic consequences. For example, the total transport volume of inland waterway transport declines and there are shifts between the different modes of transport (the market share of shipping decreases as a result of the competitive disadvantage). The costs for shipping companies also increase if the fleet can no longer be used optimally (especially the larger ships). Thus, a significant strength of inland waterway transport - the economic advantage of large cargo capacities - is largely negated during low water periods.

In addition to cargo shipping, the operation of passenger ships (see also under "Tourism, leisure, recreation") and ferries may be affected, as they may no longer be able to reach their berths due to the low water level.

Power generation

Due to the low discharge, reduced power generation at river water power plants is inevitable. Since heat discharge(from cooling and service water) into the bodies of water are subject to restrictions, production in power plants (nuclear, coal-fired plants, etc.) must be partially restricted. Special permits temporarily allow a higher discharge temperature and thus cause higher mixing temperatures in the body of water than in normal operation.

Industry

Low water can also have consequences for manufacturing and commerce, which can lead to significant economic damage.
In the case of prolonged periods of low water, bottlenecks in supplies, such as coal, liquid petroleum products (e.g. heating oil and motor fuels), ores and agricultural raw materials may occur as a result of limited shipping (see under "Shipping").

Agriculture

Low rainfall and severe evaporation - caused by high temperatures - can have a negative impact on agriculture. In 2003, for example, there were regional restrictions or bans on water abstraction from smaller bodies of water, which led to isolated conflicts between public authorities and farmers.
In addition to significant production and yield losses in crop production (e.g. cultivation of animal feeds, cereals, vegetables) favourable conditions for viticulture (quality of wines at a reduced amount) may also occur.
In 2011, the salinisation of surface water in the western Netherlands (high chloride levels due to seawater intrusion) threatened to result in lower crop yields and, as a countermeasure, the level of water in the polders had to be bolstered.

Tourism, leisure, recreation

In the areas of tourism, leisure and recreation there are both negative and positive effects of periods of drought and low water. Ecological consequences for fish stocks (see Chapter 6.3.1) affect the yields of sport and recreational anglers as well as professional fisheries. In addition, in individual cases, tourism can also limit storage management. For

example, the Altmühl transition in Bavaria (see Fig. 4) can only be operated as long as there is still enough water in Altmühl, Brombach and Rothsee for tourism purposes.
The restrictions mentioned in the shipping section apply to the operation of private boats and passenger ships. On the other hand, it can also lead to a (local) increase in tourism when a low water period is associated with warm weather. In 2003 the excursion traffic on the High Rhine/Lower Lake Constance was limited, but there were altogether more passengers due to the nice weather. In Germany long-haul passenger ships could not be used in phases, whereas short-haul passenger shipping recorded an increase in passenger numbers. Dry rivers and dams can also have an attractive effect on people ("low-water tourism", LAWA, 2007). However, the quality of bathing water, in particular of smaller bodies of water, can be impaired by high concentrations of pollutants and the development of blue-green algae (cyanobacteria) and locally pose a health risk to the population (bathing and other recreational activities on the water).

Security (in particular of infrastructures and (flood protection) installations)

Especially in the Netherlands, the instability of (peat) dykes (flood defences) is a problem at low water levels. There are peat dykes on a total of 3500 km in the Netherlands, especially in Utrecht's Hollandse Veenweidegebied, North Holland, Friesland and Groningen. In August 2003, for example, the peat dikes sank in two places, and water flowed into low-lying polders (this led to up to 40 cm of water in the apartments near Wilnis).
To forestall subsidence and salinisation in the Netherlands, the water level in the polders had to be maintained in 2011 as well.
In Germany, due to the low water, a few WWII bombs came to the surface on the Rhine in 2011 and they were salvaged and defused.

6.4 National low water management

The information in this chapter is based on a survey of the states of the Rhine catchment area as well as reports on past events (ICPR (internal), 2017). Different measures and tool boxes are available in the states. Sustainable low water management encompasses both precautionary and operational measures (see Fig. 6) (BY-LfU, 2016; Wahliss, 2017). The aim of low water precaution concepts and measures is to minimise the development and effects of low water in advance and in the long term. Operational low-water management targets short-term measures that can be taken in acute low-water situations. Essentially, there are 4 areas to consider: Analysis of past and future low water events, assessment of their impacts on water uses, preparedness for/protection against future events, measures and dealing with a concrete low water event.

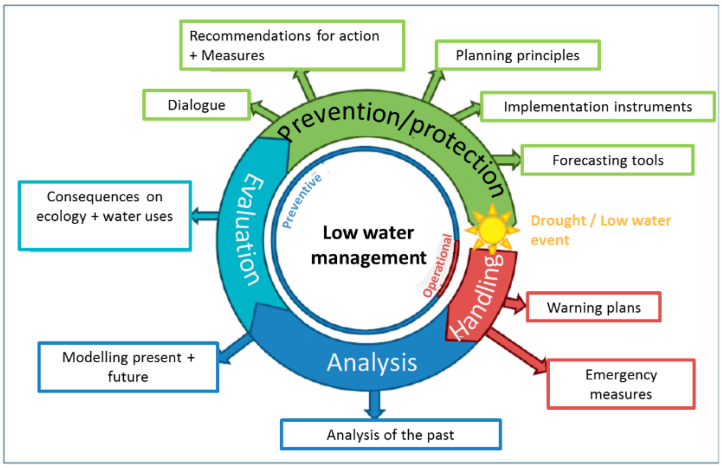


Figure 6: Cycle of low water management and related fields of action (BY-LfU, 2016; Wahliss, 2017)

6.4.1 Monitoring, forecasting, information and warning

Low water management requires a comprehensive information base. It starts with monitoring data and ranges from information and warning services for assessing the current situation to forecasts of further developments.

Monitoring, models and forecasting: The regional and national low water monitoring basically takes place via a network of gauging stations, at which the water level is measured and is then converted into a discharge value. The two hydrological parameters of water level and discharge are recorded with a time resolution of 5 minutes (Switzerland), 10 minutes (Netherlands) or up to 15 minutes (Germany, Luxembourg). Depending on the measuring site, water temperature and water quality are measured with different time resolutions as non-hydrological parameters.

A majority of states also publish at least one water level forecast daily for flood-relevant gauges, even outside flood periods, which also automatically includes low-water situations (see details in the box below). Water balance models produce discharge forecasts for the body of water - and in Germany partly also water temperature forecasts.
There are different models in Switzerland. In Germany the BfG uses LARSIM in RLP, BW and HE as well as WAVOS. On the Main, BY uses SOBEK instead of LARSIM. Flood models are used for some of the centres in France, and weather and water balance models in Luxembourg and the Netherlands. In the Netherlands, forecasts are generated and published daily, and there is a weekly report on significant low water events.

For low groundwater levels, there are only conceptual methods and no operational modelling. For the monitoring in Bavaria (Low Water Information Service [Niedrigwasserinformationsdienst - NID], see details below), a distinction is made between shallow and deep measuring points. The shallow measuring points also indicate short-term fluctuations and give indications of the water supply to streams and rivers in dry periods. The deep measuring points tend to show long-term fluctuations.

At the EU level, the European Drought Observatory (EDO) is worthy of note here (Cammalleri/JRC, 2017). The EDO web pages contain information relevant to drought, such as maps of indicators derived from various data sources (e.g. precipitation measurements, satellite measurements and modelled soil moisture). Various tools allow the analysis of the information and "Drought News" gives an overview of the situation if there are impending droughts.

Although long-term forecasts or prognoses would be relevant for different uses (e.g. shipping), they still pose a major challenge. In the Rhine catchment area, such projects are still in a test phase and are limited from a technical point of view. Low water management requires longer forecast periods than floods. The topic was discussed by scientists and users during the joint CHR symposium (CHR, 2017). Interesting contributions were presented, such as a statistical approach to the monthly and seasonal forecast of Rhine (low) water levels based on hydrological, atmospheric and oceanic data (applied by the BfG to develop monthly to seasonal forecast products for German waterways) (Ionita-Scholz, 2017). Furthermore, the Hydrological Ensemble Prediction System (HEPS), which has been in operation since 2015 and which carries out monthly ensemble low water forecasts, was presented. In Switzerland, the conditions for long-term forecasts are difficult due to the topography and small catchment areas, so it has been noted here that "forecasts that go beyond 32 days are closer to gambling" (Zappa et al., 2017).

Warning messages and low water reports (also for raising awareness and prevention):

In Germany, this task is carried out on a federal state-specific basis. Examples are the Bavarian "low water information service" - for early responses by the water industry and available to the public - as well as the Main Ecological Alarm Plan [Ökologische Alarmplan Main (AMÖ)], to provide warning in low water situations in the short term and to prevent harmful consequences for the water ecology as far as possible (BY-LfU, 2016, Government of Lower Franconia, 2012; Wahliss, 2017).
As a rule, there are focuses on past (pronounced) events in annual water-related reports (BfG, federal states).

In Luxembourg, alerts are published solely through press releases and national event reports. There are no warning levels there, but there are recommendations for action according to experts.

In France, alarm and warning thresholds are set for the Grand Est region (Rhine-Meuse catchment area) for the classification of the hydrological situation. If necessary, prefectoral decrees are passed that restrict or suspend water use. The authorities regularly publish reports that reflect the reaching of various threshold values. In addition, at the national French level, there is a website for the public that summarises all applicable restrictions or suspensions (Propluvia).

In Switzerland, a national warning is still in development, but the Hydrological Bulletins, published twice a week, deal with possible low water situations. In addition, low water information is published via cantonal websites and www.drought.ch.

In the Netherlands, reporting and warning are done by the Landelijke Coördinatiecommissie Waterverdeling (National Coordinating Commission for Water Distribution, LCW) and there are national and regional drought reports as well as daily water level reports for the shipping industry.

Low water forecast and reports in the different states (source: Inventory and information of the flood forecasting centres on the Rhine; amended according to ICPR, 2016 (internal)):

- In Switzerland, discharge forecasts are published on the website of the FOEN (see here) and special drought forecasts on a specific page www.drought.ch (Information platform for the early detection of drought in Switzerland).

- France occasionally uses low water forecasting models. During the period of impending low water (normally from May to September), the DREAL Grand Est monitors the hydrological situation of the bodies of water on a weekly basis. If a minimum discharge threshold is exceeded, the DREAL Grand Est sends situation reports to different stakeholders. In addition, EDF operates its own low water forecasts to ensure asset safety, meet environmental standards, improve water resource management, and optimise power plant production (Puygrenier and Antheaume, 2017).
- Germany:
  - BfG / Wasserschifffahrtsverwaltung [Federal Waterways and Shipping Administration] (WSF): for the Rhine downstream from Worms: daily forecast of water levels during low water. Based on the WAVOS water level forecasting system (WAVOS is used for both low/medium water forecasting as well as flood forecasting and is operationally deployed in several river basins). At the end of autumn, as the frequency of low water levels increases, someone is always on call. Forecast for shipping among others (Germany, Netherlands): ELWIS.
  - BW: daily current (low water) forecasts for the Rhine from Constance to Mannheim and its most important tributaries (LARSIM). Additional publication of a no-rain forecast variant to show the development that will occur in the absence of precipitation over the next 7 days.
  - HE, RLP: Low water forecast for tributaries using LARSIM.
  - BY: Forecasts (also for the Main) are carried out daily and published in the flood news service / HND website of the Bavarian State Office for the Environment.
  - NRW: No real forecast but special attention to the winter precipitation (important for the groundwater recharge).
- In the Netherlands, information and forecasts are based on models drawn from weather forecasts. The WABES instrument is currently being developed in the Netherlands. On the basis of meteorological forecasts and climate development, for example, long-term forecasts are made with regard to the low-water situation in order to inform users about the availability of water at their relevant locations in the main water system. The RWsOS models are used for operational monitoring and low water reporting (e.g. for shipping).
- In Luxembourg there is no low water forecasting per se. In future it is planned to use the predictive model LARSIM in low water conditions also, in order to be able to estimate the minimum possible discharge in the forecast period in the absence of precipitation. It should then be possible to activate a specific reporting service and the preparation of situation reports. However, this requires adjustments to the model and procedure.

6.4.2 Operative management and measures

There are **different legal bases in the states:**

- Nationally, in Germany there is the Water Resources Act, in France the Environmental Act and national circulars on low water events, in the Netherlands the Water Act, the Delta Programme and the Delta Resolutions.
- Regionally there is a country-specific or cantonal arrangement in Germany or Switzerland, the (inter) departmental framework decrees in France and the water management plans of the water boards in the Netherlands.

The EU states in the Rhine catchment area are obliged to implement the WFD nationally. Thus, management plans [Bewirtschaftungspläne (BWP)] are set up, which also include the problem of low water.

Concerning the **planning and the decision on low water management measures**, in Switzerland the cantons are responsible (e.g. water supply plans), in Germany the federal states (BWP, regional development plans), in Luxembourg the national level (BWP, emergency plan for drinking water providers), in France the departments ("Arrêté-cadres" which define the following action phase related to threshold values for each gauge: vigilance, warning, increased warning/alarm, crisis), and in the Netherlands the state, the provinces and the water boards (at national and regional level: National Water Plan, BWP, development plan, water management plans of the water boards).

With regard to the **planning and organisation of (crisis) management** (coordination/resolution in advance of a drought or low water event) for the states on the Rhine, it is mainly up to the regional level (cantons, federal states, departments/regions, water boards), and also the national levels in Luxembourg, the Netherlands or France (in a very large event) to set up central coordination cells. Here different actors such as the

Comité sécheresse are responsible for the regional drought consultation. In the decision-making or advisory bodies or their plans there are information and processes for **the prioritisation** of functions and uses that must be limited or guaranteed during a dry period or a low-water event. Examples:

- The French "Arrêté-cadres" define 4 stages: the "vigilance period" (awareness actions), "warning period" (restriction measures), "alert period" (stronger restrictions) and "crisis" (termination of non-priority abstractions). In summary, the priorities - as in Luxembourg - look like this: first the drinking water supply, then the economic and recreational uses.
- In the Netherlands, it is up to the LCW to recommend measures for distributing the available water. To this end, it relies on a national displacement series (see Fig. 7), which determines which water users are given priority in case of drought (safety category, e.g. dykes and irreversible damage to nature: highest priority). In addition, there are 4 stages of crisis preparation and crisis management in the Netherlands (normal situation, signs of lack of water, lack of water, imminent crisis due to lack of water).
-

Category 1 **Security and avoidance of irreversible damage**	**Category 2** **Supply companies**	**Category 3** **High-quality use on a small scale**	**Category 4** **Other concerns (ecological consideration, including for nature)**
1. Stability of the flood protection facilities 2. Compaction and settling (bogs and high bogs) 3. Nature (in connection with soil condition)	1. Drinking water supply 2. Energy supply	• Temporary irrigation of capital-intensive plants • Process water	• Shipping • Agriculture • Nature (as long as no irreversible damage occurs) • Industry • Recreational usage of the rivers • Inland fisheries
takes precedence →	takes precedence →	takes precedence →	

Figure 7: National displacement series Netherlands (WMV, 2009a, 2009b)

Operational water management measures (including water distribution) *(see also Chapter 6 and Figure 3)*

Apart from informing and sensitising the public and the users (including about preventive/responsible action and the economical use of water resources), there are a number of measures in all states: Use of/switchover to small water supply units, (drinking) water distribution, specific measures for the discharge support and groundwater recharge as well as various usage restrictions. Critical functions are described in detail in Chapter 6.3.2. In principle, not all effects of low water can be compensated or eliminated by (operational) management measures.

Side note: Low water management and local water scarcity in Switzerland (Zahner, 2017): The Swiss method for low water management consists of 3 modules, 2 preventive and 1 for short-term (crisis) management. The first module identifies risk areas. The end product of this module is reference cards for water scarcity. Module 2 deals with the long-term management (strategic planning) of water resources. Module 3 is a toolbox for controlling the residual risk. It contains measures to deal with conflicts of use and to prevent damage to users and the ecology.

7. Investigation of historical gauge measurement series on the Rhine

7.1 Long-term behaviour of the low-water characteristic values

The striking low-water events of the last 100 years (1914-2015) were examined first. In contrast to flood events, in which there is rarely a flood in the entire catchment area of the Rhine and on all sections of the Rhine, low water events are characterised by the fact that they appear across the whole Rhine area. Low water events are linked to long-lasting and large-scale prevailing weather conditions, which are usually expressed throughout the Rhine. In total, during the above period (1914-2015) 21 low-water events from 17 years have been recorded. The reference period 1961-2010, which corresponds to the current conditions, was used for the statistical classification of the return period of the low water discharge and the low water duration. Due to this approach the return periods of the events of the first half of the 20th century appear to be "inflated", but they correspond to the return periods if these events were to occur now. Thus, the extent of the low water events relative to today's conditions can be relatively compared. Table 2 shows the return period ranges for the section from Basle to Lobith. The conditions at the Diepoldsau and Rekingen gauges are to be assigned to the nival outflow regime, where the low water events often occur during the course of the year at other times than at the other gauge. The gauge-related return periods are listed in detail in the descriptions of the respective low water years.

Basically, it can be seen that the extreme historical low water events occurred in the 1920s and 1940s. Most of the low water events occur in the autumn and winter months. In the summer events, which are rarer but less extreme with regard to the discharges, (1976, 2003 and 2006) there may be a problem with simultaneously very high water temperatures. Significant low water events occurred in the reference period in 1962/63 and 1971/72, after which the low water events decreased significantly in size, with the exception of the event in 2003. Also noteworthy are the low water years 1921 and 1976, each with three events, although here too the events of 1976 are significantly less severe. The summer events of 2003 and 2006 were associated with very high water temperatures, with the discharges in 2006 not presenting a particular low water situation.

Table 2: Overview of the low water events 1920 to 2015 on the Rhine with indication of the return periods (statistical probability of occurrence) of the smallest discharge amount "NM7Q" and the maximum shortfall duration "MaxD" <MNM7Q (Rekingen gauge to Lobith).

Low water event		**Discharge return period [a] NM7Q**	**Discharge return period [a] MaxD**	**Comment**
Nov / Dec	1920	15-100	15-50	
March-May	1921	15-100	50-100	
Sep / Nov	1921	5-100	5-100	
Nov / Dec	1921	20-100	10-15	
Oct / Nov	1943	10-20	5-20	
Aug-Nov	1947	40-100	20-100	
Jul-Nov	1949	10-100	20-100	
Sep 53-Jan 54	1954	15-100	20-50	
Sep-Dec	1959	15-55	10-100	
Oct-Dec	1962	15-70	40-75	
Jan-Mar	1963	20-65	15-50	
Oct / Nov	1971	20-35	10-35	
Oct / Nov	1972	10-35	5-20	
Jul	1976	2-15	2-5	
Aug / Sep	1976	2-5	2-10	
Oct / Nov	1976	2-5	2-10	
Oct / Nov	1985	5-15	5-10	
Aug- / Sep	2003	5-35	5-30	**high water temperature**
Jul	2006	<2	<2	**high water temperature**
Nov-Dec	2011	5-10	5-10	
Oct / Nov	2015	2-10	2-20	

(light blue)	**Within reference period of statistical classification**
(yellow)	**Extreme events**
(orange)	**Years with several low water events**

In the compilation of the discharge characteristic values of the examined gauges (for the reference period 1961 - 2010), the importance of the discharge and the low water discharge at the Basle gauge for all downstream gauges can be seen in Tab. 3 and 4. From the Rekingen gauge to the Baslegauge, the discharges are more than doubling due to the inflow of the Aare. The average water discharge of 1065 m³/s and the average low water discharge of 508 m³/s at the Basle gauge still represent about three quarters of the discharges at the Worms gauge, about 60% at the Kaub gauge and still around 50% of the discharges on the Lower Rhine.

Table 3: Medium and low water characteristic values at gauges on the Rhine

Discharge characteristics at different gauges on the Rhine				
	Period 1961-2010 (water management year)			
[m³/s]	MQ	MNQ	MNM7Q	NQ
Diepoldsau	233	72	92	41
Rekingen	445	232	238	134
Basle	**1065**	**508**	**527**	**319**
Maxau	1255	618	645	373
Worms	1431	694	720	400
Mainz	1671	824	850	501
Kaub	1713	824	851	525
Andernach	2115	967	998	622
Cologne	2175	999	1028	644
Lobith	2287	1066	1095	665

Table 4: Percentage discharge component of discharge from the Basle gauge

Percentage discharge component of discharge from the Basle gauge				
	Period 1961-2010 (water management year)			
[% from Basle]	MQ	MNQ	MNM7Q	NQ[3]
Basle	**100**	**100**	**100**	**100**
Maxau	85	82	82	86
Worms	74	73	73	80
Mainz	64	62	62	64
Kaub	62	62	62	61
Andernach	50	53	53	51
Cologne	49	51	51	50
Lobith	47	48	48	48

Due to the nival discharge regime in the Alpine region, the low-water discharge there has a minimum in winter (rainfall is bound in the form of snow) and a maximum after the snowmelt in summer. Due to the high discharge component from areas with a nival regime, the discharges on the Rhine are also supported in the downstream area by a pluvial discharge regime (mainly low water periods in the summer in the catchment areas of the tributaries) into the summer.

For further analysis and visualisation of the low water flow and the hydrological history, a graph was created for all historical low water events with the discharge hydrographs of the gauges that were investigated. Figure 8 shows the discharge hydrographs for the low

[3] NQ is the lowest value in the period 1961-2010. The calculated ratio to the NQ at the Basle gauge can come from different years for the different gauges and does not have to coincide with the year of the NQ value at the Basle gauge. In a specific low-water event, this results in different ratios and the relative discharge component from the Basle gauge can be significantly higher, especially in the case of summer low-water events.

water event in August and September 2003. The graphs are presented for all events together with the corresponding key figures and return period classifications in data sheets on the extreme events (see Chapter 7.5 and Appendix 2).

In Figure 8, the lowermost (blue) curve for the Diepoldsau gauge shows a course that differs significantly from the other hydrographs. The Diepoldsau gauge represents a nival discharge regime, which is characterised by snow backfill and snowmelt on the one hand, while on the other it contains strong anthropogenic influences due to temporal redistribution through damming and power plant operation. The next higher hydrograph of the Rekingen gauge shows a balanced course, which is mainly attributable to the seasonal course of the discharge from Lake Constance. The other hydrographs from the Basle gauge, on the other hand, show a high degree of similarity with one another and show the influence of precipitation events more clearly. The very similar course, especially in the low water range of August and September, results from the high discharge component from the Alpine and Alpine foothills area at the Basle gauge, which also contributes to the overall discharge in the downstream gauges with very high proportions and still contributes to the total discharge with around 50% even at the Lobith gauge. The low water event developed with brief precipitation-related disruptions from July 2003, leading to the lowest discharges at the end of September 2003, which were then replaced by a significant discharge event in early October 2003.

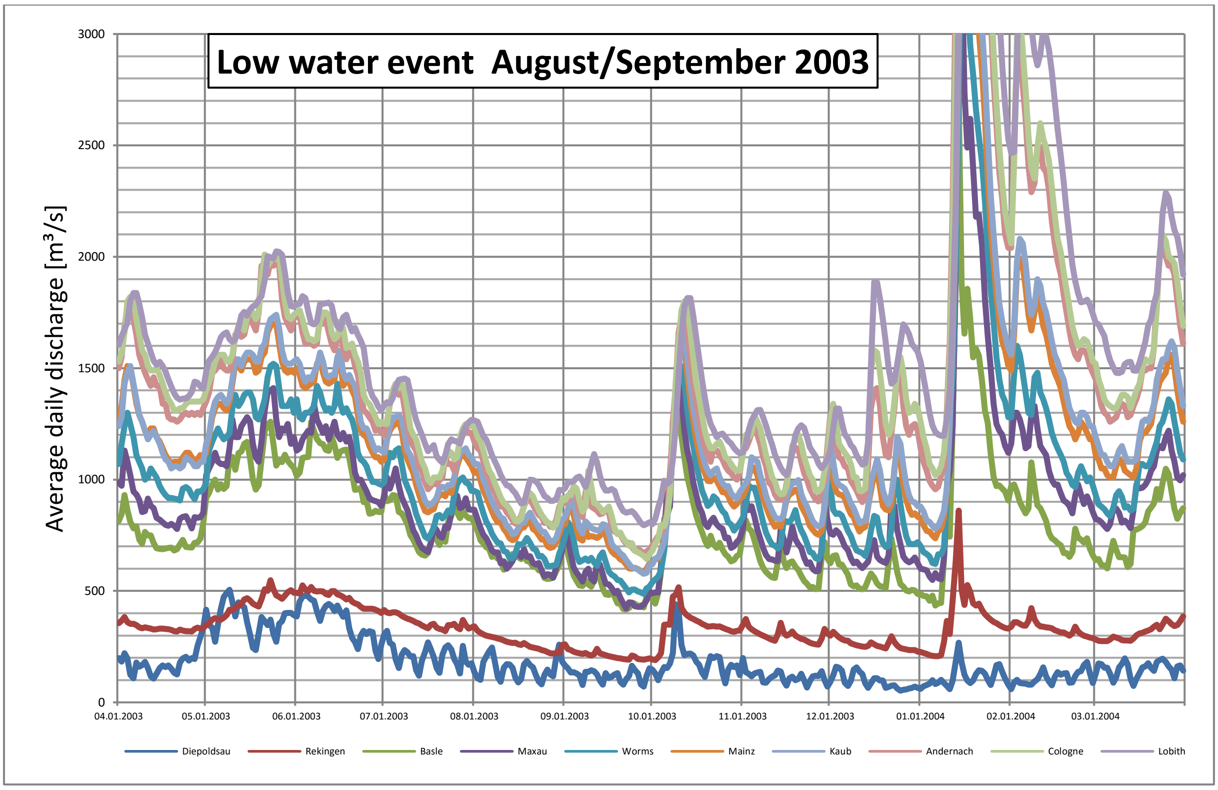


Figure 8: Discharge hydrographs for the low water event in August/September in the 2003 water management year

7.2 Reference period and low water parameters

To examine the time series for homogeneity and change behaviour, the temporal behaviour of the annual NM7Q values at the Rhine main gauges was examined by means of a jump analysis. The jump analysis is a statistical method for detecting sudden changes in a time series. As a rule, sub-periods are compared in a comprehensive manner with regard to their behaviour. If a significant breakpoint is determined, the time series examined cannot be regarded as homogenous. This means that the behaviour of the sub-time series before and after the breakpoint is different.

The time series for the NM7Q values of the present observation periods with the times of the occurring jumps for the Diepoldsau, Maxau, Kaub and Cologne gauges are shown below as examples (see Figs. 9 to 12).

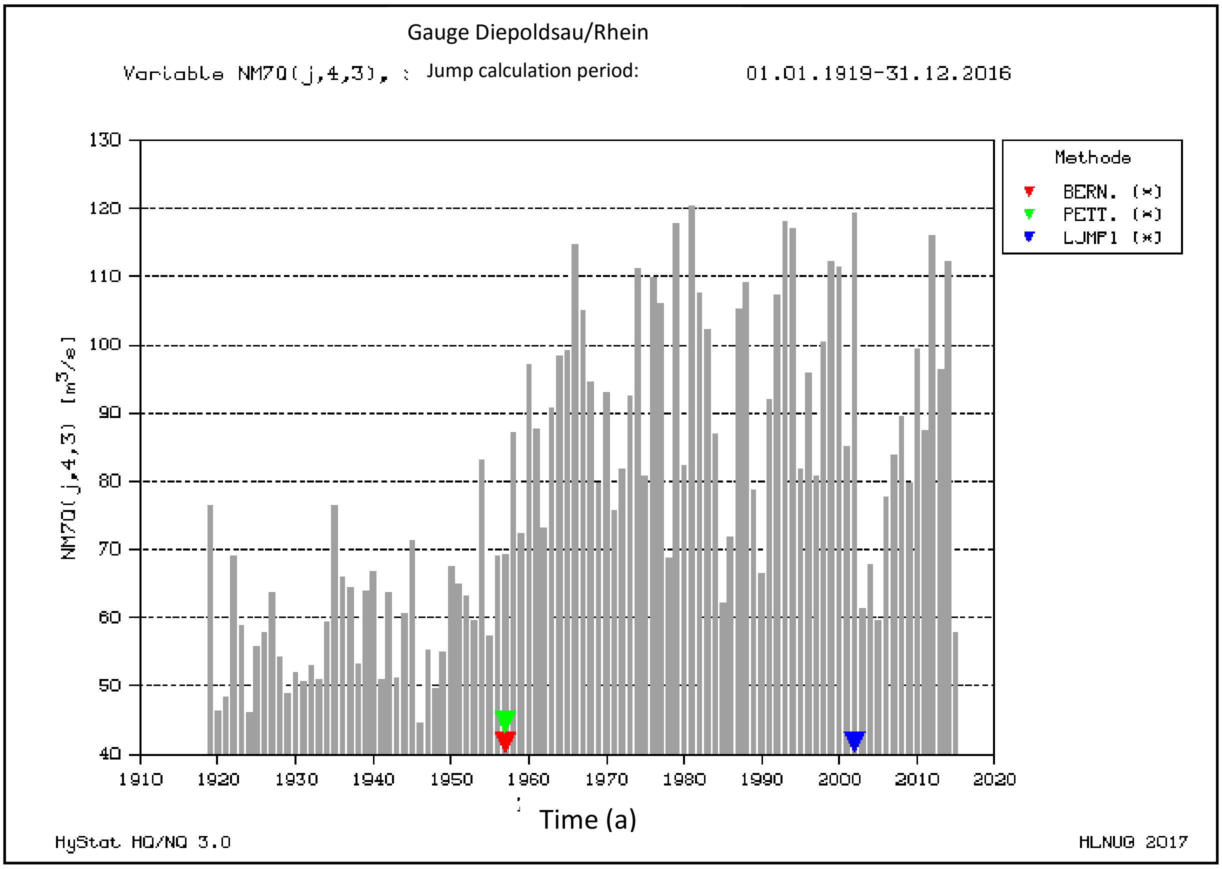


Figure 9: NM7Q annual values at the Diepoldsau gauge and detected break points

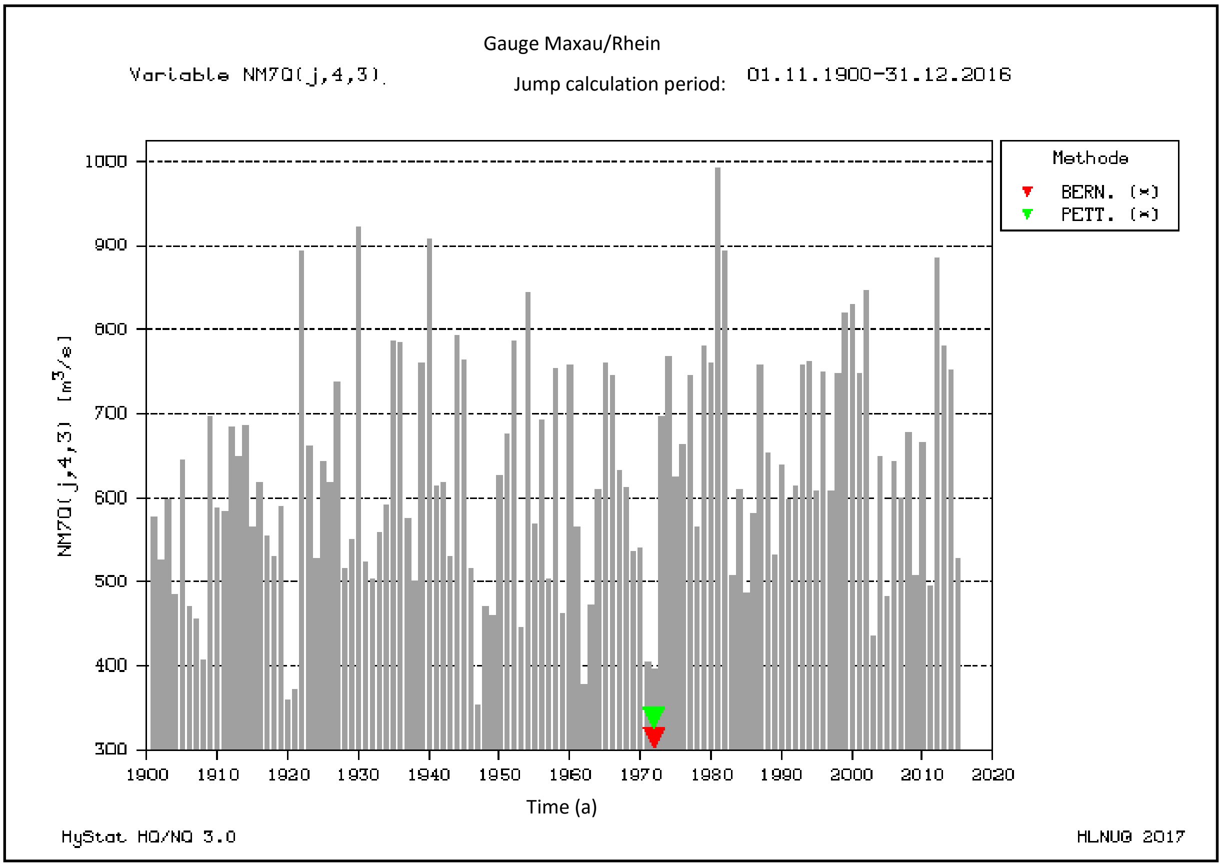


Figure 10: NM7Q annual values at the Maxau gauge and detected break points

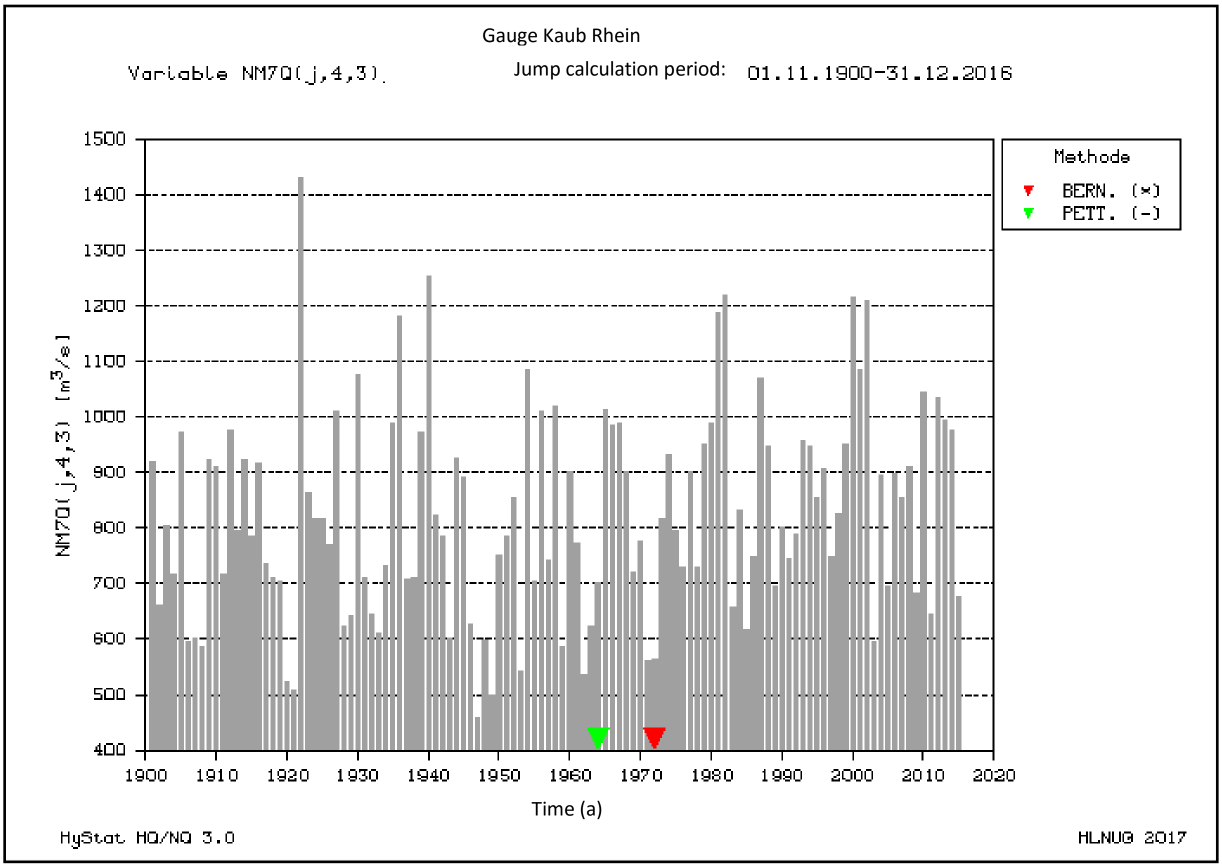


Figure 11: NM7Q annual values at the Kaub gauge and detected break points

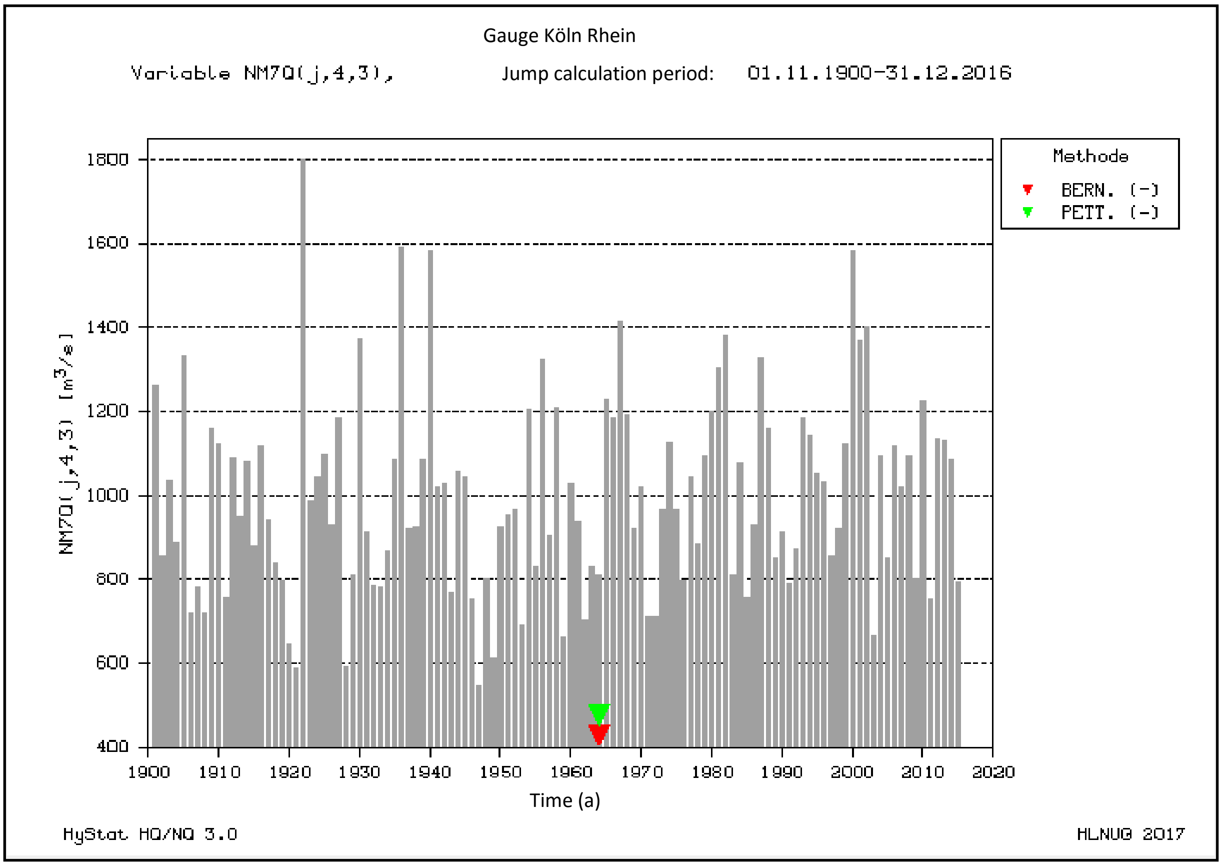


Figure 12: NM7Q annual values at the Cologne gauge and detected break points

A clear inhomogeneity can be seen for the Diepoldsau gauge, for which the low water discharges have increased significantly compared to the entire preceding period following completed dam expansion in the catchment area from about the 1960s. At the Maxau gauge the break point occurs a little later (about 1970), for the Kaub gauge the two methods for break point determination show slightly divergent ranges (1960 to 1970) and at the Cologne gauge the break point occurs again in the 1960s (see Table 5). For all gauges it can be seen that the lowest annual NM7Q values occurred before 1960, and these extreme values have not been reached since then. Trends or tendencies towards decreasing low water discharges are not discernible in the NM7Q time series since 1960.

Table 5: Time points (year) of break points according to jump analyses

Gauge	**Jump according to BERNIER**	**Jump according to PETTIT**
Diepoldsau	1957	1957
Rekingen	1964	1964
Basle	1972	1972
Maxau	1971	1971
Worms	1971	1971
Mainz	1971	1971
Kaub	1971	1963
Andernach	1963	1963
Cologne	1963	1963
Lobith	1978	1978

Corresponding to the occurrence of the significant jumps between 1957 and 1972 (with the exception of Lobith), the **time series 1/4/1961 to 31/3/2011, as a 50-year reference series**, was taken as a reference period of a quasi-stationary state representing the current conditions for the ongoing statistical classifications. This means that in the further analysis the MNM7Q for the period of the water management years 1961-2010 is used as a threshold value to check the annual NM7Q values that are to be derived from the measurement series and to determine the return periods therefrom.

7.3 Low water discharges

7.3.1 Trend analysis of the low water characteristic values

By means of the trend analysis, long-term tendencies of discharge-related series can be investigated and, if necessary, demonstrated. In particular, the determination of a trend line according to the method of minimising the least square error (LSE) was evaluated. The decision about the existence of a statistically significant trend was made with the parameter-free Mann-Kendall test (which does not require a straight-line trend) and with the t-test of the slope coefficients of the trend line (which, however, requires a normal distribution of the residuals of the estimated regression model).

The trend behaviour of the low-water discharges NM7Q shows a significantly increasing trend for the entire (non-homogeneous) observation period for the Rhine gauges from Diepoldsau to Andernach (p 0.95) (see Tab. 6), shown as an example in the time series for the Basle gauge in the graph below (see Fig. 13).

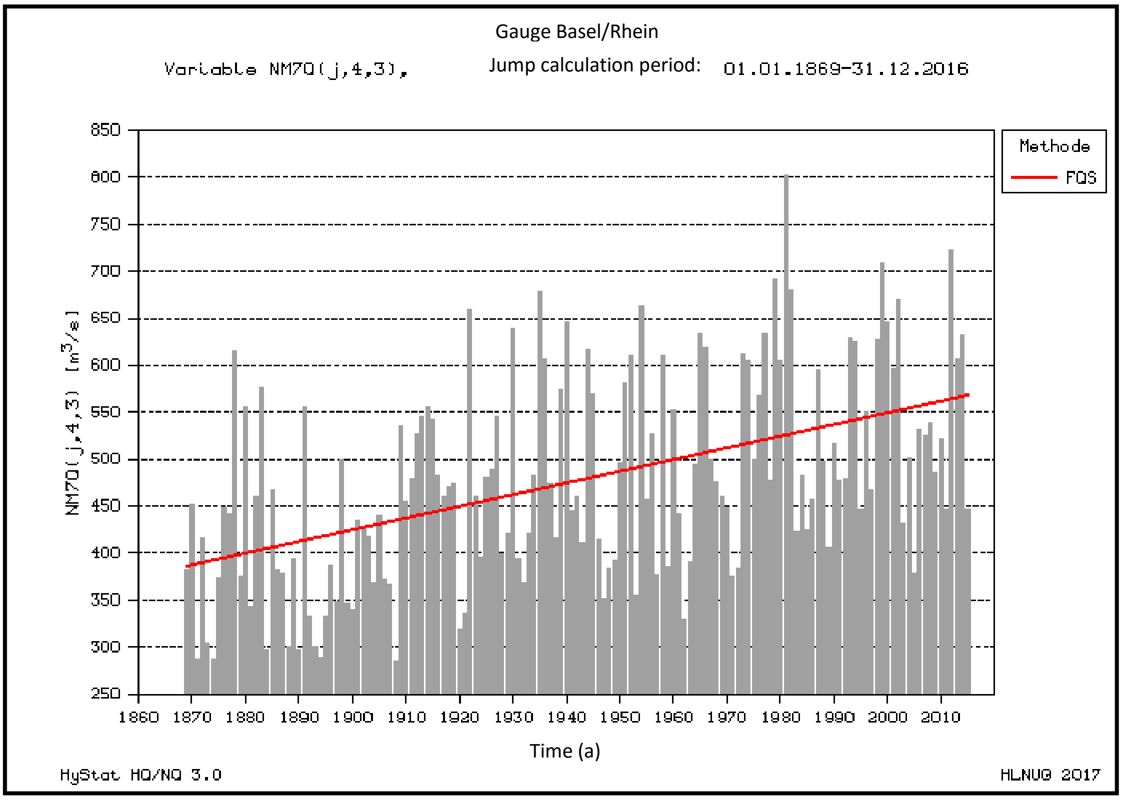


Figure 13: Trend analysis of the NM7Q series at the Basle gauge

On the other hand, no significant trend can be detected for the Cologne (see Fig. 14) and Lobith gauge (see Tab. 6).

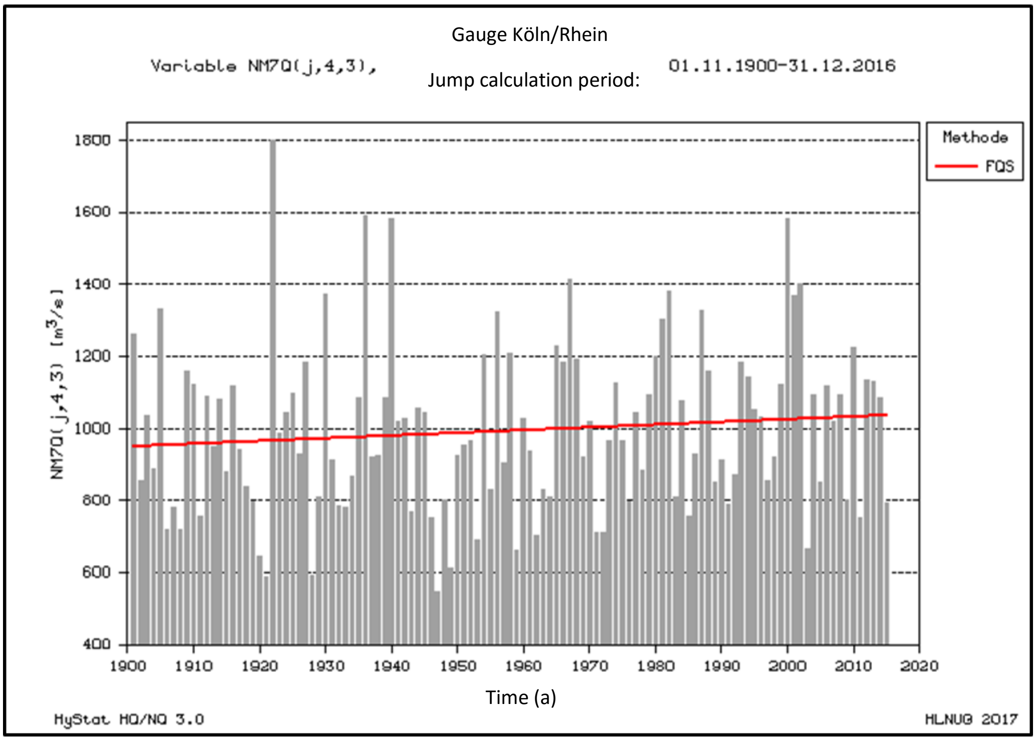


Figure 14: Trend analysis of the NM7Q series at the Cologne gauge

In a trend analysis with reference period of the specified reference periods 1/4/1961 to 31/3/2011, no significant trend according to Mann-Kendall is detectable at any of the Rhinegauges. This underlines the separation of this period after the jump analysis has been carried out and shows more or less homogeneous conditions for this reference period.

The following table shows the results of the trend tests for the characteristic NM7Q (see Tab. 6).

Table 6: Results of the trend analysis of the NM7Q series for the entire examination period and the homogeneous reference period (MK = Mann-Kendall test, FQS / t-test = t-test of the slope coefficients of the trend line).

Gauge	**Trend MK total**	**FQS / t-test total**[4]	**Trend MK 1961-2011**	**FQS / t-test 1961-2011**
Diepoldsau	+ (p= 0.95)	+ (p= 0.95)	no trend	no trend
Rekingen	+ (p= 0.95)	+ (p= 0.95)	no trend	no trend
Basle	+ (p= 0.95)	+ (p= 0.95)	no trend	no trend
Maxau	+ (p= 0.95)	no trend	no trend	no trend
Worms	+ (p= 0.95)	no trend	no trend	no trend
Mainz	+ (p= 0.95)	+ (p= 0.95)	no trend	+ (p= 0.95)
Kaub	+ (p= 0.95)	+ (p= 0.95)	no trend	+ (p= 0.95)
Andernach	+ (p= 0.95)	+ (p= 0.95)	no trend	no trend
Cologne	no trend	no trend	no trend	no trend
Lobith	no trend	no trend	no trend	no trend

According to the trend examinations, no intensification of the low water situation can be detected for the reference period (1961-2010). If the observation time is extended to the entire observation period (from the beginning of the measurement data at the beginning of the 20th century to 2015), there are, with the exception of the Lower Rhine,

[4] Corresponds to the red trend line in Figures 13 to 16.

increasing trends in the low-water discharges. Increasing trends can also be seen for longer-lasting low-water discharges on 21 consecutive days (NM21Q) (see Tab. 7):

Table 7: Results of the trend analysis of the NM21Q series for the entire examination period and the homogeneous reference period (MK = Mann-Kendall test, FQS / t-test = t-test of the slope coefficients of the trend line).

Gauge	**Trend MK total**	**FQS / t-test total**	**Trend MK 1961-2011**	**FQS / t-test 1961-2011**
Diepoldsau	+ (p= 0.95)	+ (p= 0.95)	no trend	no trend
Rekingen	+ (p= 0.95)	+ (p= 0.95)	no trend	+ (p= 0.95)
Basle	+ (p= 0.95)	+ (p= 0.95)	no trend	no trend
Maxau	+ (p= 0.95)	no trend	no trend	no trend
Worms	no trend	no trend	no trend	+ (p= 0.95)
Mainz	+ (p= 0.95)	+ (p= 0.95)	+ (p= 0.95)	+ (p= 0.95)
Kaub	+ (p= 0.95)	no trend	+ (p= 0.95)	+ (p= 0.95)
Andernach	no trend	no trend	no trend	+ (p= 0.95)
Cologne	no trend	no trend	no trend	no trend
Lobith	no trend	no trend	no trend	+ (p= 0.95)

For the summer half-year (valid for the period from 1/4 to 30/9 of each year) of the reference period, none of the gauges shows a significant trend in the NM7Q values. Also, no significant trend according to Mann-Kendall can be seen for the winter half-year (1/10 to 31/3 of each year), and according to the linear regression approach (FQS), the Worms, Mainz (see Figs. 15-16) and Kaub gauges (thus from the transition of the Upper Rhine to the Middle Rhine) show an increasing trend of the NM7Q values. There may be influences here from the Neckar and Maine catchment areas, which are further downstream.

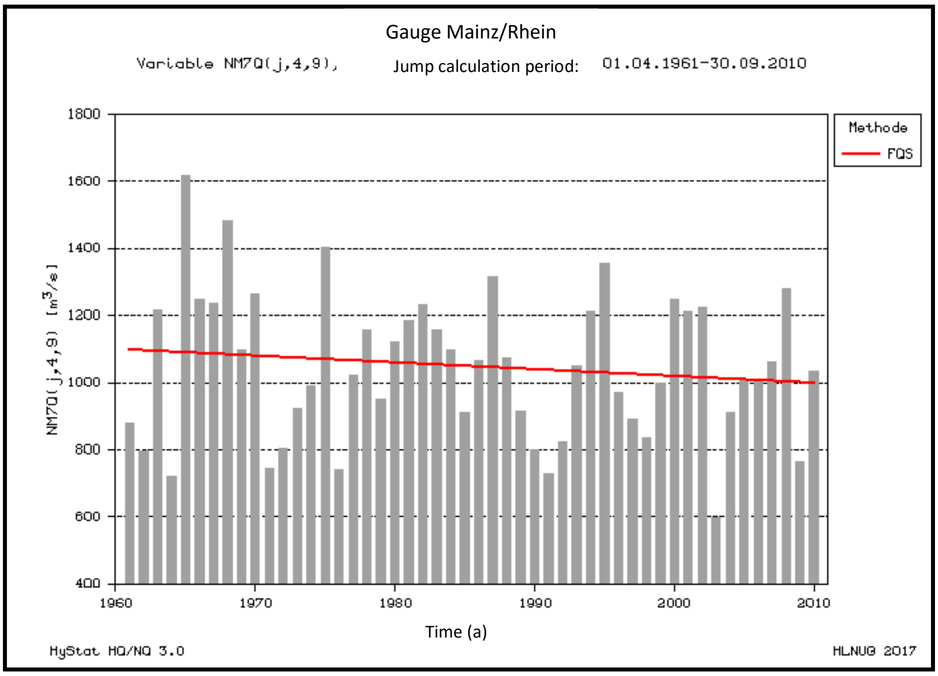


Figure 15: Trend analysis of the NM7Q series for the summer half-year (April-September) at the Mainz gauge

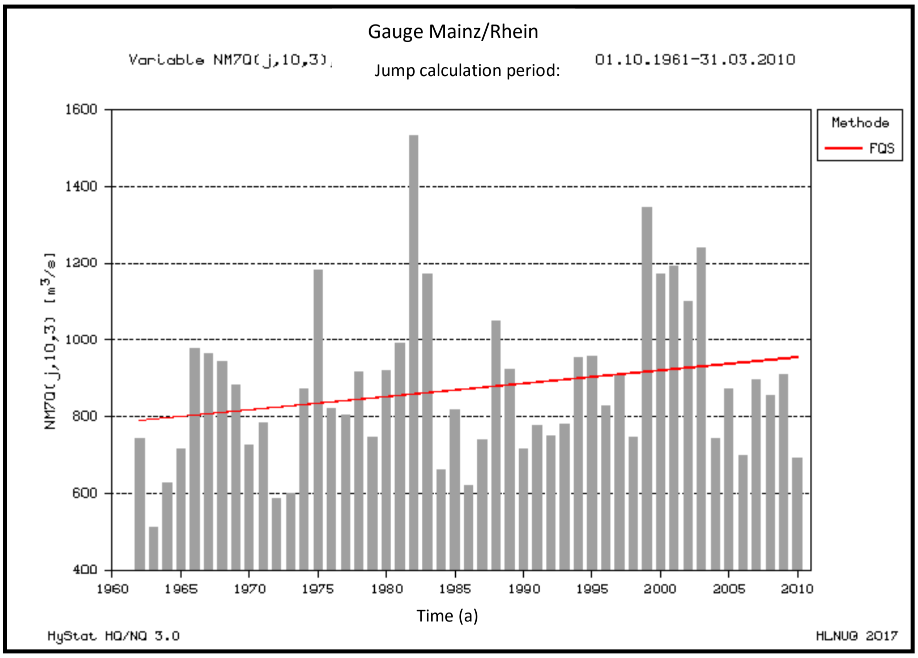


Figure 16: Trend analysis of the NM7Q series for the winter half-year (October-March) at the Mainz gauge

7.3.2 Probability analysis of the low water characteristic values

For the later classification of low-water discharges, an extreme-value statistic was carried out with the series of NMxQ values (lowest mean low-water discharges on x consecutive days). The distribution of the low water series was adjusted to the general extreme value distribution (GEV-LM) using the L-moment parameter estimation method. The low-water quantiles thereby derived are given in Tables 8 to 12 for the gauges studied. These results can be used to assign an occurrence probability (return period) to the low-flow discharges that have occurred (see Chapter 7.4). It should be noted that the statistics were determined on the basis of the 1961-2010 reference period and correspond to the current conditions (see Chapter 7.1). Earlier low water events (before 1960) appear to be linked to too low a probability of occurrence when assigned to these values. The low water discharges or durations occurring before 1960 would, however, correspond to these return periods if occurring today.

Table 8: Low water discharge NM1Q of certain recurrence intervals, determined for annual series (j) in relation to the water balance year April to March (4,3)

Low water discharge probability: Series type **NM1Q**(j,4,3), distribution GEV-LM[5], discharges in [m³/s]						
Return period:	T=2a	T=5a	T=10a	T=20a	T=50a	T=100a
Diepoldsau/Rhine	71.6	60.4	54.7	50.2	45.2	42.0
Rekingen/Rhine	229	189	170	156	140	130
Basle/Rhine	502	426	390	362	333	314
Maxau/Rhine	618	510	454	410	361	330
Worms/Rhine	693	576	518	471	419	386
Mainz/Rhine	817	687	624	574	521	487
Kaub/Rhine	816	682	617	565	511	476
Andernach/Rhine	955	793	716	656	592	551
Cologne/Rhine	985	821	743	683	619	578
Lobith/Rhine	1053	884	802	739	670	627

[5] General extreme value distribution with L-moment parameter estimation method

Table 9: Low water discharges NM3Q of certain recurrence intervals, determined for annual series (j) in relation to the water balance year April to March (4,3)

Low water discharge probability: Series type **NM3Q**(j,4,3), distribution GEV-LM, discharges in [m³/s]						
Return period:	T=2a	T=5a	T=10a	T=20a	T=50a	T=100a
Diepoldsau/Rhine	82.4	69.3	62.5	57.1	51.0	47.1
Rekingen/Rhine	231	192	173	159	144	134
Basle/Rhine	509	431	394	365	335	315
Maxau/Rhine	629	519	463	418	369	337
Worms/Rhine	701	583	524	477	426	393
Mainz/Rhine	825	693	629	579	525	491
Kaub/Rhine	825	688	623	571	516	480
Andernach/Rhine	966	801	722	661	595	554
Cologne/Rhine	993	828	750	690	627	587
Lobith/Rhine	1060	892	811	749	682	639

Table 10: Low water discharges NM7Q of certain recurrence intervals, determined for annual series (j) in relation to the water balance year April to March (4,3)

Low water discharge probability: Series type **NM7Q**(j,4,3), distribution GEV-LM, discharges in [m³/s]						
Return period:	T=2a	T=5a	T=10a	T=20a	T=50a	T=100a
Diepoldsau/Rhine	92.6	77.2	69.3	62.9	55.8	51.2
Rekingen/Rhine	234	194	176	162	147	137
Basle/Rhine	518	439	402	374	344	325
Maxau/Rhine	644	530	473	427	377	345
Worms/Rhine	716	593	533	486	434	401
Mainz/Rhine	839	702	638	588	535	501
Kaub/Rhine	841	699	632	580	524	489
Andernach/Rhine	982	812	732	670	604	563
Cologne/Rhine	1010	840	761	701	637	597
Lobith/Rhine	1075	908	829	769	705	665

Table 11: Low water discharges NM21Q of certain recurrence intervals, determined for annual series (j) in relation to the water balance year April to March (4,3)

Low water discharge probability: Series type **NM21Q**(j,4,3), distribution GEV-LM, discharges in [m³/s]						
Return period:	T=2a	T=5a	T=10a	T=20a	T=50a	T=100a
Diepoldsau/Rhine	103	87.5	80.0	74.0	67.4	63.2
Rekingen/Rhine	246	204	184	169	153	143
Basle/Rhine	555	464	422	391	358	337
Maxau/Rhine	685	563	505	461	414	384
Worms/Rhine	765	630	568	520	470	439
Mainz/Rhine	895	742	671	618	561	526
Kaub/Rhine	905	744	669	611	550	511
Andernach/Rhine	1059	862	771	700	626	579
Cologne/Rhine	1090	894	803	733	659	613
Lobith/Rhine	1148	957	869	801	729	684

Table 12: Low water discharges NM60Q of certain recurrence intervals, determined for annual series (j) in relation to the water balance year April to March (4,3)

Low water discharge probability: Series type **NM60Q**(j,4,3), distribution GEV-LM, discharges in [m³/s]						
Return period:	T=2a	T=5a	T=10a	T=20a	T=50a	T=100a
Diepoldsau/Rhine	113	98.7	92.0	86.9	81.3	77.8
Rekingen/Rhine	271	224	203	186	169	159
Basle/Rhine	644	530	476	435	390	362
Maxau/Rhine	791	647	579	526	469	433
Worms/Rhine	892	729	652	593	530	489
Mainz/Rhine	1046	855	765	695	621	574
Kaub/Rhine	1062	864	770	697	620	570
Andernach/Rhine	1274	1015	887	784	672	600
Cologne/Rhine	1308	1049	921	820	710	640
Lobith/Rhine	1351	1101	983	890	792	729

7.4 Low water durations

At the Rhine main gauges, the temporal behaviour of the annual low water duration values MaxD (maximum duration of a contiguous event below the threshold value MNM7Q) and SumD (total number of shortfall days below the threshold value MNM7Q) was examined. Table 13 shows the average values of the low water durations for the reference period 1/4/1961 to 31/3/2011. With the exception of the Diepoldsau and Rekingen gauges, the average shortfall durations of the discharge MNM7Q are 16 to 20 days. The average total number of days below the MNM7Q threshold value is around 25 days per year. Due to the occurrence of years where the threshold value was not fallen short of, these "average" values are too low for individual occurrences with threshold value shortfalls. A better interpretation can be achieved using the extreme value statistics listed below for the shortfall periods of certain return periods.

Table 13: Average annual days of falling short of the MNM7Q threshold value

Gauge	**MaxD [days]**	**SumD [days]**
Diepoldsau	7.6	24.5
Rekingen	24.2	29.2
Basle	19.6	26.7
Maxau	17.6	25.6
Worms	17.6	25
Mainz	18.1	27
Kaub	17.5	25.1
Andernach	16	24.2
Cologne	16.7	23
Lobith	17.2	24.3

The annual series are not suitable for statistically examining the probabilities of low water emergence due to the occurrence of years without shortfalls, which indicate differential durations of days where the threshold value is fallen short of. For this reason, annual series were produced according to the indirect method as defined in the DVWK "Low Water Analysis" (DVWK, 1992) and the extreme value statistical analysis was carried out with these series. The results for the Rhine main gauges for the reference period 1961-2010 are summarised in Table 14 below:

Table 14: Shortfall durations (days) of n-year low water below the MNM7Q threshold.

	T = 2a	**T = 5a**	**T = 10a**	**T = 20a**	**T = 50a**	**T = 100a**
Diepoldsau	3.5	9.1	14.0	16.6	21.2	26.3
Rekingen	7.0	30.8	49.0	65.9	85.1	
Basle	5.1	23.6	34.9	47.5	54.8	83.7
Maxau	4.9	23.4	34.2	47.4	63.7	89.4
Worms	5.4	23.5	35.1	49.3	67.8	
Mainz	5.6	24.5	38.1	55.7	80.9	
Kaub	5.5	23.3	35.7	55.0	74.4	
Andernach	5.8	23.8	39.7	52.9	73.2	85.2
Cologne	5.8	23.8	38.2	52.1	75.1	87.8
Lobith	5.4	26.2	46.1	68.4	88.9	

By means of this return period table, historically occurring low water levels can be assigned to an occurrence probability with regard to the shortfall duration (see Chapter 7.5), and for the low water event of 2003 the resulting classifications are listed in table 15. With regard to the discharge values, the Basle event must be classified as a 5-year event increasing up to Cologne as a 35-year low water event. Regarding the low water duration, the event, with the exception of the Andernach gauge, must be classified as a 5 to 10-year low water event.

The graphical representation of the temporal development of the characteristic value MaxD (maximum shortfall duration of a contiguous event per year) is shown as an example for the Kaub gauge in Figure 17, and the graphs for all gauges can be found in Appendix 3.

Table 15: Classification of low water characteristic values for the 2003 event in recurrence intervals

Low water characteristic values for the event August/September 2003

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Sep 2003	Return period Sep 2003	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Sep 2003	Return period Sep 2003
Diepoldsau	92.2	108	< 2	4	2	< 2
Rekingen	238	193	5	7	22	2-5
Basle	527	431	5	5	20	5
Maxau	645	435	20	5	31	5-10
Worms	720	500	15	5	31	5-10
Mainz	850	596	20	6	33	5-10
Kaub	851	595	20	6	32	5-10
Andernach	998	682	20	6	62	30
Cologne	1028	666	35	6	33	5-10
Lobith	1095	808	15	6	34	5-10

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

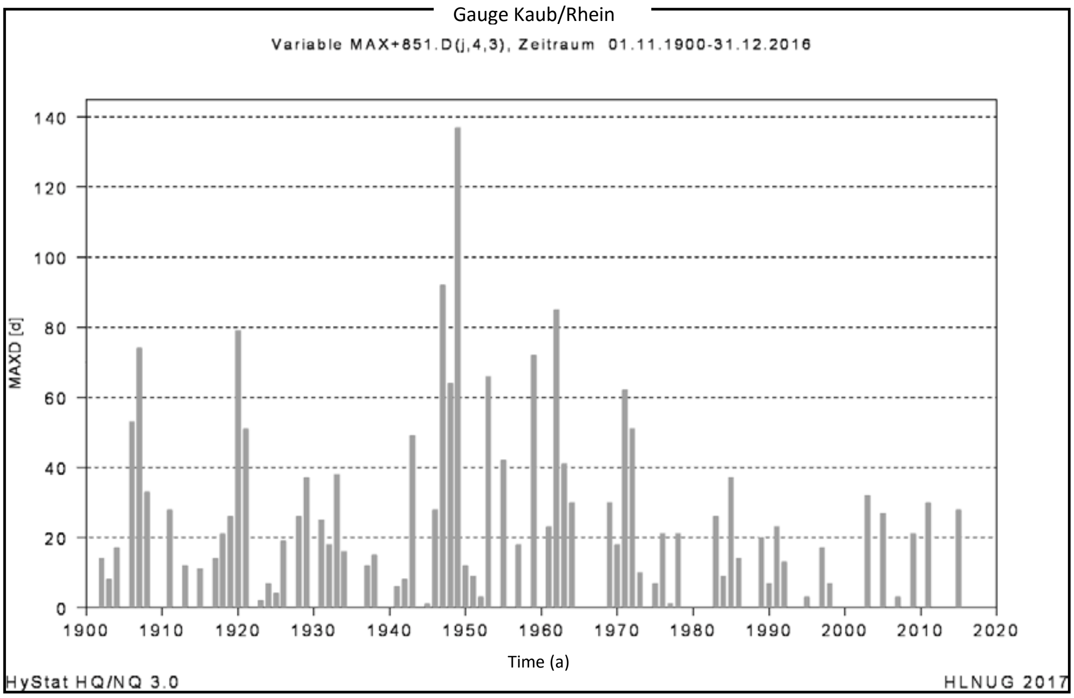


Figure 17: Annual series of the parameter shortfall duration MaxD (in days) for the Kaub gauge

Low-water events with very long durations of about 80 days of shortfall of the MNM7Q occurred especially in the early 20th century, in 1921, in the late 1940s (with up to 138 days of shortfall) and around 1960. In 1972, there were still about 60 days of shortfall, since when low water durations have been significantly shorter, often around 20 days and a maximum of 38 days. A trend towards an intensification of low water situations on the Rhine cannot be deduced from the temporal development of the low water durations.

7.5 Description and classification of selected historical low water events (example: the low water August/September 2003)

The results of the evaluation of the historic low water events on the Rhine with hydrographs and characteristic values (return period classifications for discharge and duration), i.e. the episodes 1920, 1921, 1943, 1947, 1949, 1953, 1959, 1962, 1963, 1971, 1972, 1976, 1985, 2003, 2006, 2011 and 2015 can be found in Appendix 2. This chapter details the 2003 event, which provides comprehensive information on the Rhine riparian states. In addition, the low water of 2003 can be considered a representative event for a pronounced summer event with high water temperatures. Chapters 7.1 and 7.4 show the hydrographs, characteristic values and return periods of the 2003 event in graphical and tabular form.

The impacts of the 2003 low water and other historical low water events were recorded and included in Chapter 6.3 on impacts.

7.5.1. Meteorological development of the low water of 2003

Before the year 2003 turned into a pronounced dry year, it began with above-average precipitation (November 2002 to January 2003). From February 2003, a high-pressure system then developed over Western Europe, blocking moist western air masses and allowing the supply of warm, dry air masses from North Africa. The result was a significant precipitation deficit (especially in February, March and August 2003), the impact of which was felt in all Rhine riparian states from July 2003 onwards. This weather situation led to dryness and to ever more noticeable and long-lasting low water until October 2003 (which was then again followed by above-average precipitation). A dry meteorological period combined with a heatwave (especially in August 2003) extended across large parts of western, central and southern Europe from March to September 2003. As a result of the low water levels and the intense sunshine, a strong warming of the bodies of water also occurred.

7.5.2. Hydrological development of the low water of 2003

As a consequence of the circumstances described above, and especially the low precipitation, a low water period developed in the river system of the Rhine from the end of June or the beginning of July 2003 until the beginning of October 2003 (the time at which the river levels rose steeply again due to precipitation). The lowest discharges were recorded at the end of September 2003. Important weir-controlled tributaries, such as the Neckar, Main and Moselle also had lower discharges. Due to the summertime meltwater feed from the Alpine catchment area and the balancing influence of Lake Constance, the low water period on the Rhine started later than on the large tributaries and other rivers (Elbe, Oder).

As a result of the extraordinarily high heat in the high mountains, which caused strong melting of snow and glaciers, the rivers with a high alpine catchment area (like the Alpine Rhine) had an exceptionally high amount water flowing through them (Diepoldsau gauge: no low water in September 2003). Centres of dryness of the bodies of water were on the northern side of the Alps the Jura and the lower Mittelland (the Basel gauge was more affected by the low water than Rekingen). The discharge in the German part of the Rhine dropped as early as March/April 2003, but the long-term mean low-flow discharge ($MNQ_{1931/2000}$) was not fallen short of until mid-August 2003. At the same time as the extremely high air temperatures in mid-August 2003, the water level in the Rhine fell to very low levels by the last third of September 2003 (e.g. 65 cm in Koblenz on 15 August 2003). The lowest Rhine discharge in the Netherlands (Lobith gauge) in 2003 was very similar to that of 1976 (around 800 m^3/s in Lobith) and also led to serious problems, although a total of three periods of low water occurred in 1976 with a longer overall low-water duration.

As a result of the low water levels and the intense sunshine, a strong warming of the bodies of water occurred. Several temperature records were broken. Temperatures reached up to 26 °C in the High Rhine, and 28 °C in the rest of the Rhine. The warming occurred to varying degrees in the tributaries. For example, the weir-controlled rivers (Moselle, Main, Neckar, Saar) were more affected by the warming than free-flowing tributaries.

8. Possible effects of climate change on future low water conditions on the Rhine

8.1 Results from available investigations in the Rhine area

Previous effects of climate change on the low-water discharge events on the Rhine cannot be clearly demonstrated due to a variety of anthropogenic interventions in the water balance. The development of low water discharges at the Rhine gauges shows a moderation of the low water extremes in the 20th century. According to Belz et al. (2007) the Basle, Maxau, Worms, Kaub, Andernach and Cologne (winter half-year only)gauges show an increasing discharge for NM7Q of the hydrological year or the hydrological winter half-year over the period 1901 to 2000. Looking at the period 1951-2000, the increasing discharge trend for the Basle, Maxau and Worms gauges can still be confirmed, while there are no reliable trends for the other downstream gauges. The decreasing NM7Q trends for the downstream tributaries Lahn and Mosel observed in this period are partly responsible for this.

Discharge projections derived from climate projections can be used to derive and quantify the effects of climate change on low water discharges by systematically comparing low water characteristic values for a reference period (1971-2000) and a future period (2021-2050 "near future" or 2071-2100 "remote future"). It should be noted that climate scenarios are based on different assumptions about future emission developments and that a large number of global and regional climate models exist, none of which takes preference compared to the others. For the above reasons, several different discharge projections are to be evaluated as an "ensemble" in order to estimate the effects, and ranges of possible future changes in the low water discharges are to be derived from these.

Ranges for the change in the NM7Q discharge for the hydrological summer and winter half-years, based on the results of the CHR project **"Rheinblick 2050"** (Görgen et al., 2010), were compiled in the **ICPR EG KLIMA**.

Table 16: Range for the change in the NM7Q at different Rhine gauges (source: ICPR Technical report 188, ICPR, 2011)

Parameter	**Gauge**	**Scenario corridors**	
		Change % Near future	***Change % Remote future***
NM7Q hydrological summer half-year (May-Oct)	Basle	-10% to +10%	*-20% to -10%*
	Maxau	-10% to +10%	*-20% to -10%*
	Worms	-10% to +10%	*-25% to -10%*
	Kaub	-10% to +10%	*-25% to -10%*
	Cologne	-10% to +10%	*-30% to -10%*
	Lobith	-10% to +10%	*-30% to -10%*
NM7Q hydrological winter half-year (Nov-Apr)	Basle	+5% to +15%	*0% to +15%*
	Maxau	0% to +10%	*-5% to +15%*
	Worms	+5% to +15%	*-5% to +15%*
	Kaub	0% to +15%	*-5% to +15%*
	Cologne	0% to +15%	*0% to +20%*
	Lobith	0% to +15%	*-5% to +15%*

Colour coding of 21st century change signals (key)

Orange	decreasing trend
Grey	no clear trend
Blue	increasing trend

The results indicate a range from a -10% decrease to a +10% increase in NM7Q discharges for the hydrological summer half-year in the near future. In the hydrological winter half-year, no changes or only slight increases (0 to +5%) are shown up to a general increase by up to 15% at the end of the range for the Rhine gauges. For the remote future, the effects tend to shift in the direction of lesser low-water discharges; for the summer half-year the ranges are completely in the negative range of change.

Concerning the future developments of water temperatures with summer low water events, the study by the **ICPR Expert Group STEMP** (ICPR, 2014) showed that the comparison of average August water temperatures (representative for summer) over the Rhine longitudinal section between the reference period from the studies of the time (2001- 2010) and the near future (2021-2050) shows an increase in the average August water temperature of about 1.5 °C, while in the remote future (2071-2100) the increase is about 3.5 °C. This warming is due to climatic conditions, without an additional effect due to significant heat inputs[6] (ICPR, 2015). In addition, in the near future, the ecologically critical number of days with water temperatures above 25°C is expected to increase compared to the reference, with up to double the low discharge. Furthermore, in the remote future, the days on which 25 °C and 28 °C are exceeded will increase sharply. These findings show that low water events in the summer half-year (such as those from 2003 and 2006) could become increasingly significant on the Rhine in the future in terms of their ecological impact.

According to the **KLIWAS** project (BMVBS, 2015), the characteristic value NM7Q in an ensemble examination for the Rhine gauges for the near future in the water management year (1/4 to 31/3) ranges between -5% and + 10%. In the remote future, the range will tend towards lower discharges from -10% /-20% to + 10%. The change in the so-called equivalent discharge (GlQ) at the Kaub gauge (719 m³/s, approx. NM7Q5) was

[6] Due to the interim shutdown of several nuclear power plant blocks in the Rhine catchment area these statements are already outdated. Reliable predictions of heat input trends could further improve forecasts for water temperature. (ICPR, 2015)

investigated in KLIWAS with regard to the development of low-water durations. While the GlQ at the Kaub gauge is fallen short of for an average of 18 days during the reference period, the possible margin for the near future is between 10 and 25 days, i.e. between a slight decrease and a slight increase. For the remote future, a range of 15 to 50 days is more likely to lead to a significant increase in the number of shortfall days.

Continuously decreasing low water characteristic values for 3 model runs were determined by the **KLIWA** Working Group based on the regional model COSMO-CLM4.8 and the emission scenario A1B for the near future in the hydrological year (see Tab. 17) (HYDRON, 2017).

Table 17: Changes in low water conditions for the near future at the Kaub gauge (change in discharge in %, duration change in days)

	MNQ	MNM7Q	MNM21Q	maxD < MNQ	sumD < MNQ
run1	-8.9 %	-8.8 %	-9.2 %	+ 12.6 d	+ 17.8 d
run2	-8.9 %	-9.0 %	-8.7 %	+ 6 d	+ 4.6 d
run3	-4.0 %	-4.4 %	-6.2 %	+ 8.1 d	+ 10.1 d

However, these results do not represent a model range in the sense of using several different model chains, but rather show the variation of a model chain under different initial conditions. For these discharge projections there are decreases in low-water discharges of between 5 and 10% at the Kaub gauge. The shortfall durations below the MNQ threshold used here increase by between 5 and 17 days. These changes result mainly from significant changes in the hydrological summer half-year (NM7Q decreases between -5 and -13%). For the hydrological winter half-year, both decreases of the NM7Q (Run2: -7.2 %) and minimal changes (Run1: -1.2 %. Run3: 0.4 %) result, depending on the run.

8.2 Investigation of the discharge projections COSMO-CLM4.8-A1B

Since an increase in low-water discharge is not critical, the COSMO-CLM4.8 discharge projection, which predicts declining low-water discharges, was taken from the range of possible future developments for further investigation as an unfavourable variant with regard to the impacts, in order to describe possible knock-on effects. To achieve direct comparability with the investigation methodology in the EG LW, these discharge projections were evaluated with reference to the water balance year and with determination of recurrence intervals. Since all three runs are equally probable, they were considered and evaluated as a total collective for the near future (2021-2050) (see Tab. 18).

Table 18: Low water characteristic values for COSMO-CLM4.8-A1B discharge projection

Model projections COSMO-CLM4.8-A1B: **NM7QT**, discharges in [m³/s]						
Return period:	**T=2a**	**T=5a**	**T=10a**	**T=20a**	**T=50a**	**MNM7Q**
Worms/Rhine 1971-2000 simulated	748	643	595	558	520	762
Worms/Rhine 2021-2050 simulated	696	581	529	489	446	711
(2021-2050) – (1971-2000) [%]	**-7 %**	**-10 %**	**-11 %**	**-12 %**	**-14 %**	**-7 %**
Kaub/Rhine 1971-2000 simulated	909	765	700	651	599	929
Kaub/Rhine 2021-2050 simulated	826	684	620	572	521	846
(2021-2050) – (1971-2000) [%]	**-9 %**	**-11 %**	**-11 %**	**-12 %**	**-13 %**	**-9 %**
Cologne/Rhine 1971-2000 simulated	1077	894	810	746	679	1101
Cologne/Rhine 2021-2050 simulated	972	792	709	647	581	996
(2021-2050) – (1971-2000) [%]	**-10 %**	**-11 %**	**-12 %**	**-13 %**	**-14 %**	**-10 %**

According to this scenario, the MNM7Q values will increasingly decrease downstream from Worms (-7%), through Kaub (-9%) to Cologne (-10%) in the near future (2021-2050). The n-annual NM7Q values defined in Chapter 9.1 as low water discharge threshold values, show very similar changes for all gauges with decreases of -10% for a 5-year NM7Q to -14% for a 50-year NM7Q.

To consider the change in the maximum contiguous MaxD shortfall durations lower than the threshold value NM7Q2, the number of days on which the NM7Q2 determined in the reference period was fallen short of during a low water event is listed for different return periods in Table 19.

If the low-water discharges are decreasing altogether, it is expected that, if the threshold value NM7Q2 from the reference period is adhered to, there will be longer shortfall durations below this threshold value. While there are only 4 shortfall days for an average 2-year event in the model reference period, in the future scenario they increase dramatically to 11 to 13 days. For the rarer events of a 5 to 20-year event, the shortfalls still increase by half to three-quarters in comparison with the reference period.

Table 19: Model projection shortfall duration MaxD < NM7Q2 in days

Model projection COSMO-CLM4.8-A1B: **Shortfall duration MaxD < NM7Q2(ACTUAL)** in [days]					
Return period:	**T=2a**	**T=5a**	**T=10a**	**T=20a**	**T=50a**
Worms simulated 1971-2000 < 748 m³/s	4	22	37	47	61
Worms simulated 2021-2050 < 748 m³/s	11	33	55	76	
(2021-2050) – (1971-2000) [%]	**184 %**	**52 %**	**49 %**	**62 %**	
Kaub simulated 1971-2000 < 909 m³/s	4	24	39	51	62
Kaub simulated 2021-2050 < 909 m³/s	13	37	61	80	
(2021-2050) – (1971-2000) [%]	**253 %**	**54 %**	**55 %**	**58 %**	
Cologne simulated 1971-2000 < 1077 m³/s	4	23	37	46	54
Cologne simulated 2021-2050 < 1077 m³/s	13	38	58	81	
(2021-2050) – (1971-2000) [%]	**260 %**	**63 %**	**57 %**	**77 %**	

The methods and time intervals deployed throughout the study are used so that the effects can be compared with the other results. The results represent a projection with slight decreases in the low water characteristic values (decrease by -4 to -9% for the MNQ of the hydrological year - see Chapter 8.1), while in the ranges of other investigations there are also projections with a discharge increase in the near future.

8.3 Effects to be considered under the aspect of low water prevention

The results of these investigations show changes in low-water parameters in the near future ranging from decreases of -5% to increases of 10% when considering the water balance year from 1 April to 31 March. Change percentages for hydrological years and half-years from other bandwidths cannot be compared directly because they do not correspond to the low-water regime on the Rhine. When the hydrological year or the hydrological summer/winter half-years are used, the low water periods typical of the Rhine are interrupted from September to December and are not recorded as a whole event. It is not clear whether the low water discharges will decrease in the near future or only in the remote future. In the near future, in the sense of a **precautionary consideration**, the less favourable case of a moderate decrease in low water discharges of the order of 5 to 10% must be assumed. The effects of such a scenario have been investigated, and they result in decreases of 7% to 14% in the T-year low water NM7QT values. The associated tripling of shortfall durations is very high for a frequent 2-year event, while for less frequent 5- to 20-year events, shortfall durations increase by a half to three-quarters.

The results presented here represent a picture of a possible future based on the assumptions or starting points chosen for the analysis. Other discharge projections could lead to different results.

9. Low water monitoring

The monitoring of the occurrence of low water or the examination of historical discharge series with regard to the occurrence of low water requires threshold values in order to define the low water fall and, where applicable, to classify it in its expression.

9.1 Derivation of a classification of low water conditions

Low water is referred to when the current discharge has fallen below a typical threshold value for the body of water. Fixed threshold values, which are usually long-term MNQs or similar characteristic values, or temporally variable (usually monthly) characteristic values can be taken as the respective comparison value. To differentiate the degree of low water present, graded threshold values are needed to classify low water events from "normal" to "extreme". To map a synoptic overview of the gauges investigated on the Rhine, NM7Q values are used for different recurrence intervals related to the long-term reference time series (1961-2010) of the respective gauges for the classification of low water conditions. Table 20 lists the selected low water classes in terms of their severity and description, and contains a colour legend to indicate shortfalls of certain low-water threshold values.

Table 20: Definition of low water classes

Colour	Class	Severity	Designation
green	**0**	**>= NM7Q(T2)**	**normal = no LW**
yellow	**1**	**< NM7Q(T2)**	**frequent LW**
orange	**2**	**< NM7Q(T5)**	**less frequent LW**
red	**3**	**< NM7Q(T10)**	**rare LW**
purple	**4**	**< NM7Q(T20)**	**very rare LW**
black	***5***	***< NM7Q(T50)***	***extremely rare LW***

(coordinated with the ICPMS)

Normal low-water discharges are present as long as the respective 2-yearly NM7Q is not undershot. If this first threshold value is undershot, the class "frequent low water" is reached, as long as the discharges do not fall below a 5-year NM7Q. If discharges occur in the class lower than NM7Q(T5) to NM7Q(T10), the situation is designated as "less frequent low water". If a 10-year NM7Q is undershot, "rare low water" occurs and with a 20-year NM7Q shortfall, "very rare low water". The highest low water class "extremely rare low water" is reached with the undershooting of a 50-year NM7Q discharge at the respective gauge. This classification was determined after coordination with the ICPMS, which means, for example, that in the low-water monitoring on the Moselle the same classifications are used by the ICPMS as are used on the Rhine. The corresponding statistical investigations to derive the characteristic values required for the threshold values were made in Chapter 7.3.2. The required NM7Q(T) values for the Rhine gauges are listed there in Tables 8 to 12.

An implicit link between the low-water threshold values and the undershot low-water durations has been omitted in order to keep the threshold values simple and comprehensible. Nonetheless, it seems worthwhile during monitoring to also track the previous low water shortfall durations (in days) in addition to the low water class that has been attained.

9.2 Validation of low water classification using historical time series

The historical time series of the gauges were subjected to "retrospective monitoring" by means of the low-water classification specified in the previous chapter.

In Figure 18, the annual occurrence of these low water classes with duration of the days with a shortfall is shown as an example for the Basle, Kaub and Lobith gauges. The historical low water events described in Chapter 7.1 and Appendix 2 can be traced even more clearly with this monitoring, and further events that have not been described so far can be identified. The results for all gauges examined are listed in Appendix 4. The high low water classes and the significantly longer low water events in the first half of the last century are clearly visible. The events of 1920/1921, 1946-1949, 1962 and 1971 are clearly visible at almost all the gauges. In the overall period class 5 "extremely rare low water" is attained three times at the Basle and Kaub gauges and four times at the Lobith gauge, although during different events. This is due to the different discharge regime of these gauges. Class 4 "very rare low water" is reached at the Basle gauge in 6 years, at the Kaub gauge in 8 years and at the Lobith gauge in 7 years. While a total shortfall duration of 140 days in 3 years is reached at the Basle gauge, at the Kaub gauge there are clearly exceedances for 140 days in 4 years, and of these even 180 days in 2 years. At the Lobith gauge there are also exceedances on 140 days on three occasions, and in 1921 a total of 215 days was reached. Since the mid-1970s, the low-water events have been less pronounced, and at the Basle gauge in 2005 the class 3 "rare low water" (T < 10 to 20a) was reached once, at the Kaub gauge this was the case twice (1985 and 2003), while at the Lobith gauge class 3 was reached in 1991 and 2003. After the clearly perceived event in 2003, it is still possible to find 4 years at the Kaub gauge where class 2 "less frequent low water" is reached.

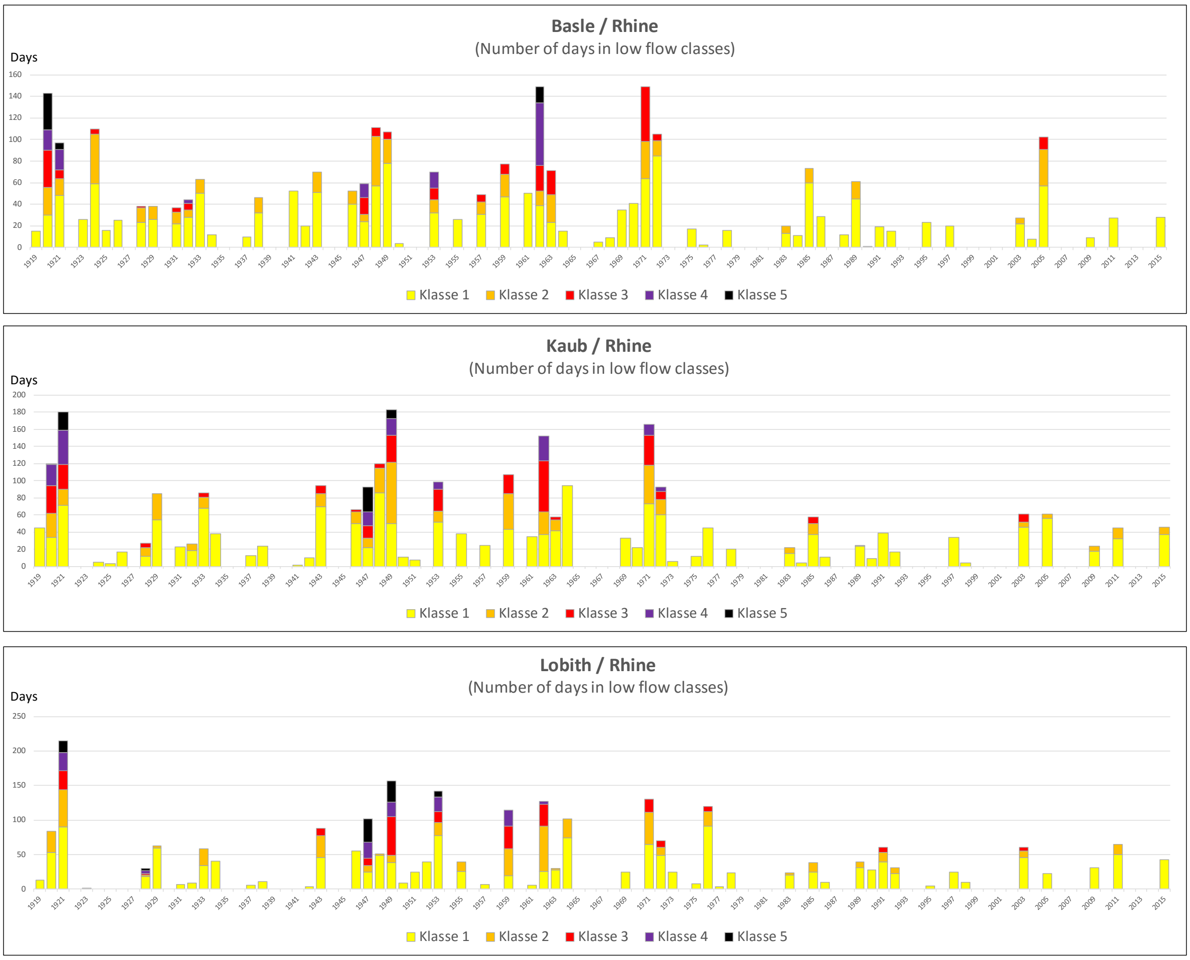


Figure 18: Retrospective monitoring at the Basle, Kaub and Lobith gauge

Tables 21 to 23 compare the annual average number of days with discharges in the defined low water classes for different decades and sub-periods.

Table 21: Mean annual low water days Basle gauge

Year	Class 1	Class 2	Class 3	Class 4	Class 5
1921 - 1930	22.3	8.8	1.4	1.9	0.6
1931 - 1940	15.4	4.5	1.0	0.3	0.0
1941 - 1950	32.6	10.6	3.0	1.3	0.0
1951 - 1960	13.6	4.4	2.7	1.5	0.0
1961 - 1970	21.7	3.9	4.6	5.8	1.5
1971 - 1980	18.4	4.8	5.7	0.0	0.0
1981 - 1990	17.1	3.6	0.0	0.0	0.0
1991 - 2000	7.7	0.0	0.0	0.0	0.0
2001 - 2010	9.6	3.9	1.1	0.0	0.0
1921 - 2010	17.6	4.9	2.2	1.2	0.2
1921 - 1960	21.0	7.1	2.0	1.3	0.2
1961 - 2010	14.9	3.2	2.3	1.2	0.3

Table 22: Mean annual low water days Kaub gauge

Year	Class 1	Class 2	Class 3	Class 4	Class 5
1921 - 1930	16.2	6.0	3.4	4.0	2.1
1931 - 1940	18.5	2.0	0.5	0.0	0.0
1941 - 1950	30.1	14.1	6.2	3.6	3.9
1951 - 1960	16.6	5.5	4.7	0.9	0.0
1961 - 1970	26.3	3.9	6.3	2.9	0.0
1971 - 1980	21.6	6.3	4.5	1.8	0.0
1981 - 1990	10.0	2.1	0.8	0.0	0.0
1991 - 2000	9.4	0.0	0.0	0.0	0.0
2001 - 2010	12.0	1.7	0.9	0.0	0.0
1921 - 2010	17.9	4.6	3.0	1.5	0.7
1921 - 1960	20.4	6.9	3.7	2.1	1.5
1961 - 2010	15.9	2.8	2.5	0.9	0.0

Table 23: Mean annual low water days Lobith gauge

Year	Class 1	Class 2	Class 3	Class 4	Class 5
1921 - 1930	17.0	6.0	2.9	3.1	2.0
1931 - 1940	10.8	2.4	0.0	0.0	0.0
1941 - 1950	22.6	5.3	7.8	4.4	6.5
1951 - 1960	19.5	7.1	4.8	4.5	0.8
1961 - 1970	15.9	9.5	3.2	0.4	0.0
1971 - 1980	26.6	7.9	3.6	0.0	0.0
1981 - 1990	11.5	2.4	0.0	0.0	0.0
1991 - 2000	10.2	2.2	0.8	0.0	0.0
2001 - 2010	10.0	0.9	0.6	0.0	0.0
1921 - 2010	16.0	4.9	2.6	1.4	1.0
1921 - 1960	17.5	5.2	3.9	3.0	2.3
1961 - 2010	14.8	4.6	1.6	0.1	0.0

The variation for the average shortfall durations in the decades, which predominantly coincides for the gauges, can be seen from Tables 21 to 23. The 1940s were by far the most pronounced low-water decade. Discharges of class 1 occurred during this decade in Basle and Kaub on about 300 days, and in Lobith it was 226 days. While class 2 occurred on 106 days in Basle, it was 141 days in Kaub and only 53 days in Lobith. The low water class 3 to 5 occurred on 137 days in Kaub, which was clearly more days than in Basle (43 days), while in Lobith it was even 187 days. The decade with the fewest low waters was the 1990s. In Basle, class 1 occurred on 77 days in this decade (Kaub 94 days, Lobith 102 days), while class 2 was not reached in Basle and Kaub, but in Lobith it was reached on 22 days. In Lobith, class 3 was even reached on 8 days in the 1990s; the decade from 2001 to 2010 there had even less low water than in the 1990s.

The comparison of the sub-period 1921-1960 with the reference period 1961-2010 illustrates in particular for the less frequent low water classes 2 to 5 the decline of low water situations in the more recent reference period at the Kaub and Lobith gauges.

The review of the set low water threshold values or low water classes by comparison with historical events confirms the adequacy of these threshold values. The low-water threshold values are sensitive enough to detect even smaller but more frequent events over the last 40 years and still differentiate between different low-water severities. On the other hand, the specified low-water classes do justice to the great historical events, which naturally occur less frequently, but stand out from the total collective in particular due to representation of the total duration of the low-water days.

Thus, the suitability of the set low water threshold values for future monitoring can be confirmed. However, in addition to the low water discharges, the number of contiguous shortfall days should also be monitored.

10. Conclusions

Low-water discharge regime of the Rhine

The quantitative proportions from different sub-basins of the Rhine are significant for the natural low-water discharge. The gauge-related analysis of discharge values for some monitoring stations along the Rhine also illustrates the importance of the discharge components from the Alpine and Alpine foothills area for the low-water range of the entire course of the Rhine. In addition, the changing discharge regime with a winter minimum in the nival area (to Basle) and a summer minimum in the pluvial area (downstream of Worms) creates a certain resilience against extreme low water events for the entire Rhine.

The historical low-water events occur along the course of the Rhine to varying degrees, especially in the case of extreme events. 100-year events in the southern Upper Rhine (Basle) were able moderate themselves until a 15-year event in Lobith (event in March-May 1921). On the other hand, events of moderate return period occurred in Basle (10 - 40-year) and developed downstream to over 100-year events on the Lower Rhine (events in 1947 and 1949). The smaller low-water events of recent times tend to display uniform characteristics (1971: 20 – 30-year; 1976: 2 – 5-year; 1985: 10-year; 2003: 5 – 20-year; 2011: 10-year; 2015: 5 – 10-year).

Low water influences

An inventory of existing discharge influences on the low-flow run-offs in the Rhine shows a positive balance in terms of discharges and abstractions. In addition, it is above all the influence of storage management in the Alpine region since the 1960s - 1970s that has led to significantly increasing low water discharges for the lowest low water levels that occur in the winter season in accordance with the Rhine discharge regime. Since the mid-1990s, water from the Danube catchment area has been fed to the Main (transfer system completed in 1999). Overall, positive influences on the low-water discharge on the Rhine predominate.

Vulnerabilities

After taking stock of existing low water vulnerabilities, there are many economic implications that are, however, difficult to quantify. Cross-border shipping is affected with its dependent persons and economic sectors. With declining discharge, hydroelectric power plants can only produce smaller amounts of electricity. Ecological impairments arise especially for summer low water. In particular in the regional water systems of the Rhine delta there is also the risk of salt water intrusion on the Rhine with low water, and peat dykes located there may become unstable with low water.

Investigation of historical discharge series

According to the evaluation of historical discharge series, low water levels on the Rhine were much more pronounced in the first half of the last century and occurred with lower discharges and longer shortfall durations than in the last 50 years. With regard to the low water discharges, a significantly increasing trend can be determined for the Rhine from Diepoldsau to Andernach for the entire period from 1901 to 2010. This trend is mainly attributable to the influence of storage management in the Alpine region. The increasing trend of annual precipitation in the 20th century for the Rhine catchment area may also be contributing to that. No trends can be detected for the low-water discharges for the period from 1961 to 2010. The current perception of low water events is influenced on the one hand by the long absence of significant low water events and on the other by increased vulnerability.

Based on a detailed analysis of the historical discharge series, discharge-related threshold values for the classification of the low water situation into five characteristic states from "normal" to "extremely rare low water" were derived for the Rhine in coordination with the International Commissions for the Protection of the Moselle and the Saar (ICPMS). The suitability of this classification, which provides a differentiated classification of low water events, has been validated by applying it to historical discharge time series. Extreme events can be clearly distinguished from smaller events, with sufficient sensitivity to minor low water events.

Possible future impacts of climate change

The low-water discharge developments due to climate change in existing discharge projections for the period 2021-2050 for the Rhine range from decreases of 10% to increases of 10% and show no clear development. For the remote future (2071-2100), the discharge projections for the hydrological summer half-year consistently show significant low water discharge reductions.

For a pessimistic scenario with low water decreases of 5 to 10% of the MNM7Q (long-term average low water discharge on 7 consecutive days) for the period 2021-2050, there are greater decreases from 7 to 14% for 2 to 50-year low water discharges with increasing return period. The decrease in the discharge is accompanied by a significant extension of the low water duration.

Low water events in the summer half-year could become increasingly significant on the Rhine in future, especially in terms of their ecological impact. With low discharges, water temperatures can increase more in summer. An example of this is the low water events in 2003 and 2006. According to research by the ICPR Expert Group STEMP, summer water temperatures on the Rhine are expected to rise by 1.5 °C in the near future and over 3 °C in the remote future. For the near and remote future, especially with low discharge, this means an increase in days with water temperatures above 25 °C (ecologically critical threshold value) in the Rhine.

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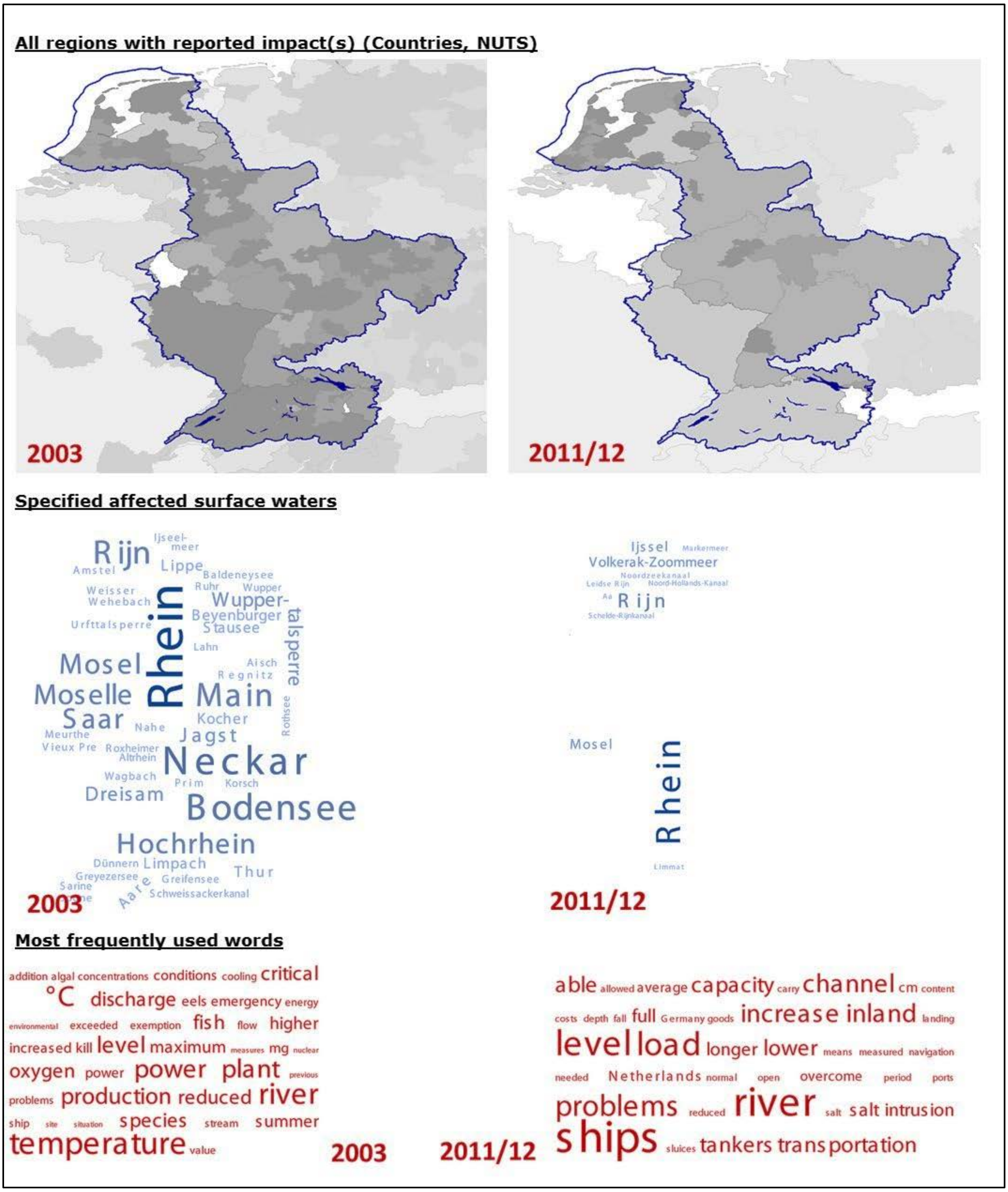
Appendices

Appendix 1: Comparison of the effects of low water events in 2003 and 2011 based on the European Drought Impact Inventory (EDII) (Kohn, 2017)

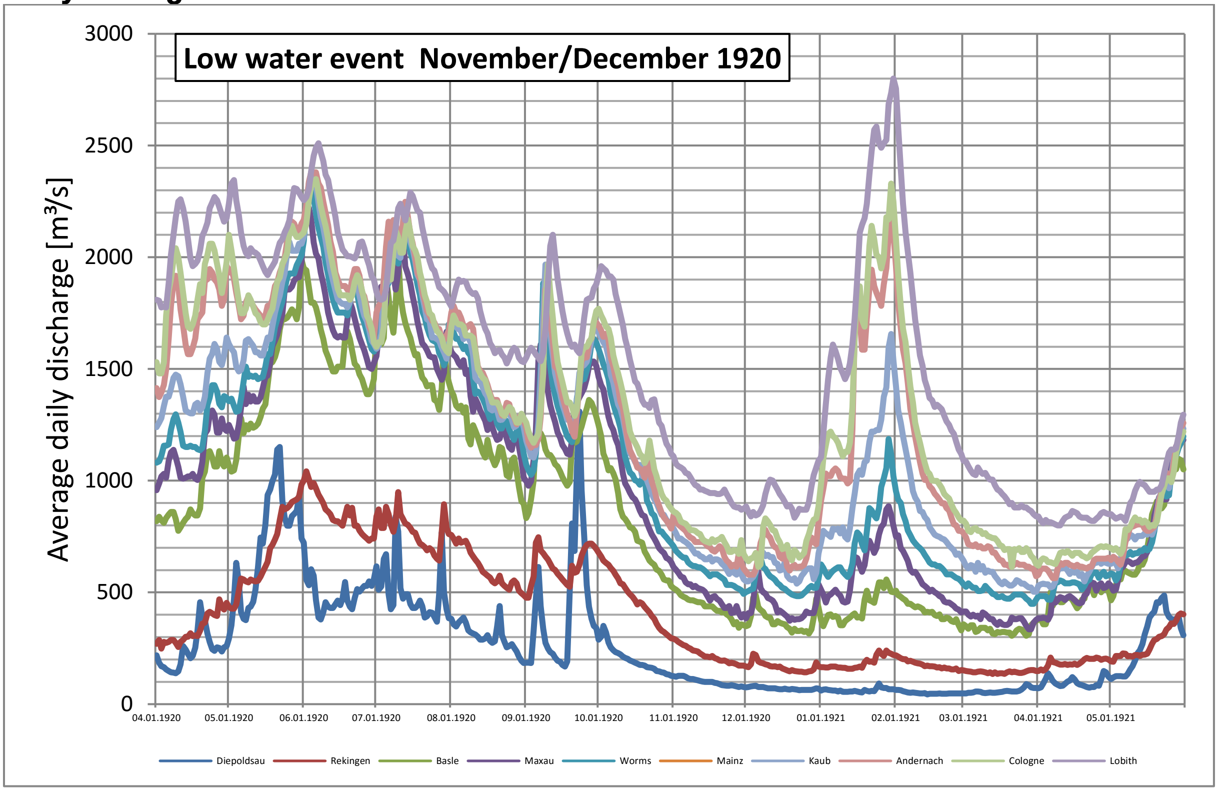


Appendix 2: Descriptions of selected low water events

Comment: *In addition to the event in 2003, which was described in detail in Chapter 7.5, the ICPR has obtained detailed information on meteorological and hydrological developments as well as on the impact of specific events in Switzerland.*

Low water event: November/December 1920

1 Hydrological curves:



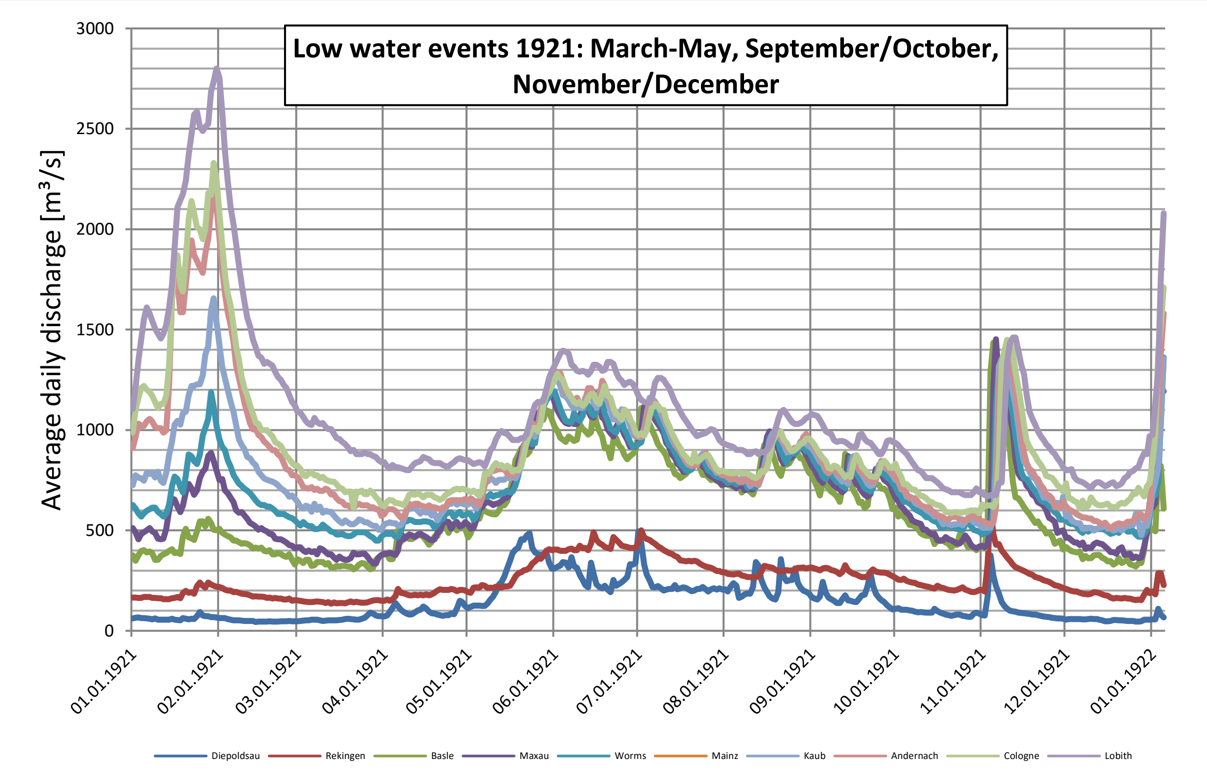
2 Characteristic values:

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Nov/Dec 1920	Return period Nov/Dec 1920	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Nov/Dec 1920	Return period Nov/Dec 1920
Diepoldsau	92.2	64	15 - 20	4	42	> 50
Rekingen	238	145	50	7	75	> 50
Basle	527	326	100	5	85	> 50
Maxau	645	382	50	5	76	> 50
Worms	720	489	20	5	75	> 50
Mainz	850	-	-	6	-	-
Kaub	851	559	20	6	79	50
Andernach	998	596	50	6	72	50
Cologne	1028	645	50	6	69	40
Lobith	1095	858	15	6	60	15

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Low water events 1921: March-May, Sep/Oct and Nov/Dec

1 Hydrological curves:



2 Characteristic values:
Event March – May 1921

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Mar - May 1921	Return period Mar - May 1921	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Mar - May 1921	Return period Mar - May 1921
Diepoldsau	92.2	49	100	4	67	> 50
Rekingen	238	138	100	7	108	> 50
Basle	527	318	100	5	95	> 100
Maxau	645	359	60	5	96	> 100
Worms	720	468	30	5	99	> 50
Mainz	850	-		6	-	
Kaub	851	523	50	6	96	> 50
Andernach	998	589	50	6	97	> 100
Cologne	1028	637	50	6	100	> 100
Lobith	1095	809	15	6	85	> 50

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Event September / October 1921

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Sep/Oct 1921	Return period Sep/Oct 1921	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Sep/Oct 1921	Return period Sep/Oct 1921
Diepoldsau	92.2	75	5	4	17	20
Rekingen	238	199	5	7	25	2-5
Basle	527	414	5-10	5	27	5-10
Maxau	645	420	20	5	33	10
Worms	720	494	20	5	36	10
Mainz	850	-	-	6	-	-
Kaub	851	523	50	6	51	20
Andernach	998	544	100	6	78 *	50 *
Cologne	1028	590	100	6	119	> 100
Lobith	1095	682	75	6	79 *	> 50 *

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

*Low water period interrupted by a day with Q > threshold value, otherwise it would be return period > 100

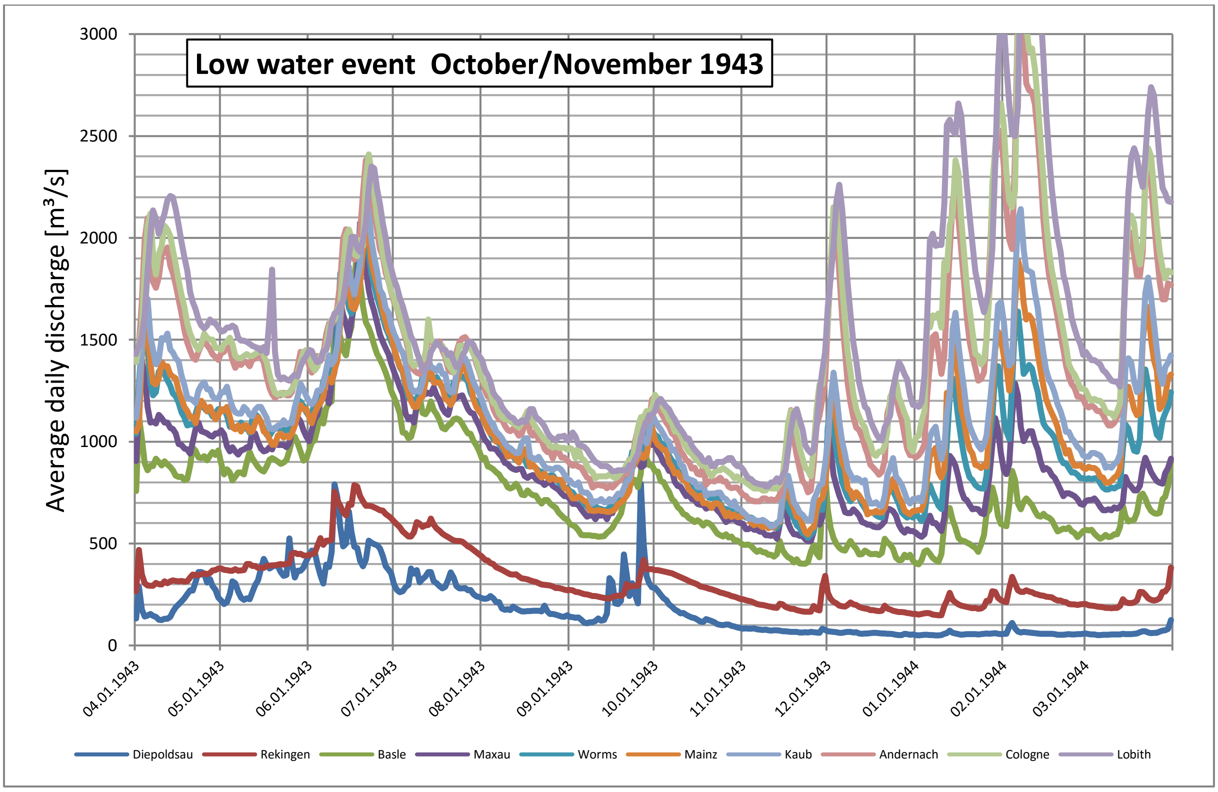
Event November / December 1921

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Nov/Dec 1921	Return period Nov/Dec 1921	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Nov/Dec 1921	Return period Nov/Dec 1921
Diepoldsau	92.2	48	100	4	50	> 100
Rekingen	238	157	20	7	38	5-10
Basle	527	336	50	5	42	15
Maxau	645	371	50	5	43	15
Worms	720	483	50	5	45	15
Mainz	850	-	-	6	-	-
Kaub	851	509	70	6	48	15
Andernach	998	527	> 100	6	49	15
Cologne	1028	623	60	6	49	15
Lobith	1095	729	30	6	45	10

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Low water event: October/ November 1943

1 Hydrological curves:



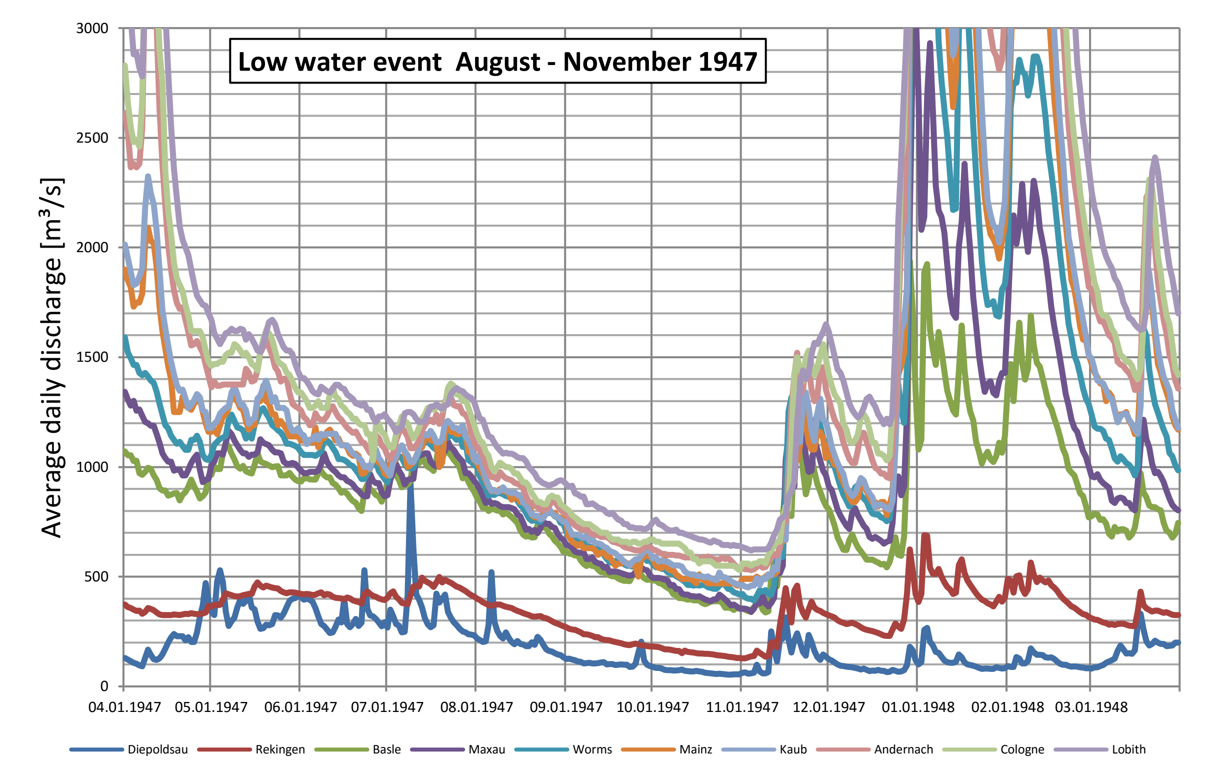
2 Characteristic values:

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Oct/Nov 1943	Return period Oct/Nov 1943	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Oct/Nov 1943	Return period Oct/Nov 1943
Diepoldsau	92.2	64	20	4	32	>100
Rekingen	238	170	15	7	29	5
Basle	527	410	15	5	38	10
Maxau	645	530	5	5	21	5
Worms	720	556	5-10	5	23	5
Mainz	850	586	20	6	52	20
Kaub	851	601	20	6	49	20
Andernach	998	712	15	6	39	10
Cologne	1028	769	10	6	37	10
Lobith	1095	791	15	6	41	5-10

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Low water event: August - November 1947

1 Hydrological curves:



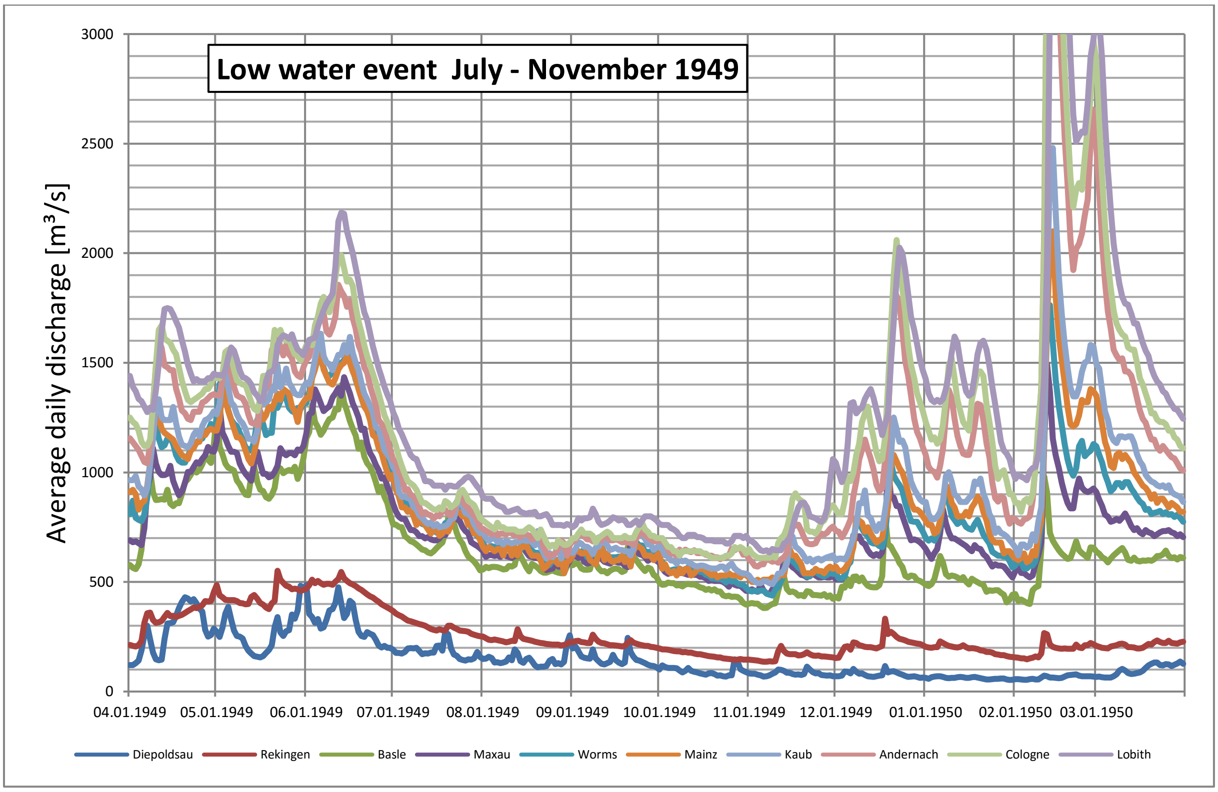
2 Characteristic values:

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q 1947	Return period 1947	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q 1947	Return period 1947
Diepoldsau	92.2	55	50	4	41	>100
Rekingen	238	131	100	7	68	20
Basle	527	351	40	5	60	55
Maxau	645	353	70	5	75	70
Worms	720	407	70	5	75	>50
Mainz	850	467	>100	6	93	>50
Kaub	851	460	>100	6	92	>>50
Andernach	998	536	>100	6	105	>100
Cologne	1028	546	>100	6	104	>100
Lobith	1095	624	>100	6	104	>>50

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Low water event: July - November 1949

1 Hydrological curves:



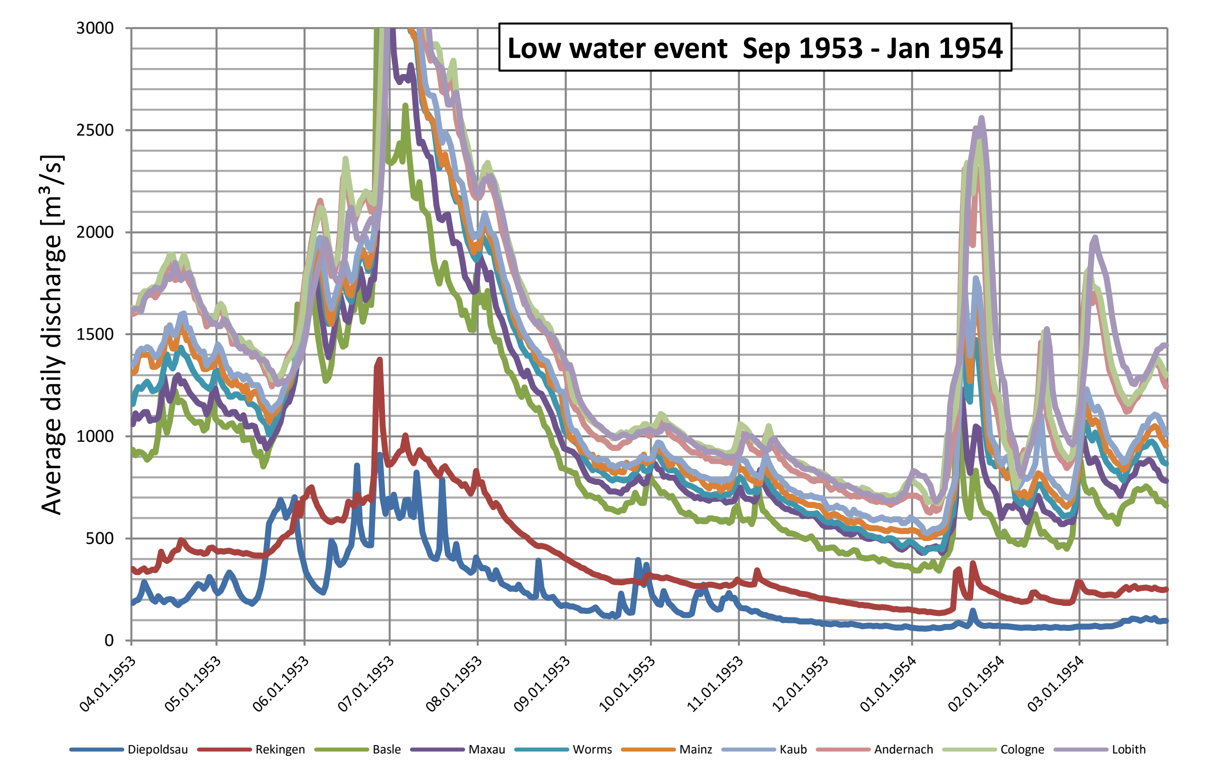
2 Characteristic values:

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Jul -Nov 1949	Return period Jul-Nov 1949	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Jul-Nov 1949	Return period Jul-Nov 1949
Diepoldsau	92.2	72	5-10	4	14	10
Rekingen	238	138	100	7	99	>50
Basle	527	392	10	5	44	20
Maxau	645	460	10	5	75	>50
Worms	720	452	35	5	131	>>50
Mainz	850	506	75	6	169	>>50
Kaub	851	497	>100	6	137	>>50
Andernach	998	587	>100	6	158	>100
Cologne	1028	611	70	6	156	>100
Lobith	1095	644	>100	6	151	>>50

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Low water event: September 1953 to January 1954

1 Hydrological curves:



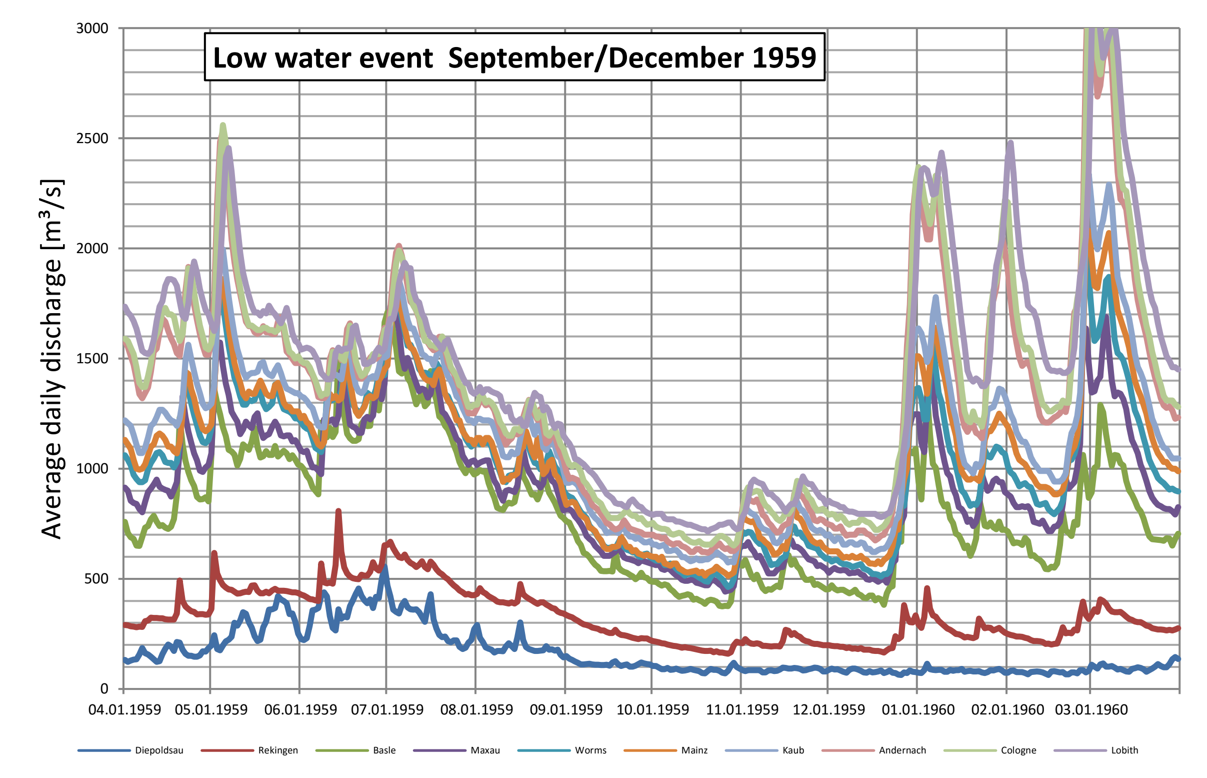
2 Characteristic values:

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Sep 1953 – Jan 1954	Return period Sep 1953 – Jan 1954	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Sep 1953 – Jan 1954	Return period Sep 1953 – Jan 1954
Diepoldsau	92.2	60	25	4	50	>100
Rekingen	238	137	100	7	56	10-20
Basle	527	354	35	5	59	>50
Maxau	645	446	15	5	60	50
Worms	720	447	40	5	63	40
Mainz	850	511	70	6	67	35
Kaub	851	542	40	6	66	35
Andernach	998	650	30	6	66	40
Cologne	1028	689	30	6	63	40
Lobith	1095	690	60	6	126	>>50

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Low water event: September – December 1959

1 Hydrological curves:



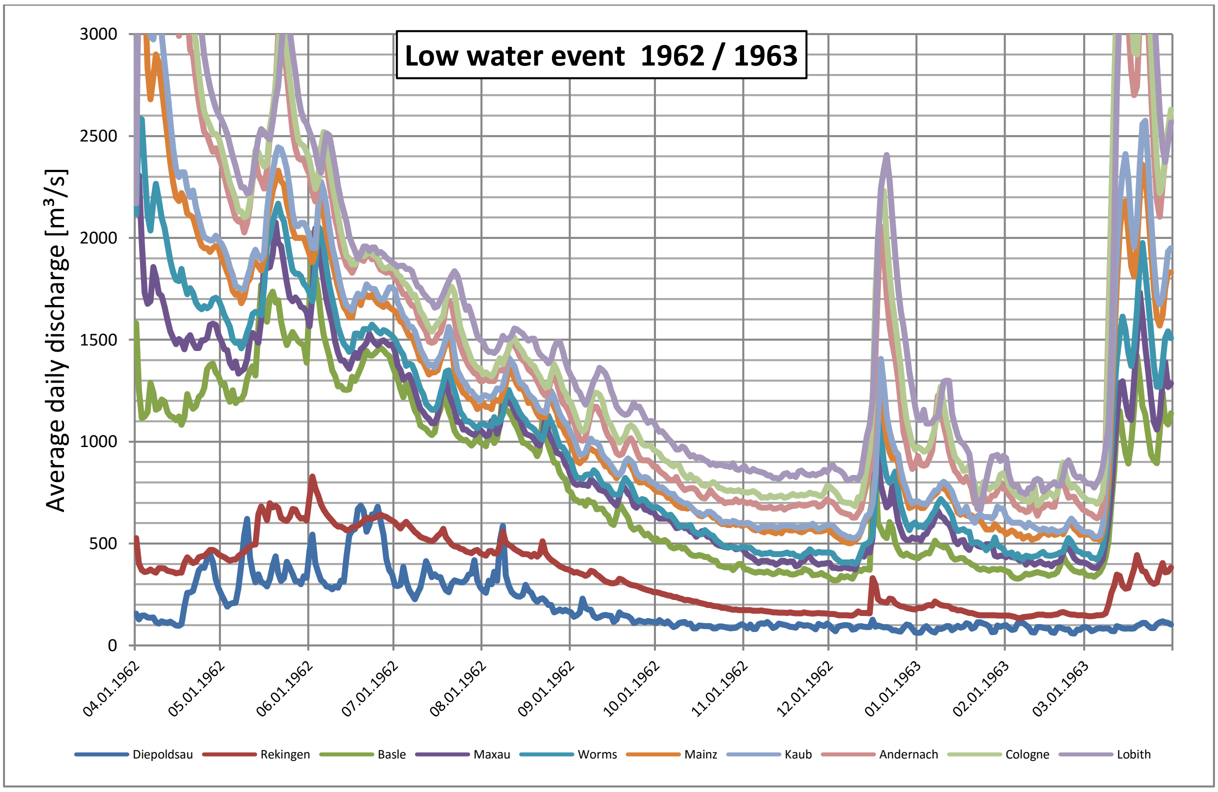
2 Characteristic values:

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Sep – Dec 1959	Return period Sep – Dec 1959	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Sep – Dec 1959	Return period Sep – Dec 1959
Diepoldsau	92.2	72	10	4	43	>100
Rekingen	238	165	20	7	54	10-20
Basle	527	386	20	5	32	5-10
Maxau	645	462	15	5	42	15
Worms	720	492	20	5	68	50
Mainz	850	529	55	6	113	>>50
Kaub	851	586	20	6	72	50
Andernach	998	625	40	6	115	>100
Cologne	1028	661	35	6	114	>100
Lobith	1095	726	35	6	115	>>50

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Low water event: October – December 1962

1 Hydrological curves:



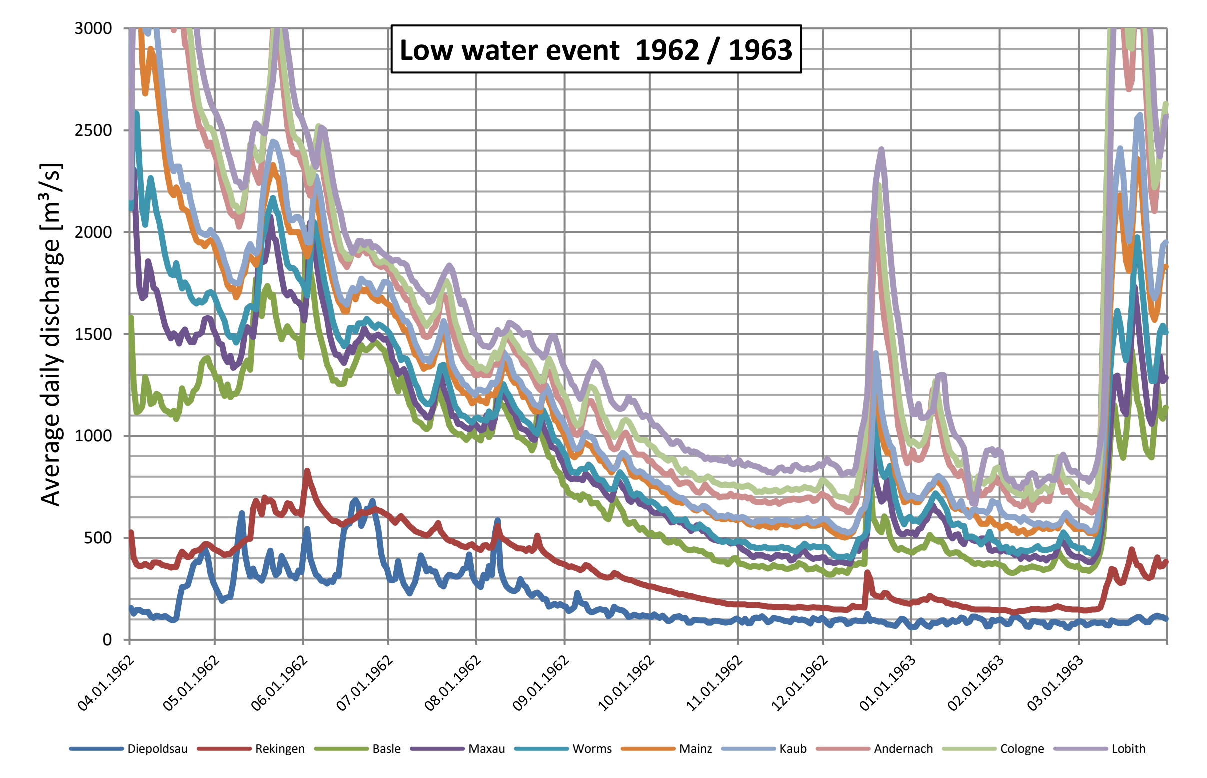
2 Characteristic values:

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Oct– Dec 1962	Return period Oct– Dec 1962	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Oct – Dec 1962	Return period Oct – Dec 1962
Diepoldsau	92.2	88	2-5	4	8	2-5
Rekingen	238	148	50	7	82	50
Basle	527	330	65	5	77	75
Maxau	645	378	50	5	77	75
Worms	720	408	70	5	84	>50
Mainz	850	512	70	6	85	>50
Kaub	851	535	50	6	85	>50
Andernach	998	642	30	6	84	50
Cologne	1028	702	20	6	82	40
Lobith	1095	824	10-15	6	76	40

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Low water event: January - March 1963

1 Hydrological curves:



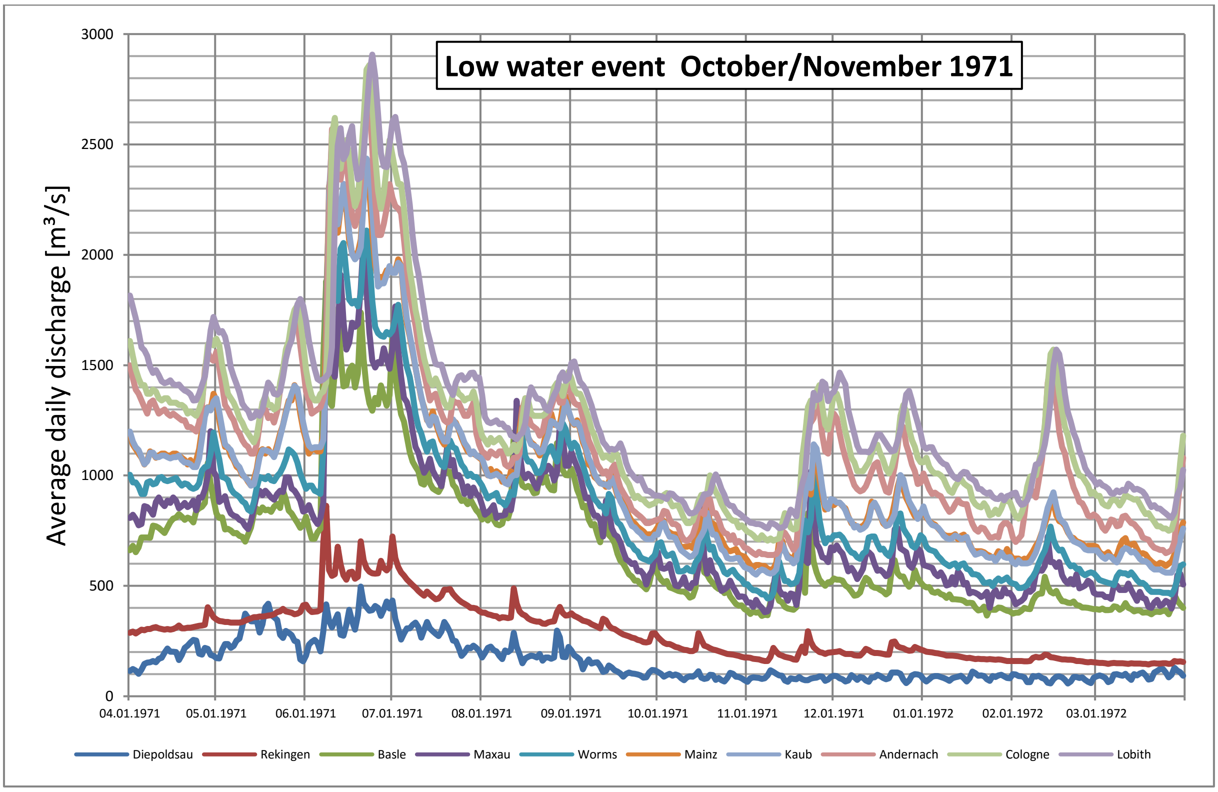
2 Characteristic values:

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Jan - Mar 1963	Return period Jan - Mar 1963	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Jan - Mar 1963	Return period Jan - Mar 1963
Diepoldsau	92.2	73	5-10	4	38	>100
Rekingen	238	139	65	7	68	20
Basle	527	338	55	5	68	>50
Maxau	645	394	35	5	60	50
Worms	720	434	50	5	73	>50
Mainz	850	530	50	6	74	40
Kaub	851	547	40	6	72	50
Andernach	998	645	30	6	56	30
Cologne	1028	712	20	6	55	20
Lobith	1095	765	20	6	55	15

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Low water event: October/November 1971

1 Hydrological curves:



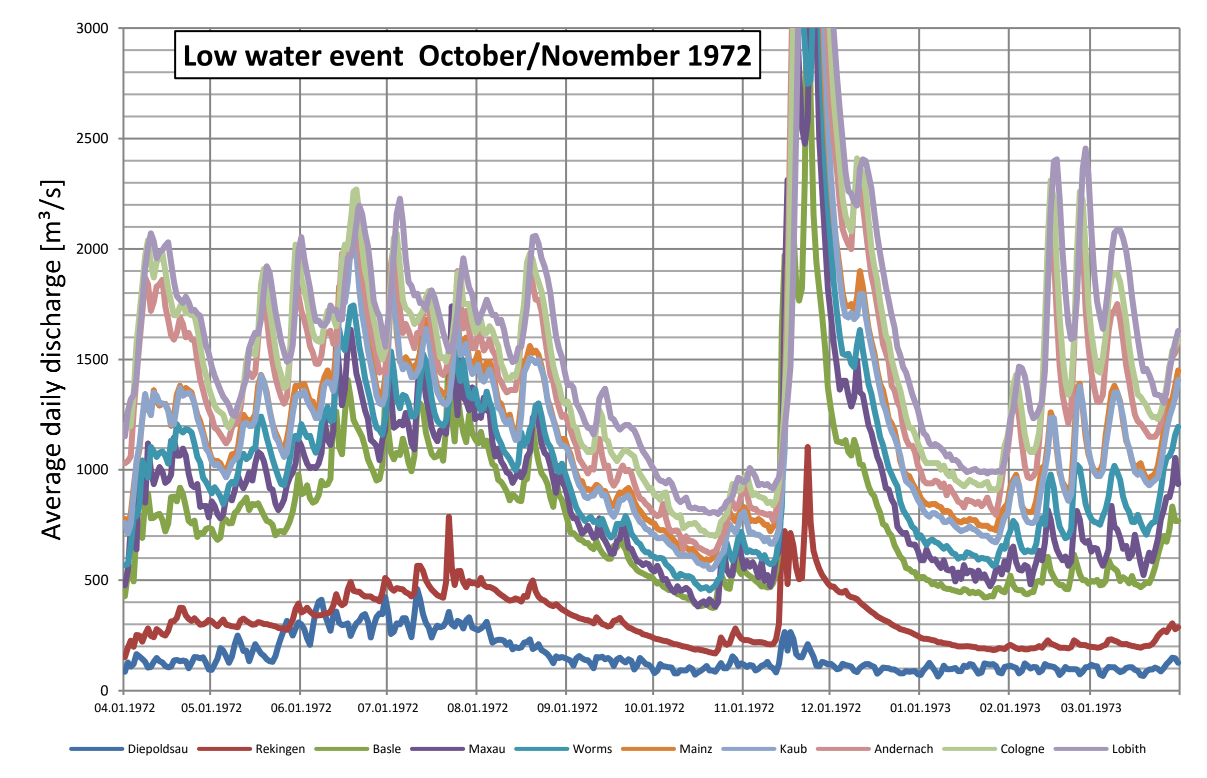
2 Characteristic values:

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Oct/Nov 1971	Return period Oct/Nov 1971	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Oct/Nov 1971	Return period Oct/Nov 1971
Diepoldsau	92.2	77	5	4	17	20
Rekingen	238	166	20	7	57	10-20
Basle	527	374	20	5	33	10
Maxau	645	404	30	5	52	30
Worms	720	462	30	5	34	10
Mainz	850	585	25	6	33	5-10
Kaub	851	562	35	6	62	30
Andernach	998	643	30	6	64	35
Cologne	1028	713	20	6	62	35
Lobith	1095	771	20	6	63	15

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Low water event: October / November 1972

1 Hydrological curves:



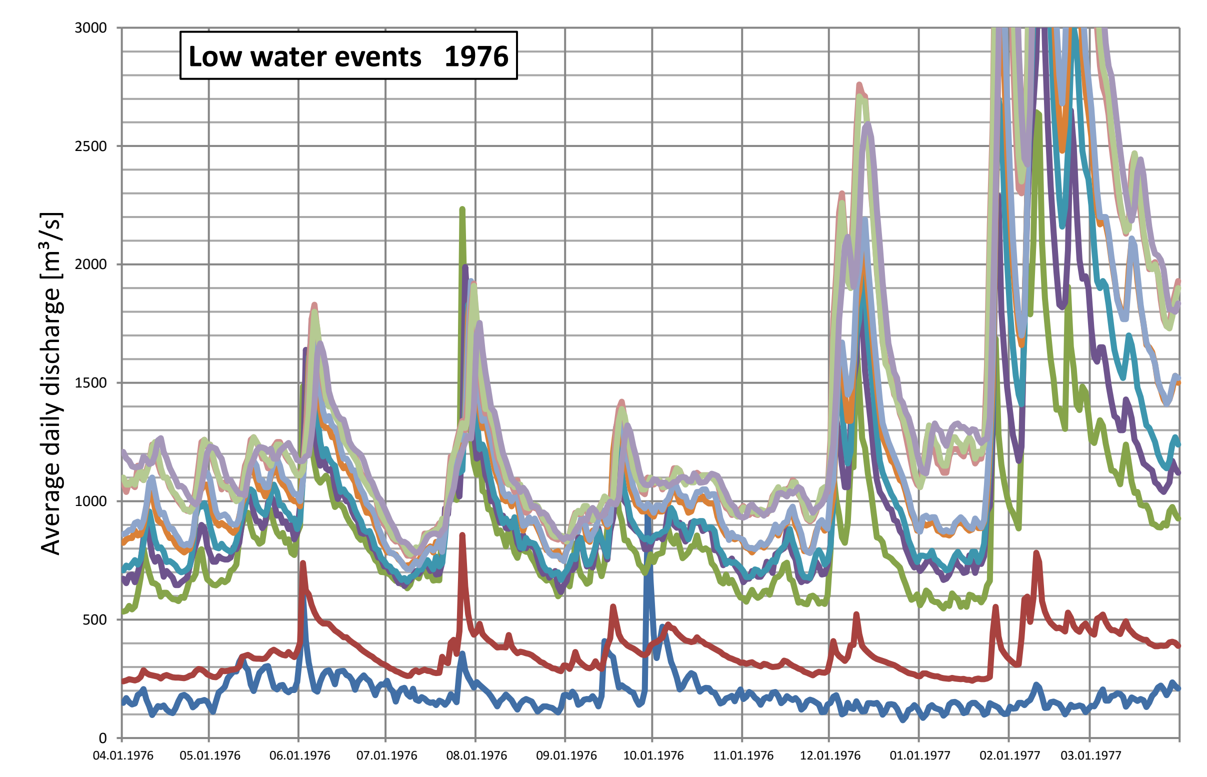
2 Characteristic values:

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Oct/Nov 1972	Return period Oct/Nov 1972	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Oct/Nov 1972	Return period Oct/Nov 1972
Diepoldsau	92.2	90	2	4	3	2
Rekingen	238	178	10	7	27	5
Basle	527	384	10	5	44	15
Maxau	645	395	35	5	37	15
Worms	720	467	30	5	38	15
Mainz	850	585	25	6	50	15
Kaub	851	565	30	6	51	15
Andernach	998	634	35	6	52	20
Cologne	1028	712	20	6	50	20
Lobith	1095	810	15	6	49	10

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Low water events: July 1976, August/September 1976 and October/November 1976

1 Hydrological curves:



2 Characteristic values:

Event: July 1976

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q July 1976	Return period July 1976	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q July 1976	Return period July 1976
Diepoldsau	92.2	149	<2	4	0	-
Rekingen	238	272	<2	7	0	-
Basle	527	656	<2	5	0	-
Maxau	645	665	<2	5	0	-
Worms	720	678	2-5	5	11	2-5
Mainz	850	739	2-5	6	22	5
Kaub	851	729	2-5	6	20	5
Andernach	998	782	5-10	6	23	5
Cologne	1028	796	5-10	6	25	5
Lobith	1095	802	15	6	29	5

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Event: August/September 1976

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Aug/Sep 1976	Return period Aug/Sep 1976	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Aug/Sep 1976	Return period Aug/Sep 1976
Diepoldsau	92.2	125	<2	4	0	-
Rekingen	238	295	<2	7	0	-
Basle	527	638	<2	5	0	-
Maxau	645	663	<2	5	2	<2
Worms	720	694	<2	5	8	2-5
Mainz	850	778	2-5	6	10	2-5
Kaub	851	770	2-5	6	10	2-5
Andernach	998	843	2-5	6	27	5
Cologne	1028	851	2-5	6	32	5-10
Lobith	1095	853	5-10	6	38	5-10

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

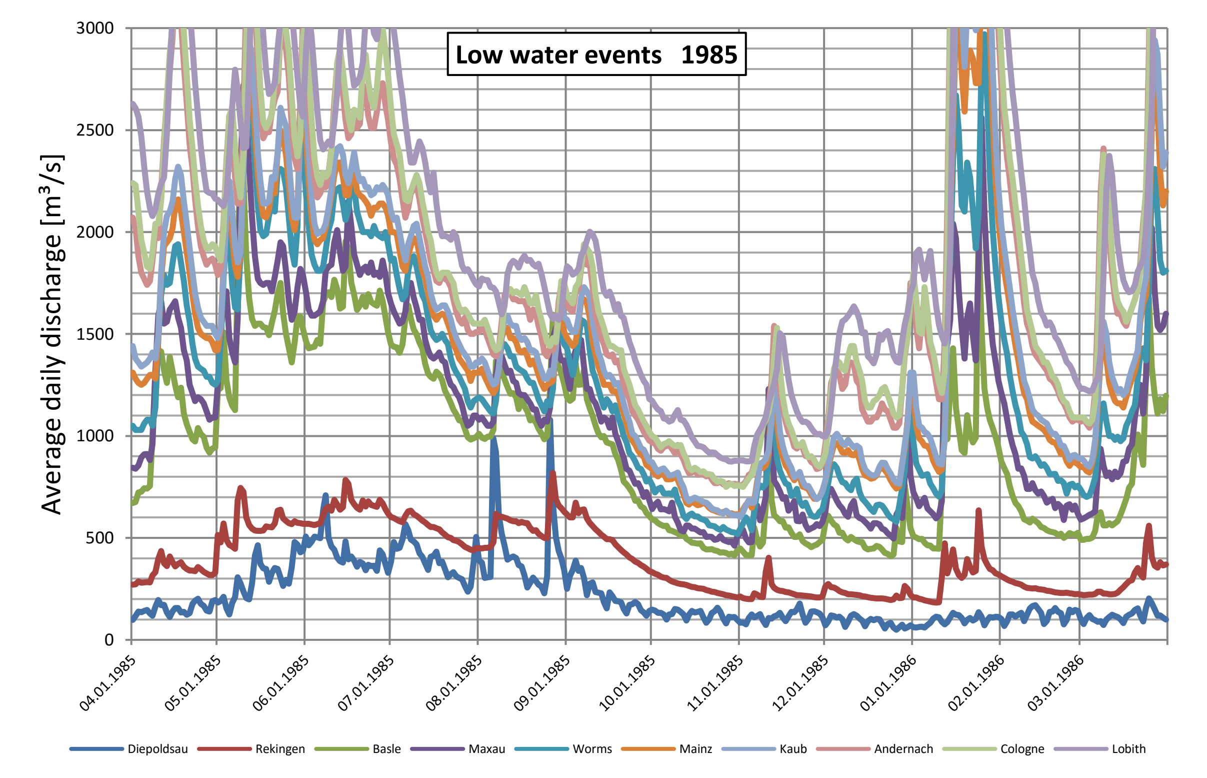
Event: October/November 1976

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Oct/Nov 1976	Return period Oct/Nov 1976	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Oct/Nov 1976	Return period Oct/Nov 1976
Diepoldsau	92.2	137	<2	4	0	-
Rekingen	238	274	<2	7	0	-
Basle	527	581	<2	5	0	-
Maxau	645	681	<2	5	0	-
Worms	720	694	2-5	5	9	2-5
Mainz	850	802	2-5	6	15	2-5
Kaub	851	809	2-5	6	15	2-5
Andernach	998	949	2-5	6	16	2-5
Cologne	1028	955	2-5	6	18	2-5
Lobith	1095	955	2-5	6	38	5-10

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Low water event: October / November 1985

1 Hydrological curves:



2 Characteristic values:

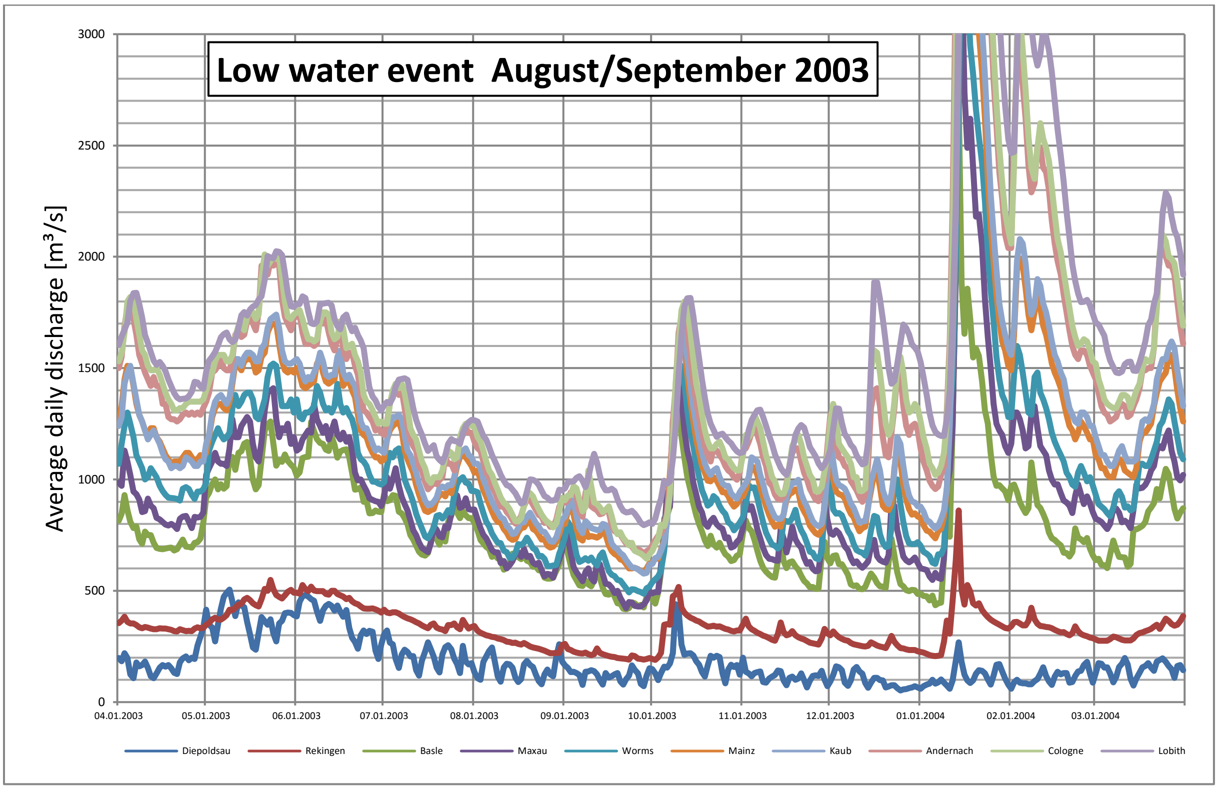
	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Oct/Nov 1985	Return period Oct/Nov 1985	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Oct/Nov 1985	Return period Oct/Nov 1985
Diepoldsau	92.2	96	<2	4	3	2
Rekingen	238	206	5	7	19	2-5
Basle	527	425	5	5	27	5-10
Maxau	645	486	10	5	29	5-10
Worms	720	534	10	5	28	5-10
Mainz	850	620	15	6	39	10
Kaub	851	616	15	6	37	10
Andernach	998	763	10	6	39	10
Cologne	1028	756	10	6	40	10
Lobith	1095	877	5-10	6	31	5-10

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Low water event: August/September 2003

(See Chapter 7.5 for a detailed description of the event)

1 Hydrological curves:



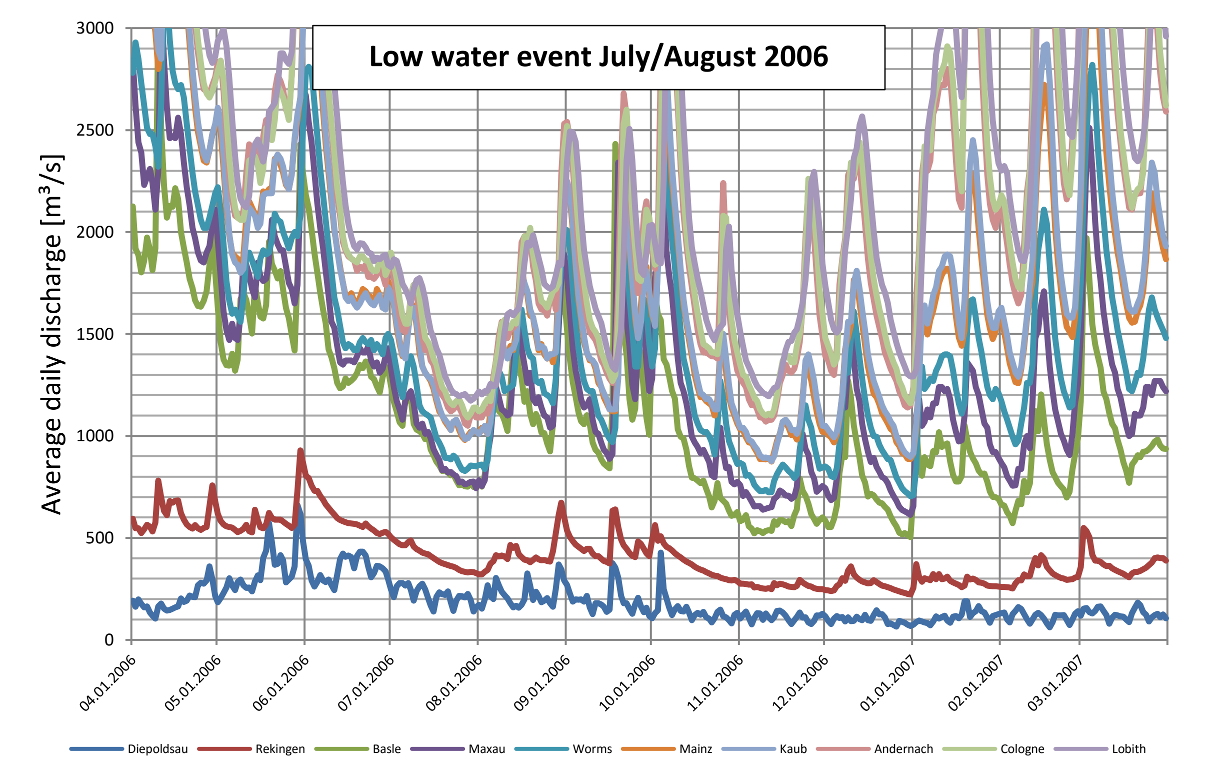
2 Characteristic values:

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Sep 2003	Return period Sep 2003	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Sep 2003	Return period Sep 2003
Diepoldsau	92.2	108	< 2	4	2	< 2
Rekingen	238	193	5	7	22	2-5
Basle	527	431	5	5	20	5
Maxau	645	435	20	5	31	5-10
Worms	720	500	15	5	31	5-10
Mainz	850	596	20	6	33	5-10
Kaub	851	595	20	6	32	5-10
Andernach	998	682	20	6	62	30
Cologne	1028	666	35	6	33	5-10
Lobith	1095	808	15	6	34	5-10

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Low water event: July / August 2006

1 Hydrological curves:



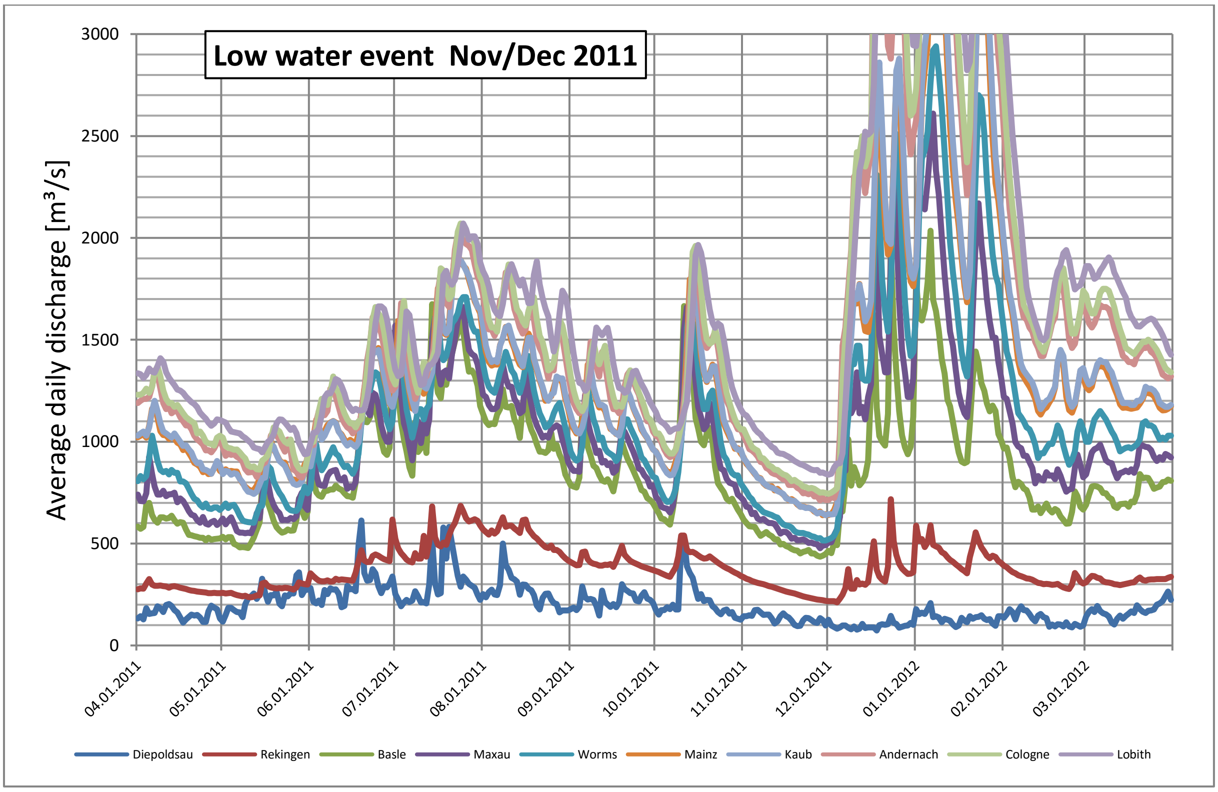
2 Characteristic values:

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Jul-Aug 2006	Return period Jul-Aug 2006	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Jul-Aug 2006	Return period Jul-Aug 2006
Diepoldsau	92.2	178	<2	4	0	-
Rekingen	238	329	<2	7	0	-
Basle	527	756	<2	5	0	-
Maxau	645	766	<2	5	0	-
Worms	720	845	<2	5	0	-
Mainz	850	1008	<2	6	0	-
Kaub	851	1008	<2	6	0	-
Andernach	998	1084	<2	6	0	-
Cologne	1028	1120	<2	6	0	-
Lobith	1095	1190	<2	6	0	-

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Low water event: November/December 2011

1 Hydrological curves:



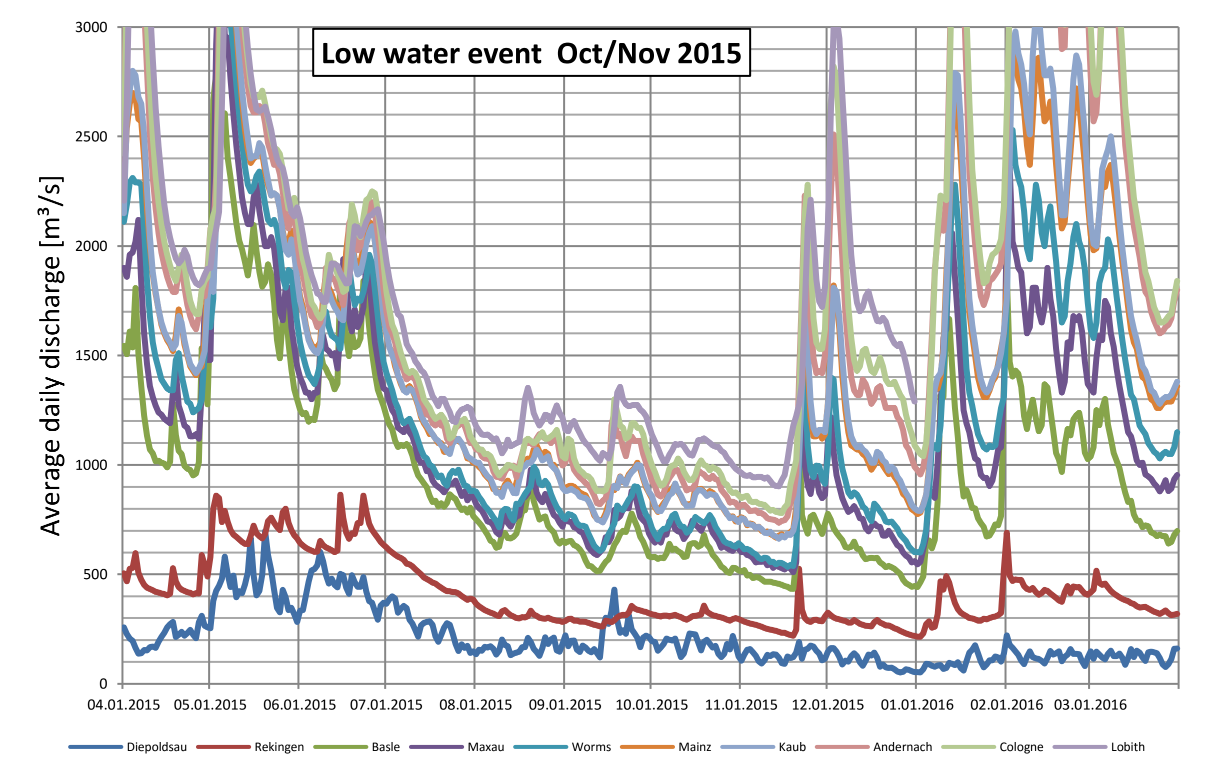
2 Characteristic values:

	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Nov/Dec 2011	Return period Nov/Dec 2011	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Nov/Dec 2011	Return period Nov/Dec 2011
Diepoldsau	92.2	92	2	4	2	<2
Rekingen	238	218	2	7	13	2-5
Basle	527	447	5	5	23	5
Maxau	645	495	5-10	5	30	5-10
Worms	720	523	10	5	32	5-10
Mainz	850	647	10	6	30	5-10
Kaub	851	645	10	6	30	5-10
Andernach	998	721	10	6	32	5-10
Cologne	1028	751	10	6	33	5-10
Lobith	1095	848	10	6	33	5-10

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Low water event: October/November 2015

1 Hydrological curves:



2 Characteristic values:

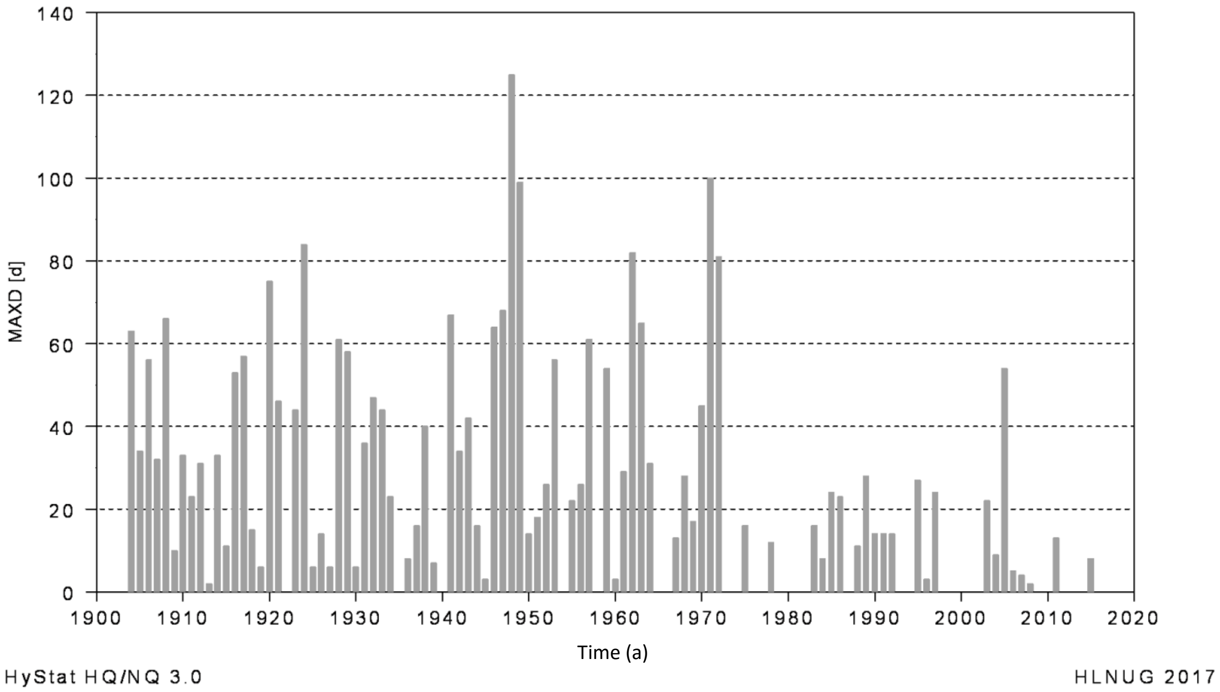
	Low water discharge [m³/s]			Low water duration [days]		
	MNM7Q 1961-2010	NM7Q Oct/Nov 2015	Return period Oct/Nov 2015	MaxD < NM7Q2 1961-2010	MaxD < MNM7Q Oct/Nov 2015	Return period Oct/Nov 2015
Diepoldsau	92.2	115	<2	4	1	<2
Rekingen	238	231	2	7	5	<2
Basle	527	447	5	5	20	5-10
Maxau	645	528	5	5	27	5-10
Worms	720	545	10	5	29	5-10
Mainz	850	678	5-10	6	28	5-10
Kaub	851	675	5-10	6	28	5-10
Andernach	998	747	5-10	6	51	20
Cologne	1028	792	5-10	6	41	15
Lobith	1095	922	5-10	6	27	5

MaxD = maximum duration of consecutive days < MNM7Q
NM7Q2 = 2-year low water discharge NM7Q
Return period data refer to the reference period 1961 - 2010

Appendix 3: Presentations of the low water durations (MaxD)

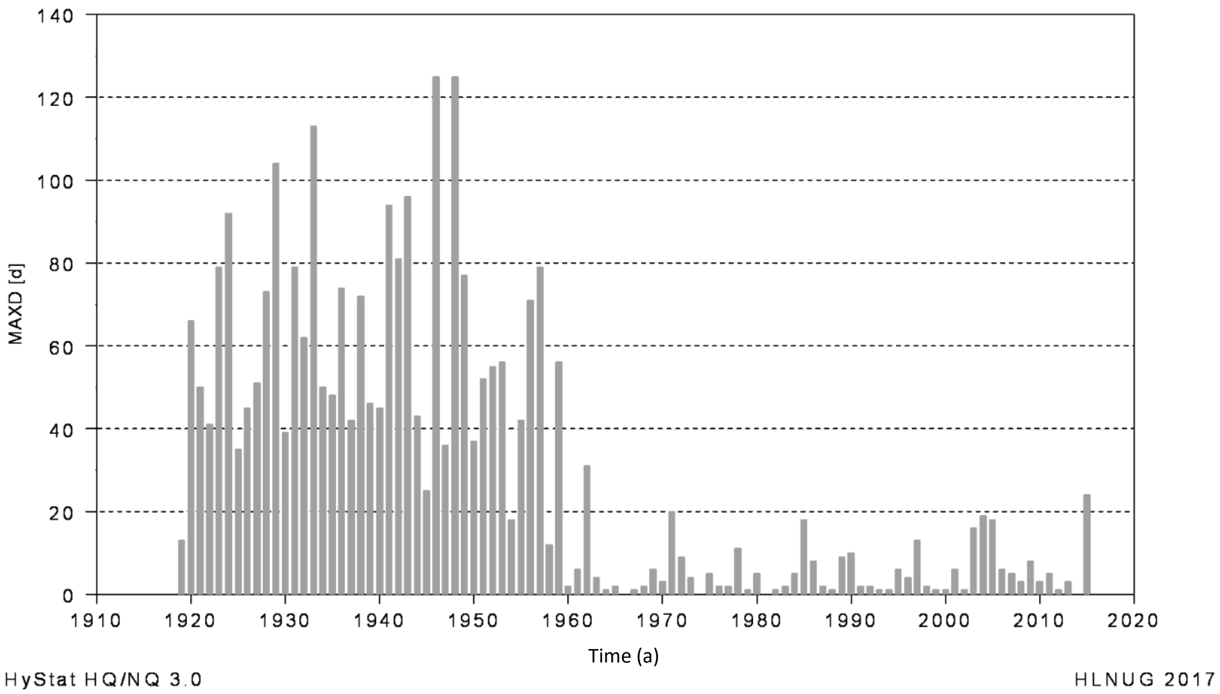
Gauge Rekingen/Rhein

Variable MAX+238.D(j,4,3), Zeitraum 01.01.1904-31.12.2016

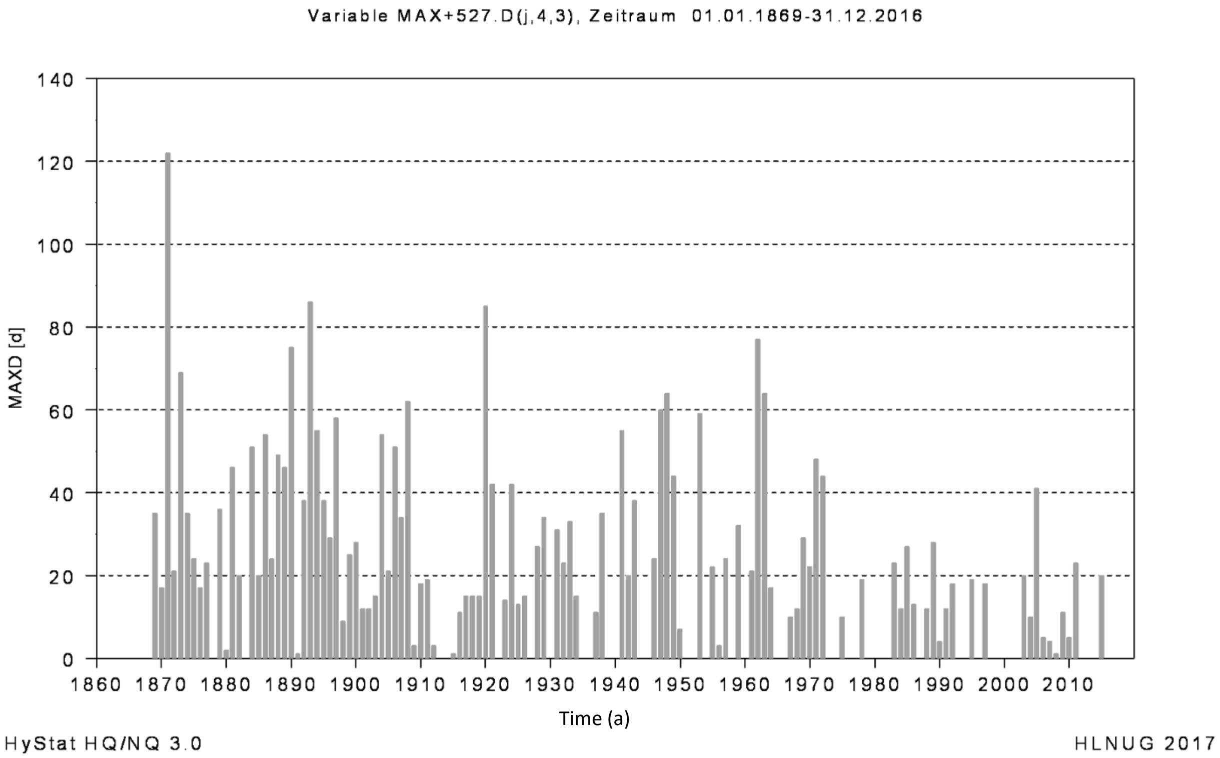


Gauge Diepoldsau/Rhein

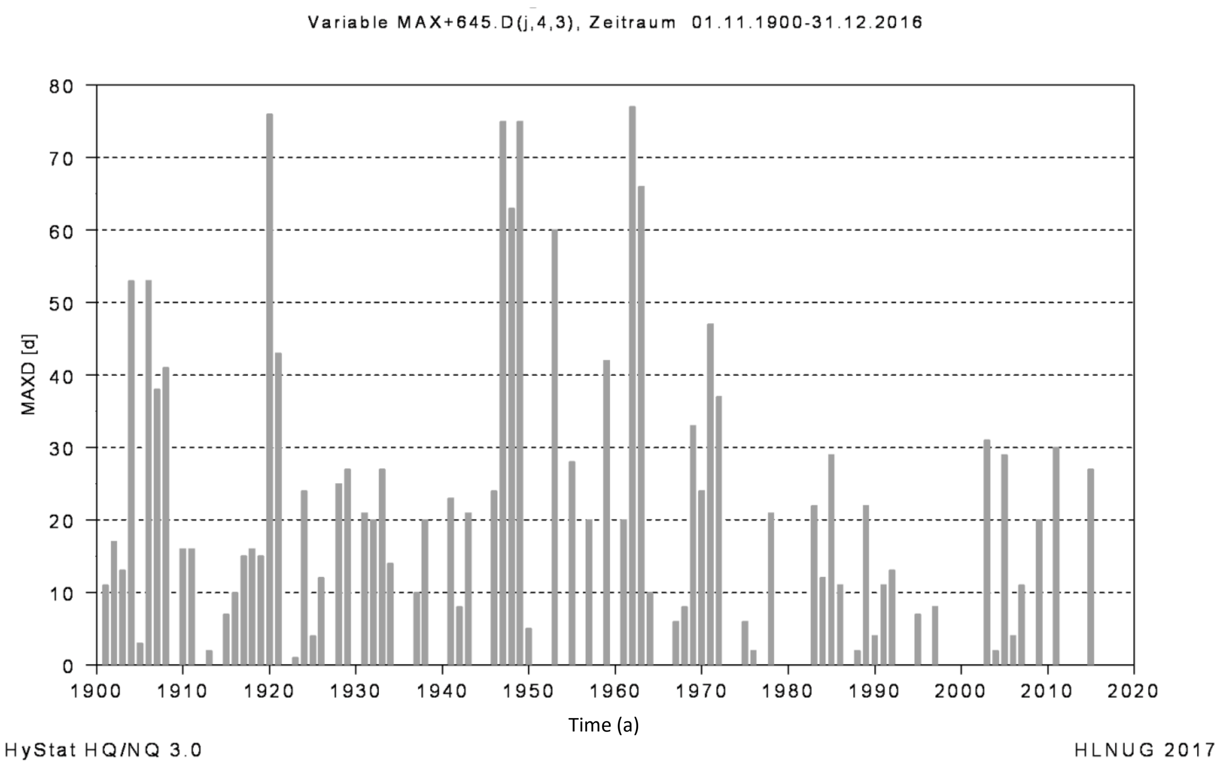
Variable MAX+92.0D(j,4,3), Zeitraum 01.01.1919-31.12.2016



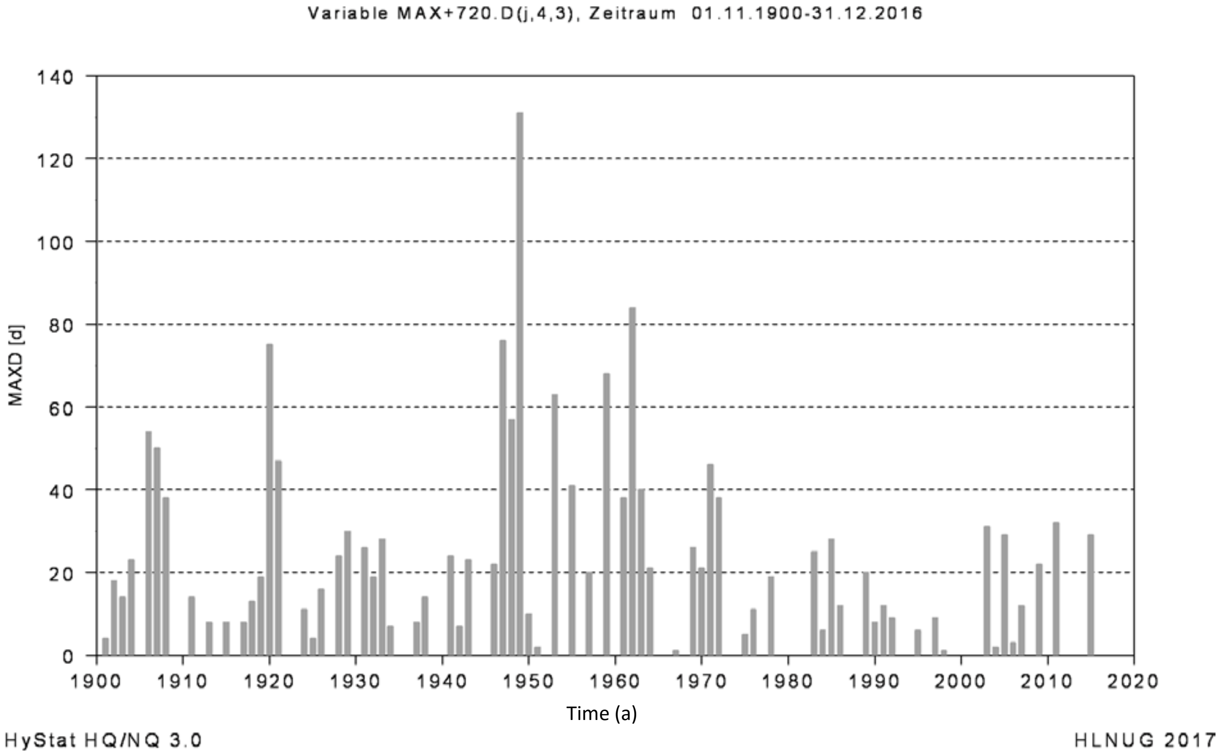
Gauge Basel/Rhein



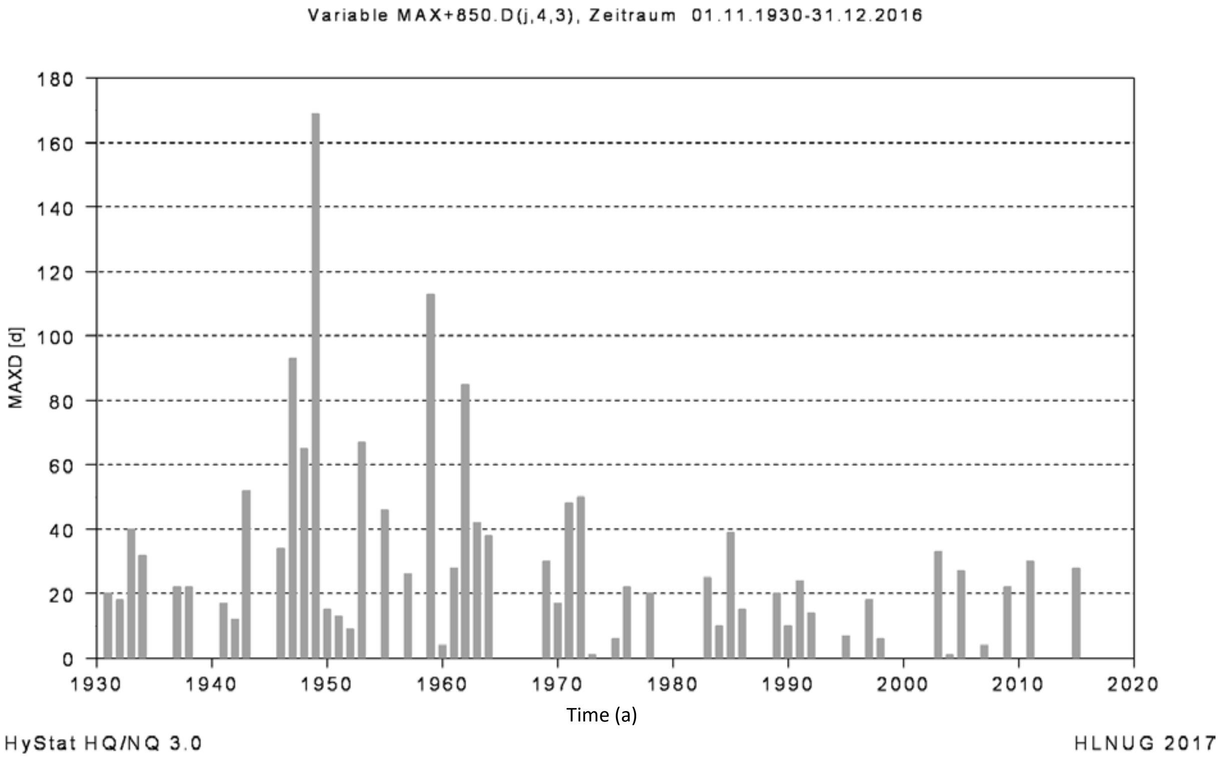
Gauge Maxau/Rhein



Gauge Worms/Rhein

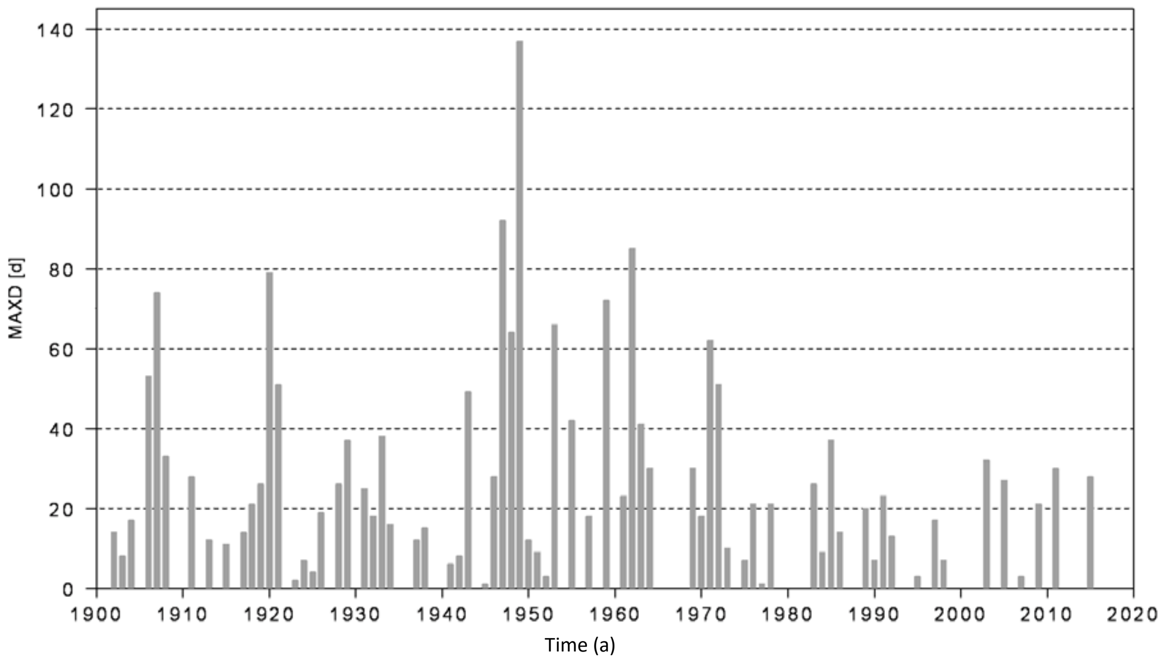


Gauge Mainz/Rhein



Gauge Kaub/Rhein

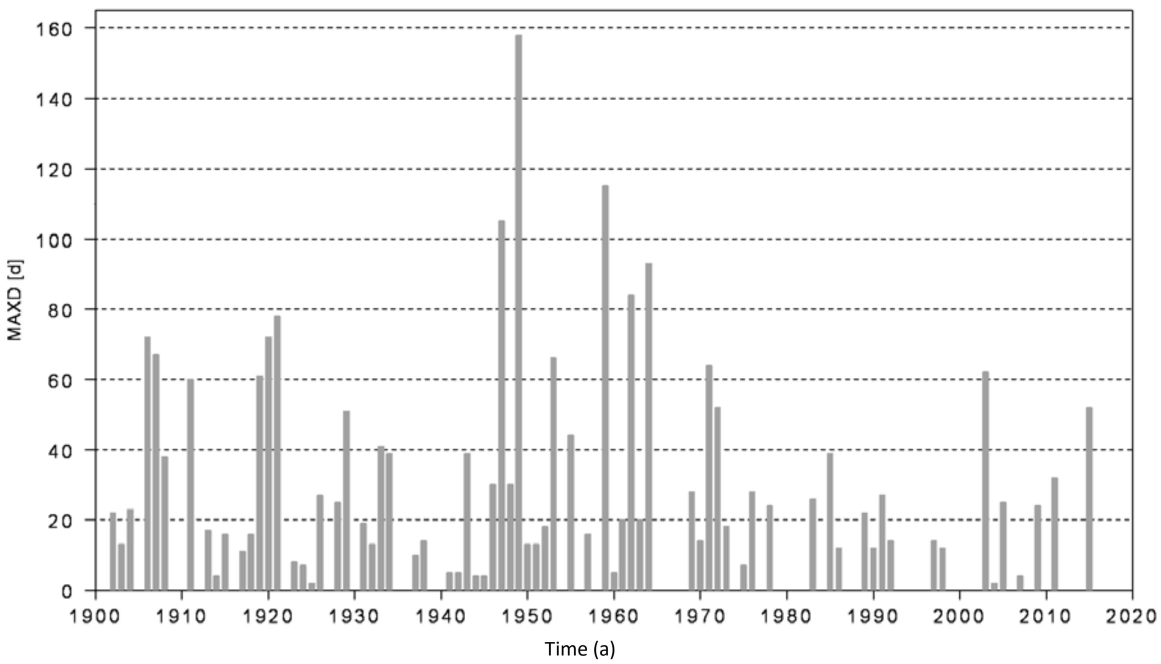
Variable MAX+851.D(j,4,3), Zeitraum 01.11.1900-31.12.2016



HyStat HQ/NQ 3.0 HLNUG 2017

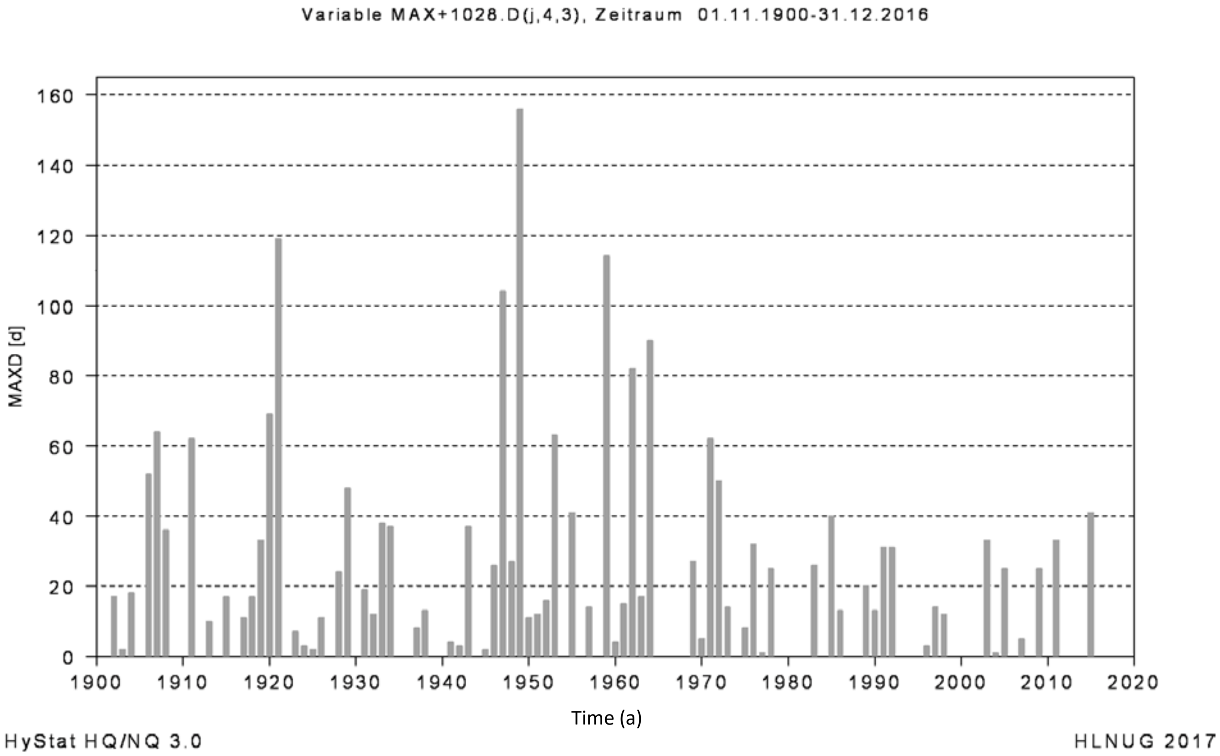
Gauge Andernach/Rhein

Variable MAX+998.D(j,4,3), Zeitraum 01.11.1900-31.12.2016

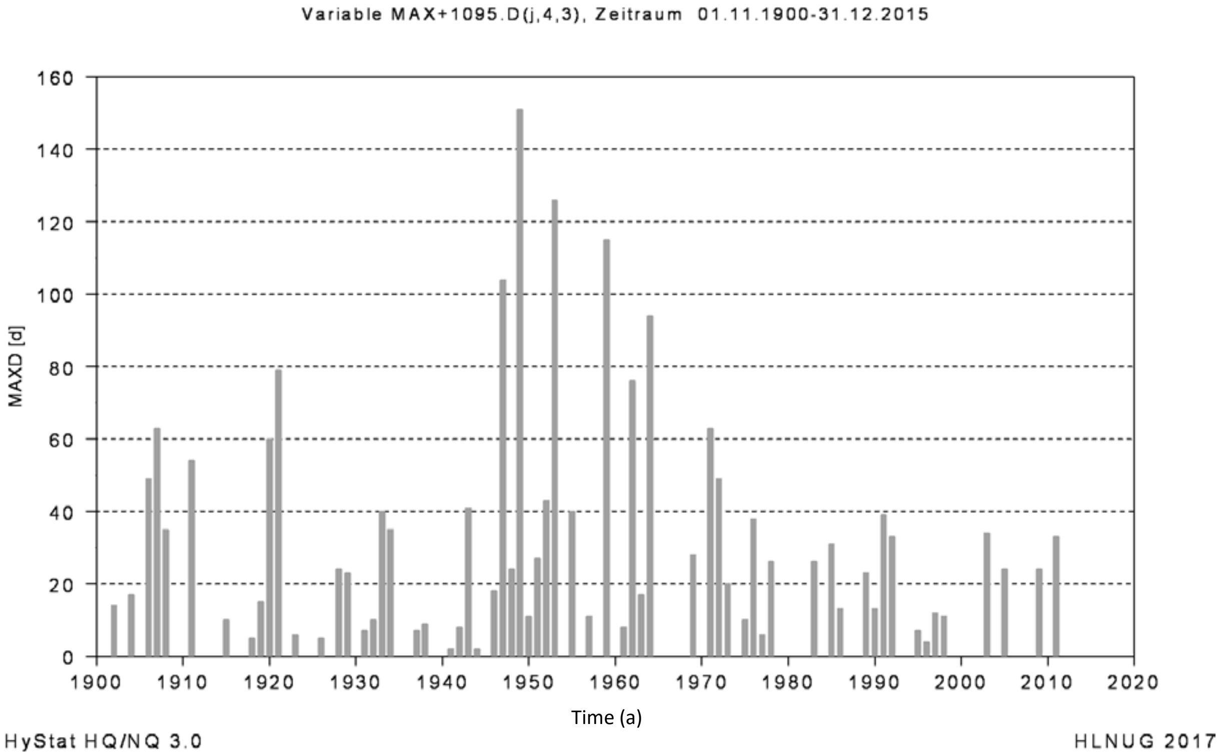


HyStat HQ/NQ 3.0 HLNUG 2017

Gauge Köln/Rhein

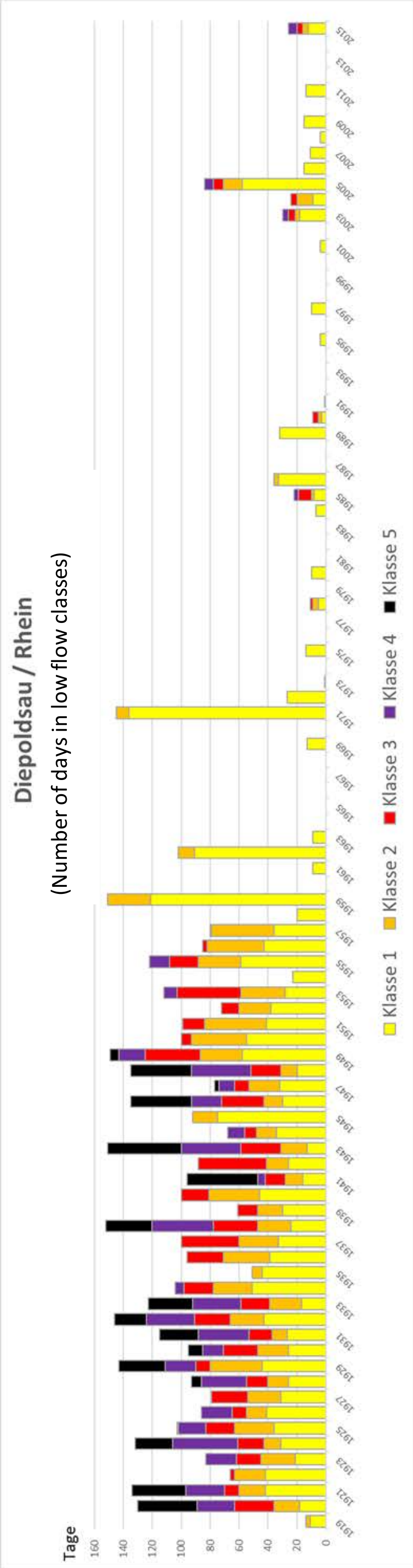


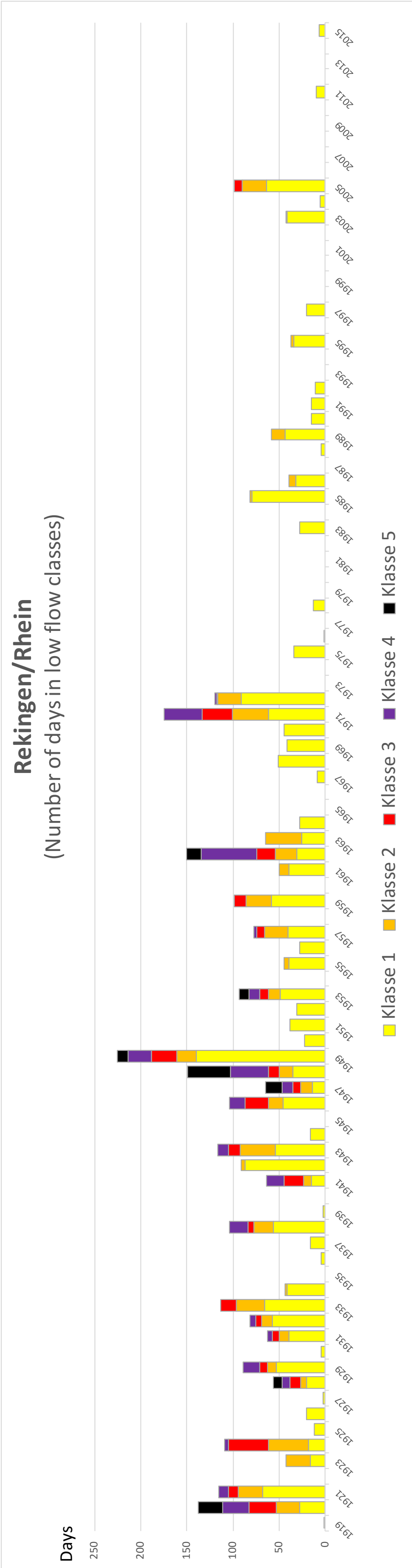
Gauge Lobith/Rhein



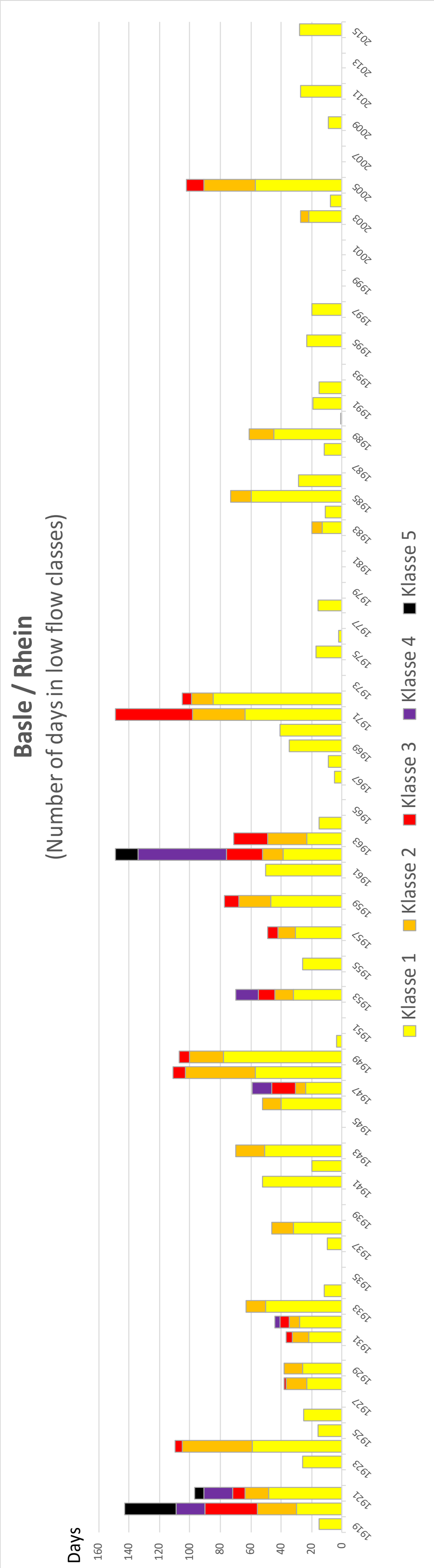
Appendix 4: Validation of low water classification using historical time series

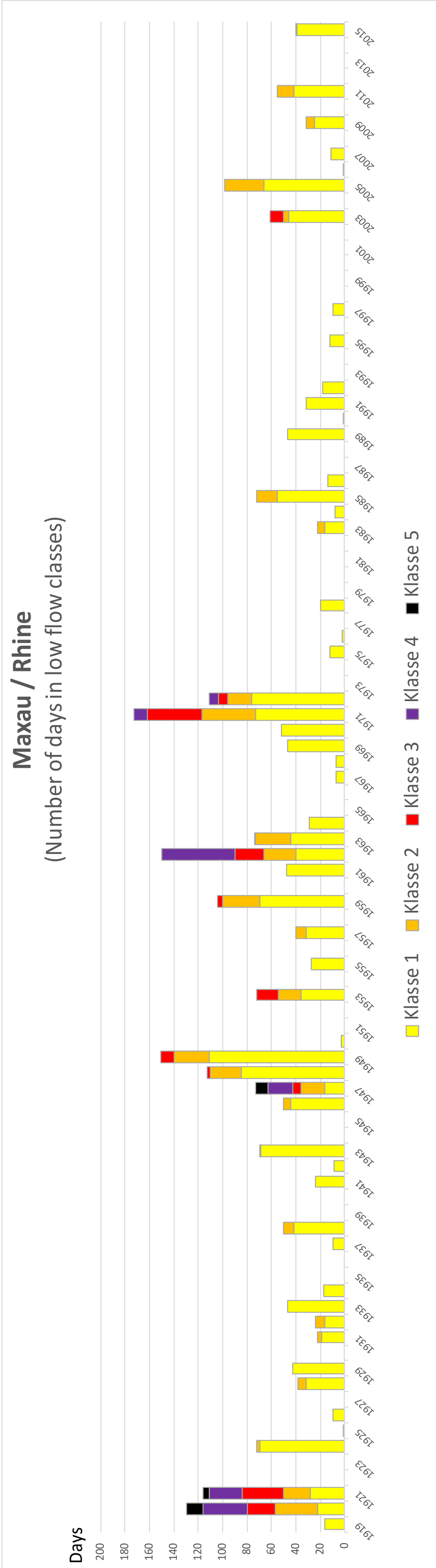
Retrospective monitoring of the Diepoldsau and Rekingen gauges



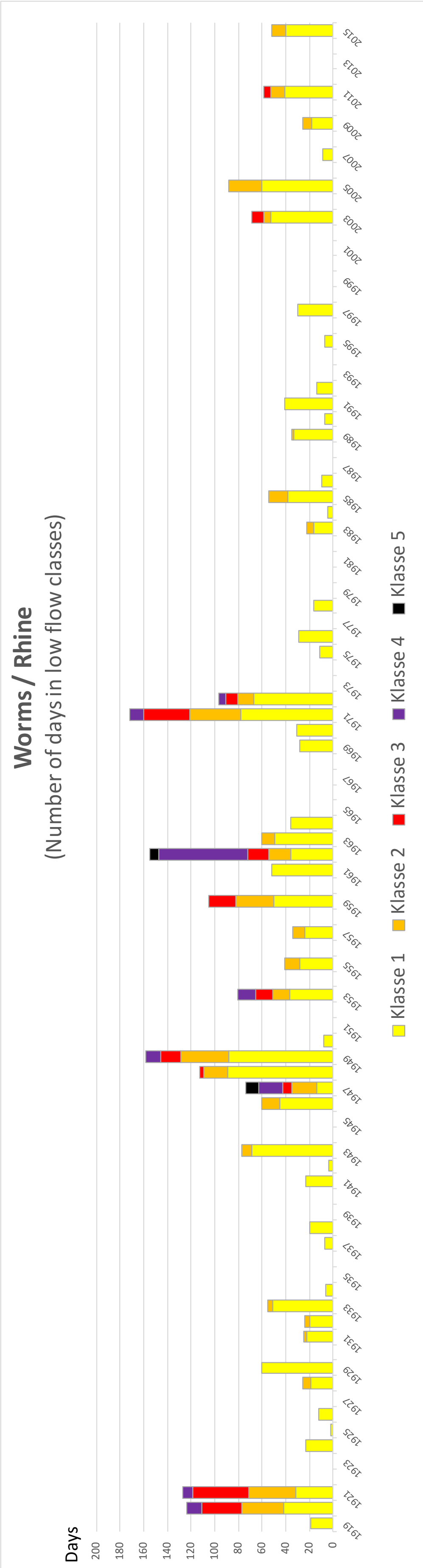


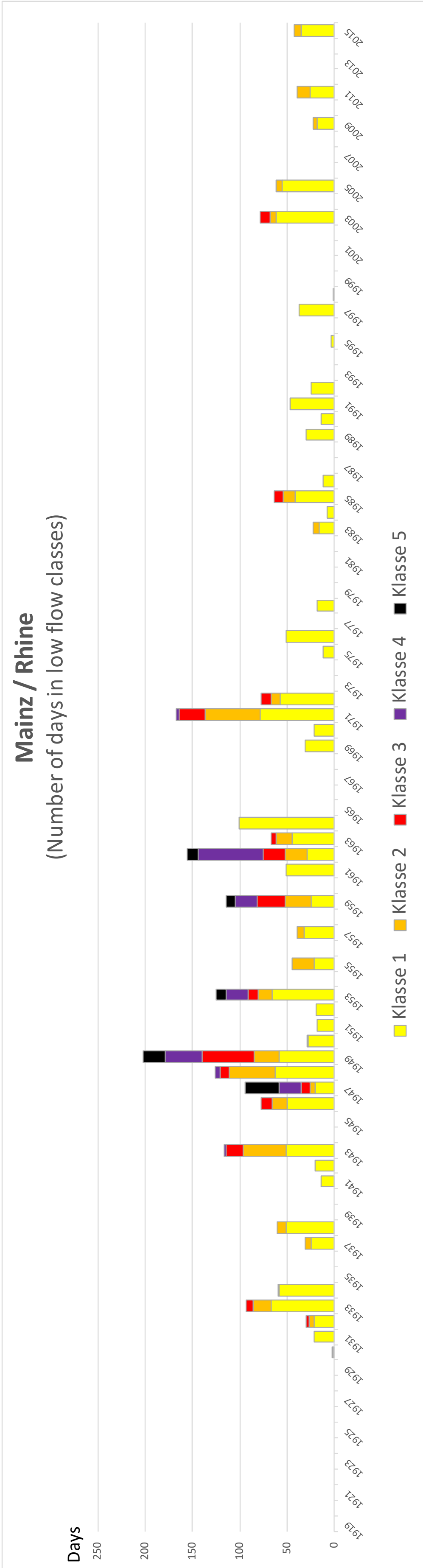
Retrospective monitoring of the Basel and Maxau gauges



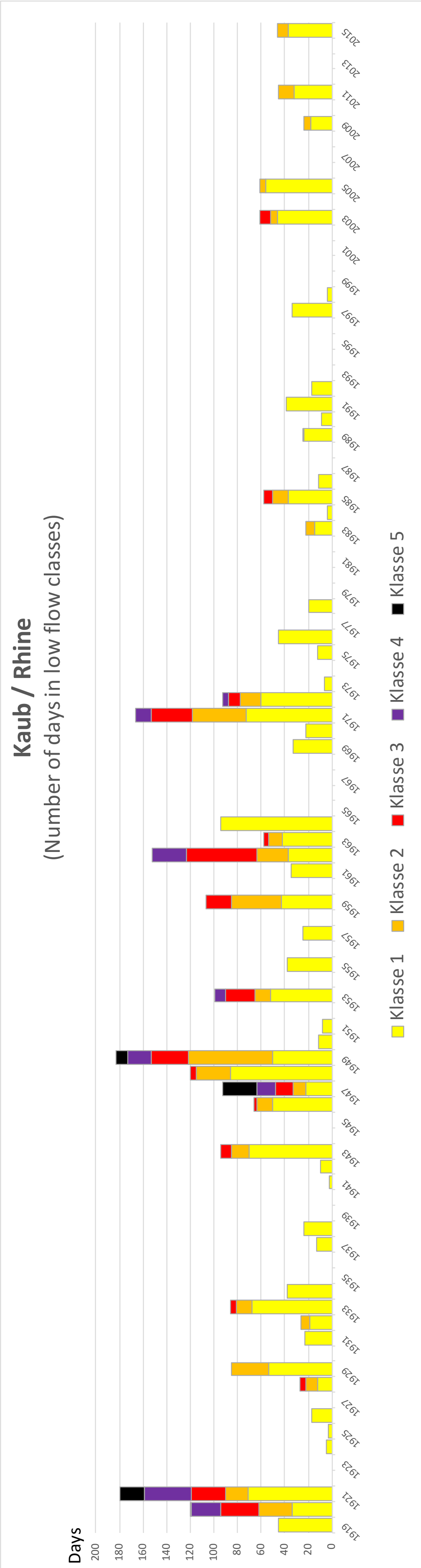


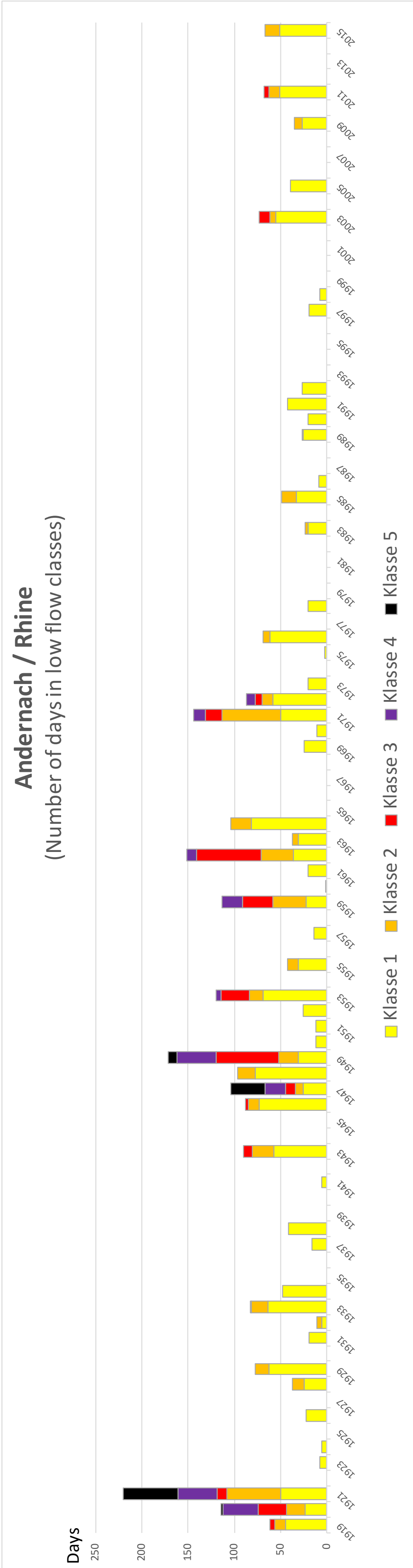
Retrospective monitoring of the Worms and Mainz gauges





Retrospective monitoring of the Kaub and Andernach gauges





Retrospective monitoring of the Cologne and Lobith gauges