Development of Rhine water temperatures based on validated temperature measurements between 1978 and 2011

IKSR
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Internationale Kommission zum Schutz des Rheins

Commission Internationale pour la Protection du Rhin

Internationale Commissie ter Bescherming van de Rijn

Report No. 209

Imprint

Publisher:
International Commission for the Protection of the Rhine (ICPR)
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ISBN-Nr 978-3-941994-36-2

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Summary

Investigations into the longstanding development of the temperatures of the Rhine indicate a clear correlation between the water temperatures and the development of air temperatures in the Rhine area. Particular climate events, such as in the winter 1988/89, in the summers 2003 and 2006 or in April 2007 are significantly visible in water temperatures.

The interpretation of time series between 1978 and 2011 shows a temperature rise of 1.7 °C for Rekingen (High Rhine), of 1.3 °C for Mainz (Upper Rhine) and of 1.2 °C for Koblenz (Middle Rhine) in this period. During the summer months, all values are distinctly above 2 °C. However, this trend is not linear across the entire period (1978-2011) but is mainly a result of a rise in temperatures during 1987-1989.

Regionally, thermal discharges further contribute to an increase of the water temperature. Until 2010, approximately 60 % of the major authorized thermal discharges into the Rhine concerned a short section of the Upper Rhine between Karlsruhe and Worms (ICPR report no. 151). Presuming that all dischargers entirely use their permitted capacities at the same time, these could contribute to a theoretical rise in temperature of 2.6 °C at maximum in the average discharge at Worms, once thermal discharges have completely mixed with the Rhine water. The actual measurable average increase in temperature at Mainz lies around 1.4 °C (related to the long-standing average discharge MQ) and falls to about 1 °C in Koblenz. The increase in temperature until Mainz is largely due to thermal discharges in the Mannheim/Ludwigshafen and Worms area, to a small extent to the natural warming of the river.

At the time being, the major tributaries Neckar, Main and Moselle hardly contribute to lowering Rhine water temperatures. With respect to average discharge and over the entire year, the contribution lies between 0.1 °C for R. Neckar and 0.2 °C for R. Moselle. However, this mostly concerns the autumn and winter months - no such contribution of tributaries is measurable during the summer months.

Compared to the two preceding decades, the frequency analysis of values in excess of certain temperature limits, e.g. 22 °C or 25 °C, shows a distinct increase in the number of days per year during the last decade. As the speed of biochemical processes depends on temperature, extreme water temperature values over a long time will affect the life processes of all aquatic organisms.

The decommissioning of four nuclear power plant units on the Upper Rhine in March 2011 seems to have reduced thermal discharges into the Rhine between Karlsruhe and Worms by about 50 %. Compared to Karlsruhe, the monitoring station Mainz equally registered a corresponding reduction of the average rise in temperature during the 2nd half of 2011.

1. Introduction

In 2003 and 2006, new maximum water temperatures were measured: the mean daily water temperature values on the Middle and Lower Rhine were registered between 28 °C and 29 °C. Since discussions on climate change had already become more intensive, in October 2007, the ministers in charge of the Rhine charged the ICPR to intensify work on the impact of climate change on the Rhine area. In 2009, and following this mandate, the ICPR presented a report on the state of knowledge (literature assessment) [ICPR 2009]. Furthermore, until 2011, a study of scenarios on the discharge regime of the Rhine was drafted [ICPR 2011]. The first report also points out the fragmentary knowledge on the development so far and on the forecast of water temperatures in the Rhine area. The report at hand and its description of the longstanding temperature development of the Rhine fills this gap.

The present report is among others based on temperature data included in an assignment of the Permanent Committee of the German Kommission zur Reinhaltung des Rheins (today: Flussgebietsgemeinschaft Rhein – Rhine River Basin Community) of 2010 to draft a common and checked data basis on water temperature data of the Rhine collected by an ad-hoc working group.

The report begins with a survey of existing water temperature studies in the Rhine area. It then deals with the data basis, in particular with the quality of temperature time series. This is followed by a survey of the development of temperatures in the longitudinal course of the Rhine and statistical data, such as a frequency analysis of extreme values and long-standing and seasonal trend analysis. The influence of tributaries and great thermal discharges on the Rhine temperature and in particular on the present development in 2011 after shutting down some nuclear power plant units in the Rhine area closes the considerations of this report.

This report only describes the development of Rhine water temperatures during the past 30 years. High water temperatures (above 25 °C) as well as low water temperatures (e.g. water temperatures below 2 °C for a longer period of time during the last winter) may affect organisms and lead to a shift in the species composition of rivers. Eventual effects of changes in water temperature on the aquatic fauna are described in [ICPR 2013].

2. Existing studies on the Rhine water temperature

The first systematic studies of Rhine water temperature were documented for the Rhine near Kehl. For 1850-59, the monthly average for 10 years was reported based on three measurements per day. The resulting average for 10 years was 10.9 °Re (Reaumur, corresponding to 13.6 °C). Further results for a 4 years average of 10.8, resp. 10.2 °Re (corresponding to 13.5 and 12.8 °C) are known for the Rhine at Freiburg and Speyer for the years 1889-1892 [Forstner, 1894]. At that time, diurnal and annual curves were registered and interpreted and comparisons with the influence of the air temperature on water temperature were made.

Summary reports on water temperatures in Middle Europe were published by Wundt in 1940 and 1967. The latter report also takes into account seven monitoring stations on the Rhine and 14 along tributaries. For the Rhine at Maxau e.g., the average water temperatures are indicated to be 11.8 °C (time series 1951/60), for Kaub 11.1 °C (time series 1946/60) and Rees 11.2 °C (time series 1951/60). The values result from daily individual measures at 1 p.m. Since experience has shown that the daily average is achieved around 11 a.m., a correcting factor of -0.5° is applied to these values. Furthermore, the present report takes a closer look at the difference between water and air temperature and at the amplitude of monthly averages. [Wundt 1940, 1967]

After World War II, water temperature data were increasingly measured at the gauges and registered in the hydrological Yearbooks. Within the international Rhine monitoring programme of the ICPR beginning in 1953, water temperatures were at first registered every fortnight and later presented as 14-days-average of continuous measurements (ICPR Annual Tables of Numbers of Chemical-Physical Measurements).

Webb presented basic studies classifying water temperatures in hydrological processes and finding an increase of water temperatures of European rivers of about 1 °C in the 20th century [Webb 1996]. The assessment of the influence of climate changes is considerably complicated by thermal discharges, urbanization (wastewater treatment plants) and the construction of impoundments [Webb 2008].

After the already mentioned years 2003 and 2006 with maximum water temperatures, and until today, there are many studies on the temperature development which also concern parts of the Rhine area. A Swiss report concerning the Rhine at Basel over the past 50 years states a rise in the water temperature by 2 °C [BUWAL 2004]. In addition, Fig. 2-1 represents the development of the annual averages until 2012 at several Rhine monitoring stations in the Swiss part of the Rhine catchment.

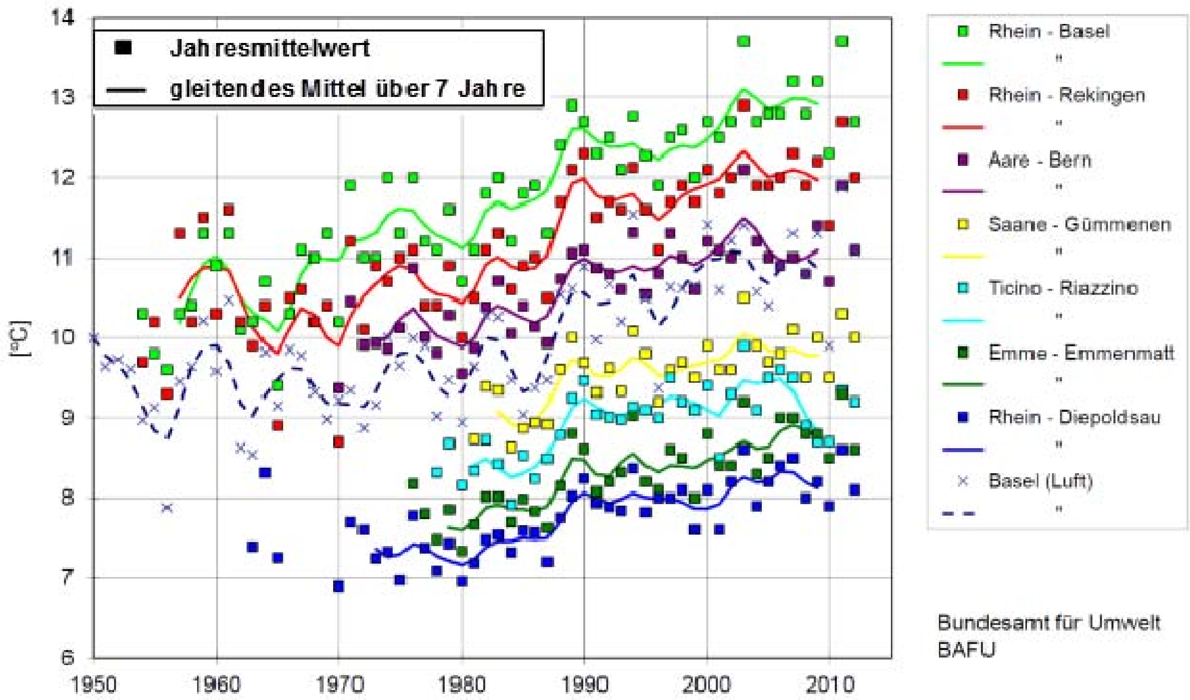

Fig. 2-1: Changes in water temperature (squares = annual averages; lines = 7 years moving average) at selected BWG monitoring stations between 1954 and 2012. Additionally, the development of air temperatures in Basel is represented (dotted line). Source: BAFU, department of hydrology, 05.03.2013

For the Lower Rhine at Kleve-Bimmen, a rise of the average water temperature > 1 °C since 1977 and an increase of years with maximal water temperatures above 25 °C are stated. It is highly probable that the rise in temperature is due to climate change, as, at the same time, the permitted waste heat discharges along the Rhine were regressing [MUNLV 2009].

Based on the data of the Lobith monitoring station, a rise in Rhine water temperature near Lobith above 3 °C is being postulated (period 1908-2000) [Liefveld & Postma 2007].

And there are further studies:

- On behalf of the Dutch Rijkswatersaat Waterdienst, Deltares has made a current study on the development of water temperatures in the Dutch Meuse catchment considering anthropogenic impact and climate change [Deltares 2012]. This catchment is adjacent to the Lower Rhine area for which findings thus also partly apply.

- In a study made by Haag, the possible impact of climate change on the temperature of streams is explained and scientific findings concerning the impact of climate change on water temperatures are summarized [Haag 2009]. Studies on the historic development and forecasting of the future development of water temperatures are presented.
- In 2009, a study of the BUND on the thermal pollution of the Rhine [Lange 2009] was published, including vast research on thermal discharges and plans for power plants along the Rhine. The study was meant as a basis for a competent examination of the consequences of the planned power plants, taking into account the management plans according to the EU Water Framework Directive and climate change.

In the past years, the most ample analysis of data on longstanding water temperature time series was carried out by Greis and Strauch [Greis 2007], [Strauch 2011], [Greis et al 2011] and concentrated on the capacity restriction of thermal power plants in Germany due to water temperature. Large parts of the Rhine area were covered by these studies. For some monitoring stations the data basis is identical with that of this report. Furthermore, significant water temperature trends were presented for selected rivers in Germany, and the effects of changing discharge patterns were discussed [Rothstein et al 2008].

3. Continuous water temperature monitoring

During the first half of the 20th century, the hydrological yearbooks for the Rhine only report daily individual measures (mostly 12 o'clock value).

The continuous water temperature measurements with temperature sensor (e.g. Pt100 sensor) and registrations of the measurement signal on strip charts began some 50 years ago. Direct digital acquisition and recording of the measurement signals only began some 20 years ago. For some monitoring stations, strip charts have later been checked and digitalised so that daily average water temperatures are available for a period of 30-35 years.

In the following, temperature measuring techniques, the handling of gaps in data and the time period of the available data basis will be treated. Contrary to what is standard in literature, this report always indicates differences in temperature in °C and not in Kelvin.

3.1 Measuring technique

The temperature sensor, the monitoring device, data transfer and control are part of the measuring technique. The measuring technique thus also refers to the measuring arrangement in the water body and/or in the monitoring station.

At the measurement locations, Pt100- or NTC temperature sensors have been in use for many years. For the usual temperature measurement ranges, the precision varies between 0.1 °C and 0.25 °C. The precision for the entire measuring chain (measurement device and data transfer) is indicated to be 0.1 °C. Regular maintenance and calibration (e.g. monthly) is decisive. Thus, the precision of temperature measurements varies between 0.1 °C and 0.3 °C. If the calibration intervals are not respected, deviations up to 0.5 °C may occur.

If the point of measurement is in the monitoring station, the influence of conduits must be known in order to secure data quality.

3.2 Handling data gaps and homogenisation of time series

For longstanding trend considerations it is necessary to dispose of equidistant time series without data gaps (daily averages). This may be achieved by linear interpolation (in case of smaller gaps of 1-2 days) or preferably by graphic comparisons with neighbouring stations. An approximate calculation of gap values is also possible using an already validated model.

If e.g. 3 % (11 values) of the daily averages are missing for one year at two neighbouring stations and the values are missing for the summer at one station and for the winter at the other, the annual averages may differ by 0.5 - 0.7 °C, even though, as a matter of fact, the same annual average applies to both stations. The deviation per station may be of 0.3 - 0.4 °C.

The homogenisation of time series means to check for systematic errors, e.g. due to changed measurement techniques by altering the point of measurement or changed surrounding conditions. These may appear due to an offset or a trend which will be superimposed to natural variability and the trend of water temperature. The statistic procedure, in particular that of the relative test of homogeneity with the help of reference time series for which an average is generated based on neighbouring comparative time series is comprehensively described by Strauch [Strauch 2011], and has been applied to measurement series of the rivers Rhine, Neckar and Main. For the present study, only visual checks and plausibility considerations of the time series of neighbouring stations have been carried through.

3.3 Time period of the data basis

For the verification of temperature trends, measuring operators provided longstanding measurement series based on daily averages (and partly on an hourly basis). The following measurement series were used for the report at hand:

Table 3.3-1: Survey of water temperature (WT) time series (daily average of continuous measurements)

WT monitoring stations	River (km)	WT time series	Source
Rekingen*	Rhine, km 90.7	1997-2011	BAFU
Weil a. Rh.*	Rhine, km 174.0	1997-2011	BAFU
Karlsruhe*	Rhine, km 359.2	1988-2011	LUBW
BASF WW Süd	Rhine, km 426	1991-2011	BASF
Mannheim	Neckar, km 3,0	2000-2010	LUBW
Worms	Rhine, km 443,3	1996-2009	LUWG
Bischofsheim	Main, km 4,0	2000-2010	HLUG
Mainz	Rhine, km 498.5	1980-2011	LUWG
Koblenz/Rh.*	Rhine, km 590.3	1978-2011	BfG
Koblenz/Moselle*	Moselle, km 2,0	1978-2011	BfG
Bad Honnef	Rhine, km 640.0	2004-2010	LANUV
Düsseldorf-Flehe	Rhine, km 732.2	2004-2010	LANUV
Kleve-Bimmen*	Rhine, km 865.0	1995-2009	LANUV
Lobith*	Rhine, km 862.3	2000-2010	RWS

* International monitoring stations of the ICPR monitoring programme

Additionally, the WT data of the gauging stations Koblenz, Cologne and Rees and data of the monitoring stations Fankel/Moselle and Lahnstein/Lahn were used for the plausibility check and in order to fill data gaps.

Furthermore, the BASF provided the entrance data of the Waterworks South (Rhine km 426) on an hourly basis (2000-2011), for 1991-1991 on the basis of daily averages and for 1952-1990 on the basis of monthly averages. These data are particularly suitable for longstanding trend analysis.

The following figure 3.3-1 indicates the locations of the monitoring stations according to table 3.3-1 along the Rhine.

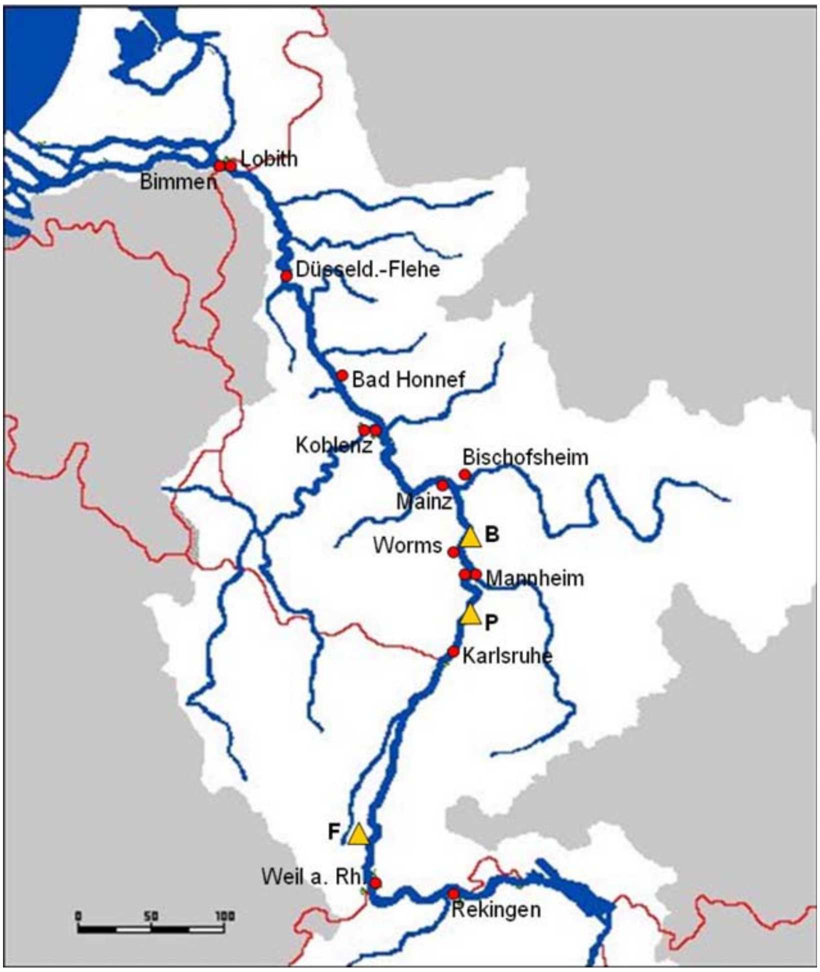

Fig. 3.3-1: Locations of monitoring stations with water temperature data (red dot) used as data basis for the report at hand (nuclear power plants (yellow triangles): F=Fessenheim, P=Philippsburg, B=Biblis)

4. Analysis of the representativeness of the temperature data of monitoring stations

A reliable assessment of the temperature development in the Rhine presupposes that the water temperatures determined at the monitoring stations are representative for the river section of the water body. Therefore, measurements at the monitoring stations Weil am Rhein, Worms and Mainz are made at several spots in the transverse profile (at the bridge abutments).

Findings for the monitoring station Worms indicate that, due to important thermal dischargers upstream the monitoring station and the mouth of R. Neckar, there is a temperature difference between the left and the right bank of 1-2 °C during about two thirds of all days.

The representative character of the data is secured by comparative measurements in the transverse structure or by a comparison of results with neighbouring monitoring stations.

For nine profiles of the Rhine between Rhine km 355 (Neuburg) and km 638 (Oberwinter) the representative character of temperature data of selected monitoring stations was checked based on longstanding measurements of the transverse profile made by the monitoring ship BURGUND.

This is illustrated by the example of the Karlsruhe monitoring station (km 359.2, right bank). The results of 4 measurements of the transverse profile per year of the BURGUND for the period 2003-2008 at Rhine km 355.4 are compared to hourly averages at the monitoring station for the equivalent point of time (one measurement of the transverse profile takes about 8-12 minutes). The average results of 21 measurements represented in Table 4-1 show:

a) That the distribution of temperature in the transverse profile of this section of the Rhine is very uniform and thus that the Karlsruhe monitoring station provides representative data.

b) That deviations of the two independent measures are within the accuracy of measurement, i.e. that they result in the same (correct) value.

Table 4-1: Rhine WT at five measurement spots; measurements of BURGUND left, middle, right and comparison with corresponding hourly averages of monitoring stations (e.g. km 359.2 right)
N represents the number of transverse profiles

WT in °C	N	left bank	middle	right bank
Oberwinter, km 638				
Average 2003-2007	15	13.66	13.71	13.74
Bad Honnef, km 640				13.67
Lahnstein, km 585				
Average 2004-2008	20	14.18	14.21	14.20
Koblenz/Rh., km 590,3		14.24		
Mainz-Weisenau, km 496				
Average 2004-2008	19	14.62	14.76	14.82
Mainz, km 498,5		14.68		
Ludwigshafen, km 424,6				
Average 2004–2008	20	13.33	13.55	13.96
BASF WW Süd, km 426			13.58	
Neuburg, km 355,4				
Average 2003–2008	21	13.73	13.69	13.68
Karlsruhe, km 359,2				13.80

At the other four measurement spots listed in Table 4-1 the measurements taken by the ships correspond well to the results of the monitoring station on the respective river bank.

Thus, the monitoring stations Bad Honnef and Koblenz equally show uniform water temperatures across the river section. The measurement of the transverse section at Mainz was made just before the mouth of the R. Main. The Mainz monitoring station is located 2.5 km downstream the mouth of R. Main and determines the water temperature at four measurement spots in the transverse structure at bridge abutments. For the purpose of the report at hand, only daily averages of the measurement spots 1 and 2 closer to the left bank were used, as they are the only ones to show the Rhine water temperature without any influence of the R. Main (see chapter 5.6). As the data show, the right bank measurement spots in the transverse profile at Ludwigshafen are influenced by thermal power plant discharges (see also chapter 5.7).

5. Analysis of the water temperature time series

5.1 Control parameters of the water temperatures of streams

An extensive description of the physical background of components of the thermal balance is found in [Haag 2009] and [LAWA 2012]. Therefore, only the most relevant factors will be treated in accordance with Fig. 5.1-1.

Meteorological components, such as the thermal exchange between the water body and the environment and discharge play a decisive role for the natural water temperature.

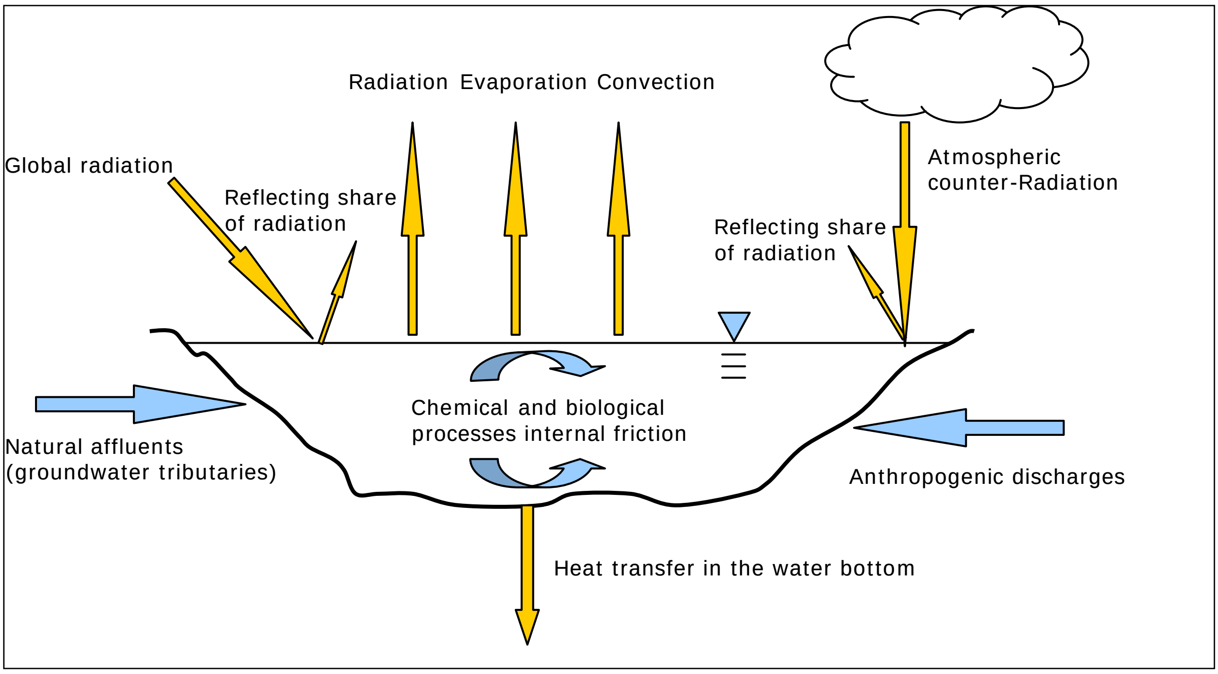

Fig. 5.1-1: Schematic illustration of the thermal exchange processes relevant for streams (according to LAWA 2012)

The short wave radiation budget is a result of incoming global radiation (direct and diffuse solar radiation) and the share reflected by the water surface (Albedo). The long wave radiation budget is a result of the thermal radiation of the atmosphere and the emission of the water body due to its own temperature.

With respect to water cooling, evaporation is the most important component of the thermal budget. If the vapour pressure at the water surface is below that of the air layer above, condensation occurs.

Convection is the direct thermal transfer between the water surface and the air. The value depends on the temperature gradient between the water surface and ambient air. Evaporation and convection are strongly influenced by wind velocity.

In the source area, water temperature corresponds to that of groundwater. With increasing distance from the source, the annual average water temperature as well as annual and daily temperature amplitudes will normally increase [LAWA 2012, p. 47]. The High Rhine has the particularity to represent the outlet of a lake. In cold winters, water temperature at the outlet of Lake Constance only slightly falls below 4 °C while, during hot summer months, the surface water temperature of Lake Constance is decisive.

5.2 Temperature development in the longitudinal profile of the Rhine

For a first survey, Fig. 5.2-1 represents the annual average Rhine water temperatures for 2000 to 2010 between the ICPR monitoring station Rekingen (upstream the mouth of R. Aare on the High Rhine) and the ICPR monitoring station Lobith (on the German-Dutch border). With respect to this period and the river section between these two stations, the average rise in Rhine water temperature is about 2 °C and presents annual variations between 1.5 °C (in 2003) and 2.3 °C (in 2008). Correspondingly, between Rekingen and Karlsruhe and between Karlsruhe and Mainz, the average rise in temperature is about 1.3 °C (the mean rise in temperature for the last 20 years between Karlsruhe and Mainz is even about 1.5 °C). A major part of this difference in temperature can be explained by the considerable cooling water discharges between Karlsruhe and Worms and is partly due to the natural warming of this reach (see below). According to the ICPR survey of thermal discharges, about 60 % of thermal discharges into the Rhine concern this reach [ICPR 2006].

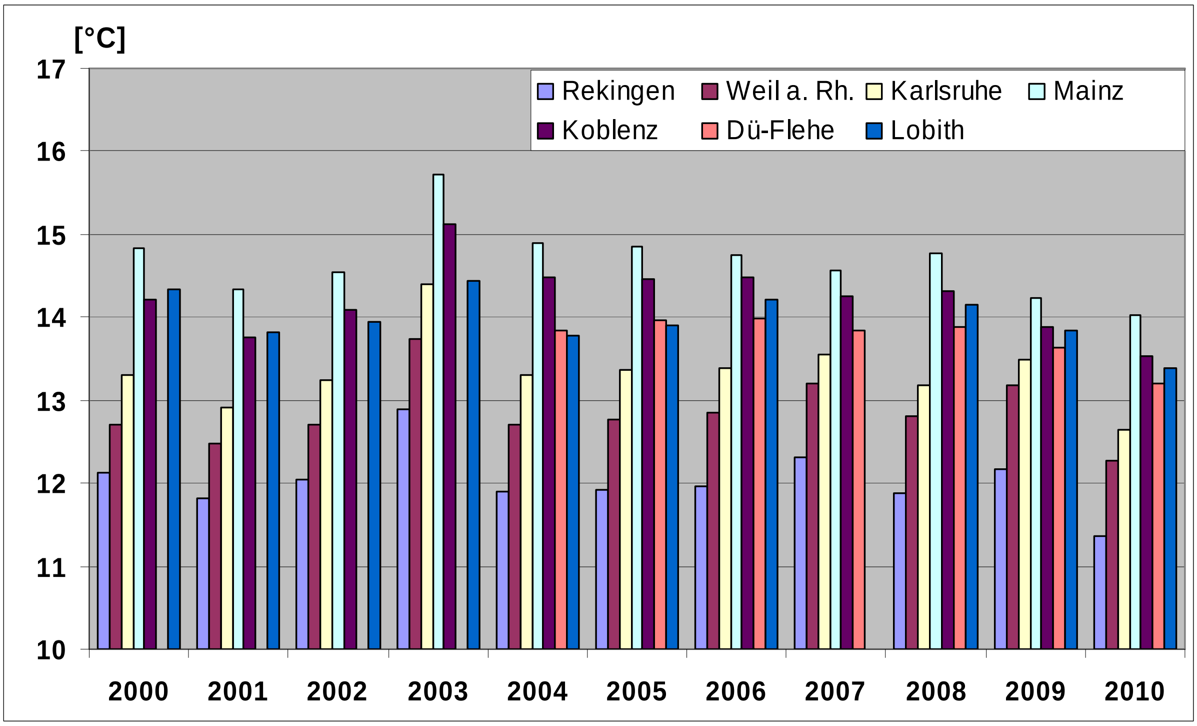

Fig. 5.2-1: Mean annual Rhine water temperatures at the monitoring stations along the Rhine

However, near Koblenz and due to the cooling process and adaptation to air temperature, the value again falls by 0.4 °C. On the further course until Bad Honnef, there is a further fall of water temperature by 0.3 to 0.4 °C. The further cooling is also caused by the mixing waters of the Moselle and of other smaller rivers of the uplands. In winter, the temperature of these tributaries is up to 4 °C below that of the Rhine. The temperatures at Bad Honnef, Cologne, Düsseldorf-Flehe and Lobith are nearly at identical levels - that means that, in these sections of the Rhine, thermal discharges and cooling processes are balanced.

A detailed representation of the temperature development is shown in Fig. 5.2-2 together with monthly averages of temperature variations between Mainz and Koblenz during 2001-2011. In the course of one year, the further cooling of Rhine water between Mainz and Koblenz is very varied, during few months in spring/summer the stream temperatures rise even more. This shows the dominating influence of radiation upon the thermal budget.

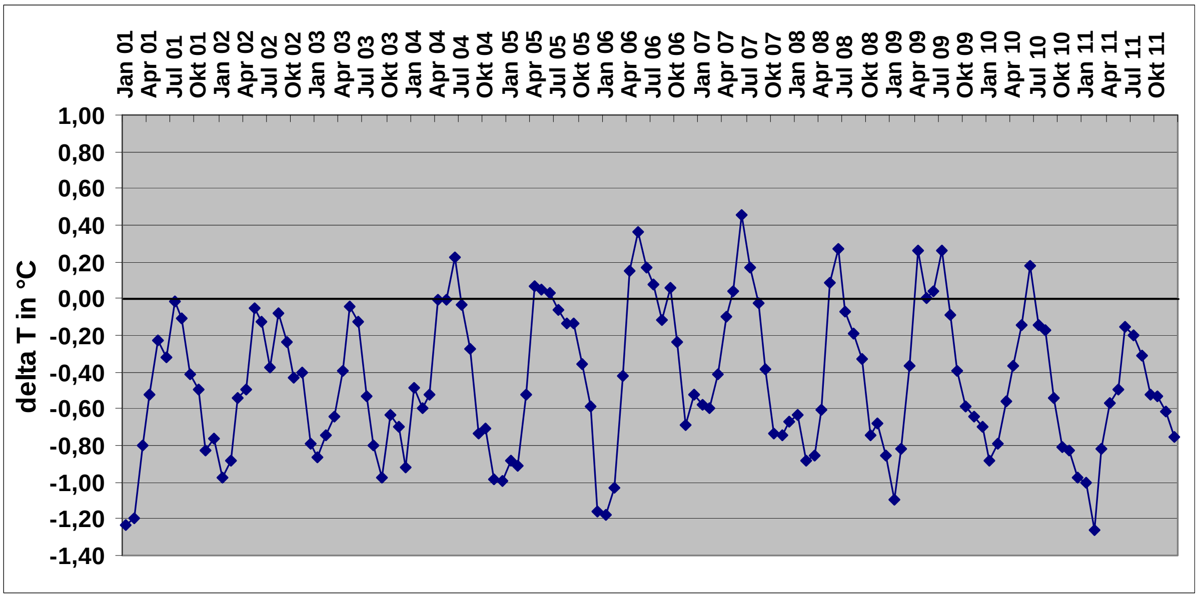

Fig. 5.2-2: Development of monthly temperature difference averages between Mainz and Koblenz during 2001-2011 (delta T = T (KO - T (MZ))

Between Basel and Karlsruhe the Rhine is flowing through a region with the highest mean air temperatures in the Rhine area. Additionally, the many impoundments in this section of the Rhine increase the temperature exchange with the atmosphere. Therefore, the increase in temperature until Karlsruhe is only to a very limited extent caused by direct thermal dischargers and is probably due to natural processes which are again reinforced by anthropogenic impacts (see also chapter 5.7).

5.3 Frequency analysis (extreme values)

A first and reliable evaluation of temperature time series is done by a counting statistics. For a period covering several years, the number of days are assessed when measurements are above or below a certain extreme value or threshold value. Taking the example of Fig. 5.3-1, a distinct increase of the days is seen, when, during 2003 and 2006, Rhine water temperatures as far as Koblenz are in excess of 22 °C and 25 °C. On the other hand, in 2009, no mean daily water temperature in excess of 25°c was registered in the entire Rhine area as far downstream as Lobith.

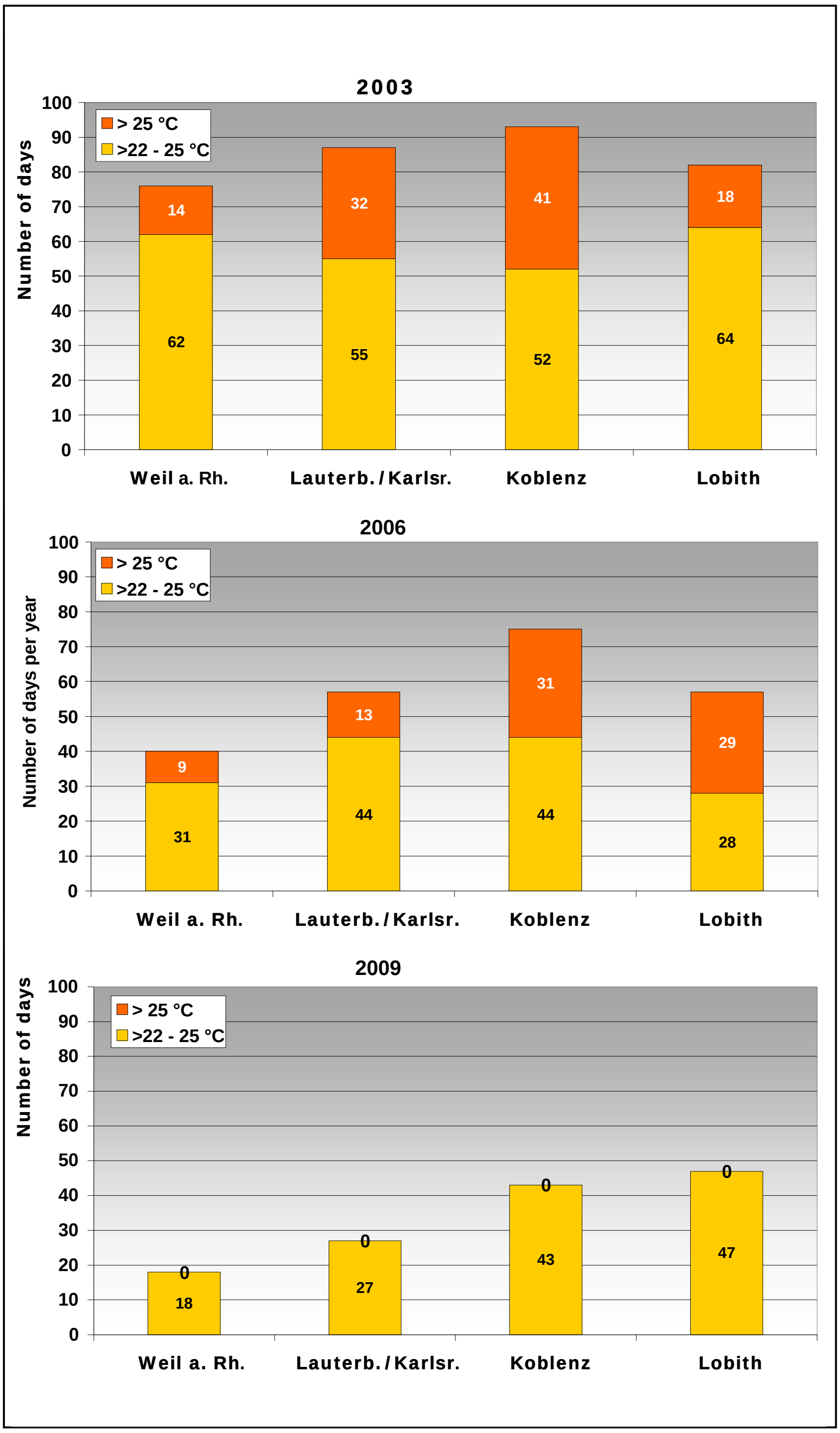

Fig. 5.3-1: Number of days with Rhine water temperatures in excess of 22 °C during 2003, 2006 and 2009

While, during the past decades, water temperatures frequently rose above 22 °C (Fig. 5.3-2), during 7 of the 12 past years, (related to Koblenz - Fig. 5.3-3) temperatures above 25 °C only occurred during one year of the period 1978-1989. Since no data are available, no statements can be made for the period 1978-1987 and 1978-1996 for the monitoring stations Karlsruhe and Weil am Rhein (see Fig. 5.3-2 and 5.3-3).

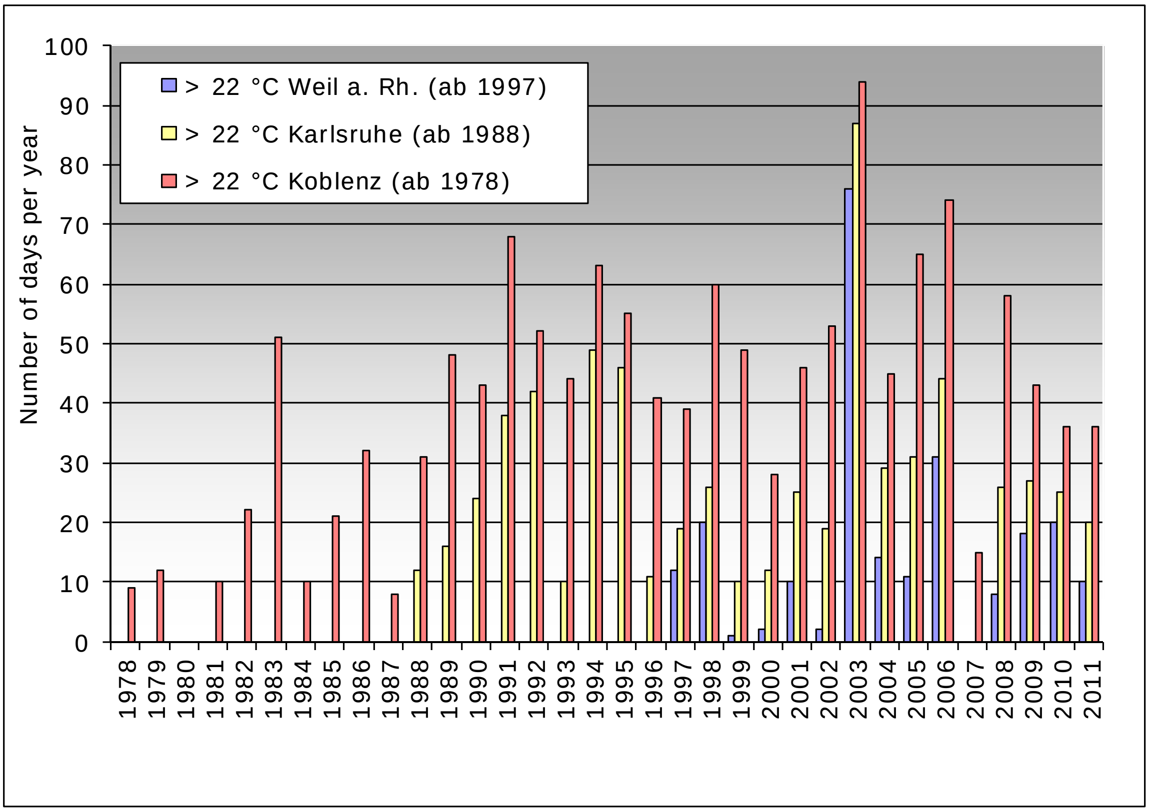

Fig. 5.3-2: Periods of Rhine water temperatures in excess of 22 °C during the past three decades

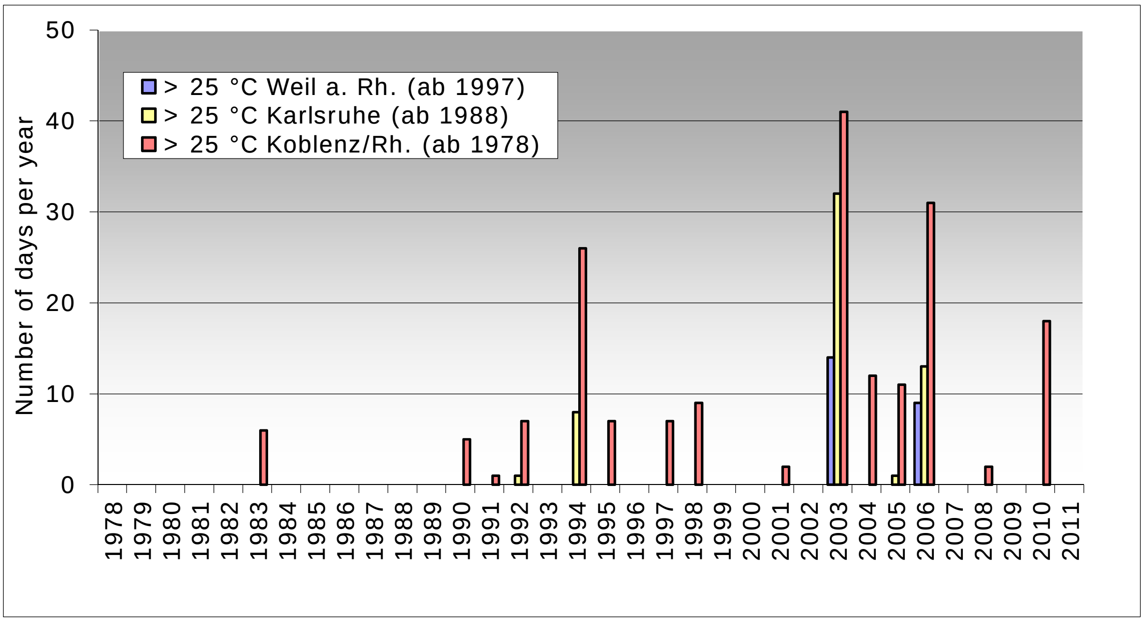

Fig. 5.3-3: Periods of Rhine water temperatures in excess of 25 °C during the past three decades

In April 2007, high water temperatures (above 20 °C) were equally measured during three weeks (until the beginning of May) in the Koblenz region. The temperatures measured were in excess of 5 °C of the longstanding average for the period, which is comparable to the corresponding extreme temperatures of the summers 2003 and 2006.

Fig. 5.3-4 represents periods when temperatures fell below certain temperatures during the winter months at Koblenz/Rhine during 1978-2011. It is conspicuous that, during the winter 2011/2012 water temperatures were below 2 °C for 11 days. This is the longest period of time during the 34-year period under consideration. The reduced thermal discharges between Karlsruhe and Worms in 2011 (see chapter 6) might have contributed to this result. Further monitoring stations with water temperature data from 2012 must be included in the evaluation in order to clarify this point.

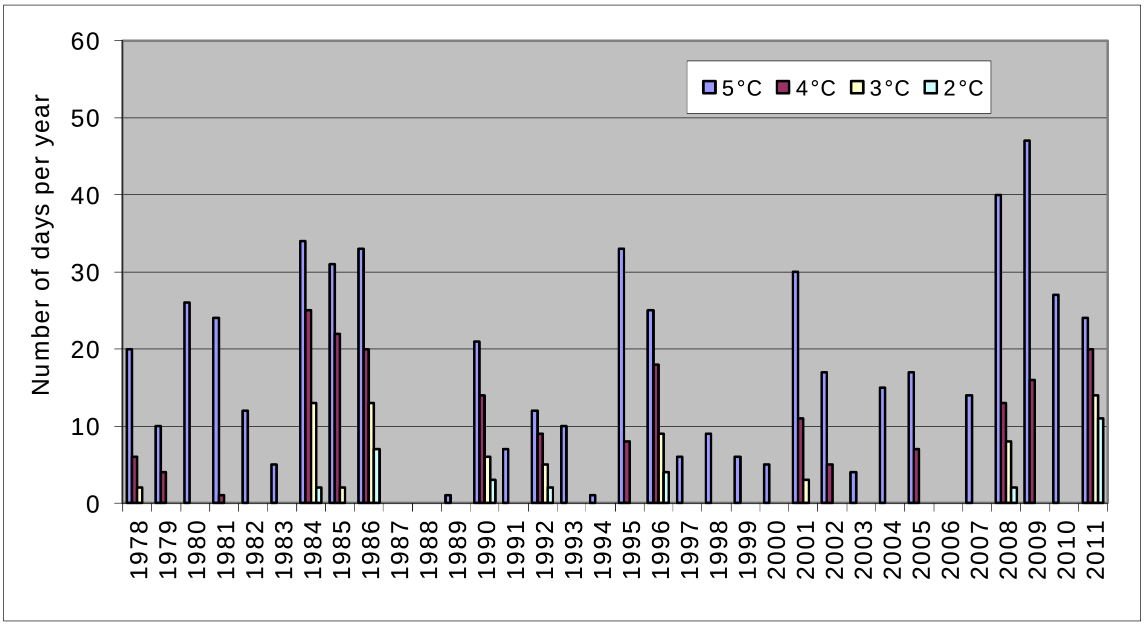

Fig. 5.3-4: Periods with Rhine water temperatures below x °C at Koblenz during 1978-2011

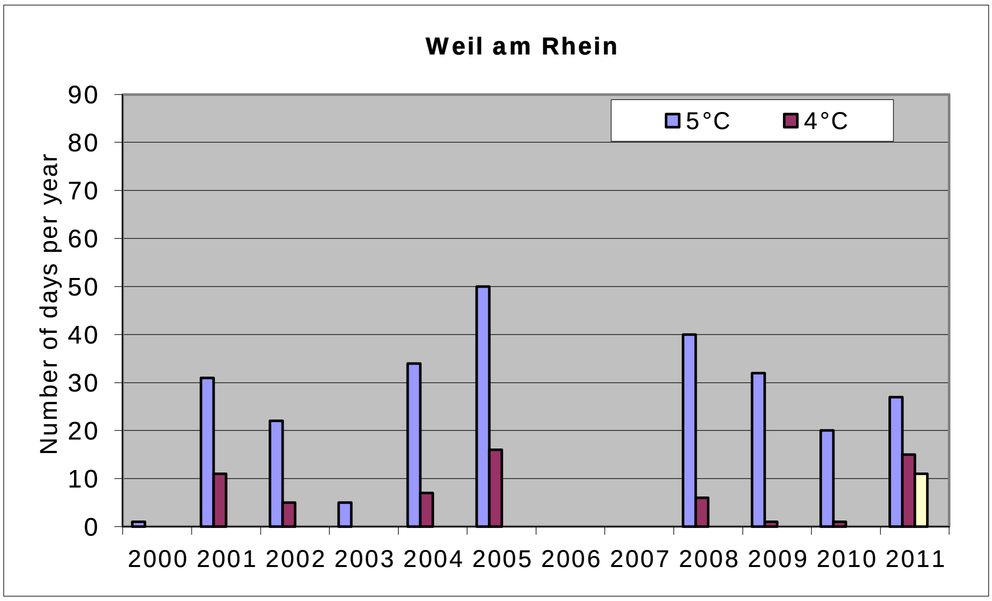

Fig. 5.3-5: Periods with Rhine water temperatures below x °C at Weil am Rhein during 2000-2011

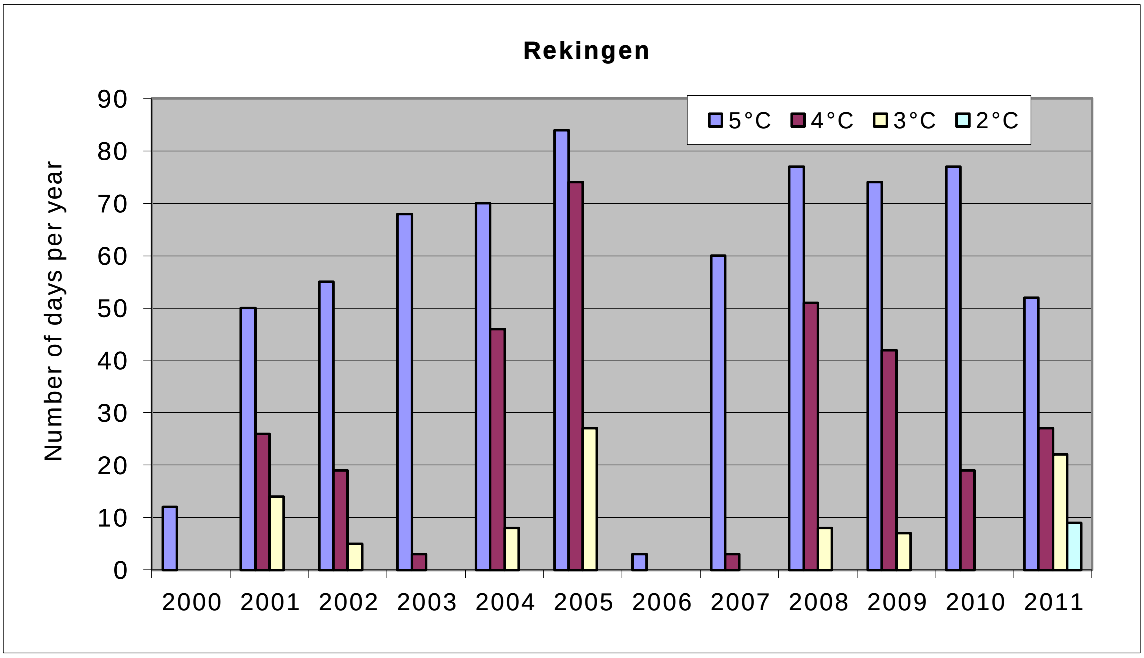

Fig. 5.3-6: Periods with Rhine water temperatures below x °C at Rekingen during 2000-2011

In a comparison of the corresponding evaluations for the monitoring stations Weil a. Rhein and Rekingen, the warm winters of 2006/2007 and 2000/2001 particularly stand out, during which Rhine water temperatures were almost always above 5 °C. However, during the winter 2011/2012, temperatures below 2 °C were equally registered.

5.4 Trend analysis

In order to be able to make statements on the development of Rhine water temperatures during the past decades, selected water temperature time series were examined with a view to detecting trends. In this connection, the Mann-Kendall trend test was used. This test does not presuppose any normal distribution or linear trend. Apart from the direction of trend, trend significance and size were calculated. Table 5.4-1 represents the trends for monitoring stations with long time series with respect to annual average and seasons.

Table 5.4-1: Trend evaluation of selected time series using the Mann-Kendall trend test

Monitoring station	Time series	Significant trend (%)	Rise / fall of the WT in °C	Average (time-related)
Rekingen	1978-2011	99.9	1.7	Annual average
BASF WW Süd	1978-2011	99.9	2.2	Annual average
Mainz	1980-2011	99	1.3	Annual average
Koblenz/Rh.	1978-2011	99.9	1.2	Annual average
Rekingen	1989-2011	-	0.5	Annual average
BASF WW Süd	1989-2011	95	0.9	Annual average
Mainz	1989-2011	-	-0.2	Annual average
Koblenz/Rh.	1989-2011	-	0.01	Annual average
Koblenz/Rh.	1978-2011	99	1.7	Spring
Koblenz/Rh.	1978-2011	99.9	2.3	Summer

Monitoring station	Time series	Significant trend (%)	Rise / fall of the WT in °C	Average (time-related)
Koblenz/Rh.	1978-2011	-	0.6	Fall
Koblenz/Rh.	1978-2011	-	-0.3	Winter
BASF WW Süd	1978-2011	99.9	2.7	Spring
BASF WW Süd	1978-2011	99.9	2.6	Summer
BASF WW Süd	1978-2011	95	1.1	Fall
BASF WW Süd	1978-2011	95	1.4	Winter
Koblenz/Rh.	1989-2011	-	-0.2	Spring
Koblenz/Rh.	1989-2011	-	-0.2	Summer
Koblenz/Rh.	1989-2011	-	0.5	Fall
Koblenz/Rh.	1989-2011	-	-0.9	Winter
BASF WW Süd	1989-2011	-	0.6	Spring
BASF WW Süd	1989-2011	-	0.6	Summer
BASF WW Süd	1989-2011	-	0.4	Fall
BASF WW Süd	1989-2011	-	0.1	Winter

The interpretation of time series between 1978 and 2011 shows a temperature rise of 1.7 °C for Rekingen (High Rhine), of 1.3 °C for Mainz (Upper Rhine) and of 1.2 °C for Koblenz (Middle Rhine) in this period. During the summer months, all values are distinctly above 2 °C. However, this trend is not linear across the entire period (1978-2011) but is mainly a result of a rise in temperature during 1987-1989. Based on the time series between 1978 and 2011, the trend towards higher temperatures is more distinct, while, for 1989 to 2011 or shorter time series, it is only very weak or inexistent.

Based on time series of daily averages available for Rekingen on the High Rhine (1997-2010), no significant trend could be detected in the annual averages, nor for the seasons (table 5.4-2). For the winter months, a fall in temperature has even been detected, without delivering any significant trend.

Table 5.4-2: Trend evaluation of selected short time series using the Mann-Kendall trend test

Monitoring station	Time series	Significant trend (%)	Rise / fall of the WT in °C	Average (time-related)
Rekingen	1997-2010	-	0.3	Annual average
BASF WW Süd	1997-2010	-	0.4	Annual average
Koblenz/Rh.	1997-2010	-	-0.3	Annual average
Rekingen	1997-2010	-	-0.4	Spring
Rekingen	1997-2010	-	0.7	Summer
Rekingen	1997-2010	-	0.6	Fall
Rekingen	1997-2010	-	-0.9	Winter
BASF WW Süd	1997-2010	-	0.00	Spring
BASF WW Süd	1997-2010	-	1.1	Summer

Monitoring station	Time series	Significant trend (%)	Rise / fall of the WT in °C	Average (time-related)
BASF WW Süd	1997-2010	-	0.00	Fall
BASF WW Süd	1997-2010	-	-0.3	Winter
Koblenz/Rh.	1997-2010	-	-0.8	Spring
Koblenz/Rh.	1997-2010	-	0.7	Summer
Koblenz/Rh.	1997-2010	-	0.1	Fall
Koblenz/Rh.	1997-2010	-	-1.1	Winter

The trend evaluation shows that, depending on the time series taken as a basis, significantly varying results can be generated.

Therefore, Fig. 5.4-1 additionally presents a diagram of the development of the annual average at five stations along the Rhine (period 1978-2011).

Air temperature has the most significant influence on water temperature (see chapter 5.5), which is clearly shown with the equidirectional development of values along the Rhine. Also, the major cooling water discharges into the Rhine section between Karlsruhe and Mainz (see chapter 5.7) are distinct. The marked change towards higher water temperatures compared to annual averages between 1987 and 1989 was reinforced by the considerable fall in discharge during these three years.

For this period of time, this change is also observed at other monitoring stations on the Rhine and its tributaries and must thus be considered to be a climate phenomenon. Hari [Hari et al 2006] has already pointed out this climate effect in his longstanding evaluation of Alpine rivers. It is explained by the particularly pronounced so called North Atlantic Oscillation (NAO) during this period. These are great variations in barometric pressure in the North Atlantic, as a result of which and particularly in winter, warm maritime air increasingly flows into Western Europe. What cannot be explained is that, during the following years, the NAO was less distinct, but air and water temperatures remained on a higher level (see fig. 5.5-1).

Depending on whether a time series comprises the period 1987-1989 or not, statistically highly significant trends can be produced.

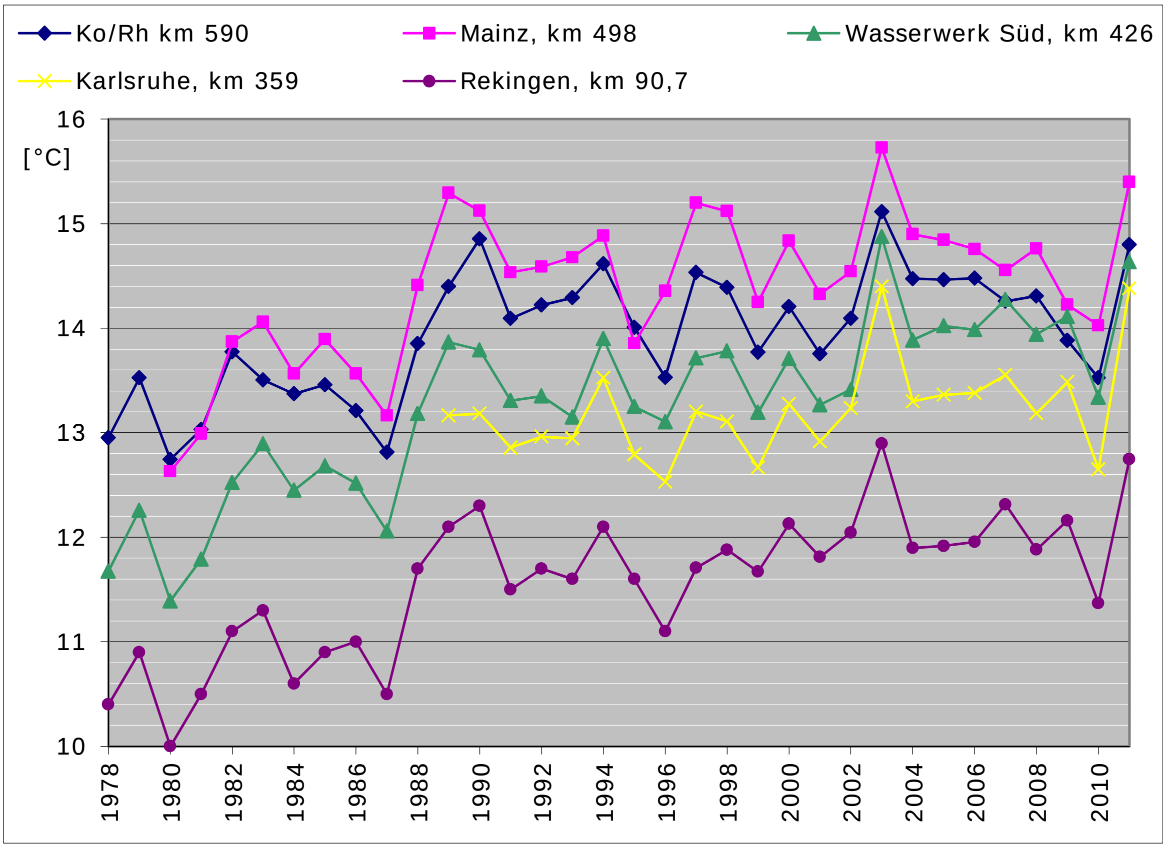

Fig. 5.4-1: Annual average Rhine water temperatures between 1978 and 2011 at five monitoring stations on the High, Upper and Middle Rhine

5.5 Correlation analysis

According to [Haag, 2009], air and stream temperatures are largely determined by the same climatic factors. Thus, a similar trend should be distinguishable in the temperature development of rivers. Since monitoring time series for water temperatures tend to be considerably shorter than for air temperatures, there are comparably few investigations into the historical water temperature development [Webb 1996].

The average water temperatures at the monitoring stations Koblenz/Rhine, BASF waterworks south and Rekingen have been compared with air temperatures in Mannheim, additionally indicating the average for the decades beginning with 1979-1988 - see Fig. 5.5-1. For the water temperatures at Rekingen, the change between the first (1979-1988) and the second (1989-1998) decade is 0.9 °C, at Koblenz 1.0 °C and at the BASF waterworks south 1.1 °C, while the change in air temperatures is 0.75 °C.

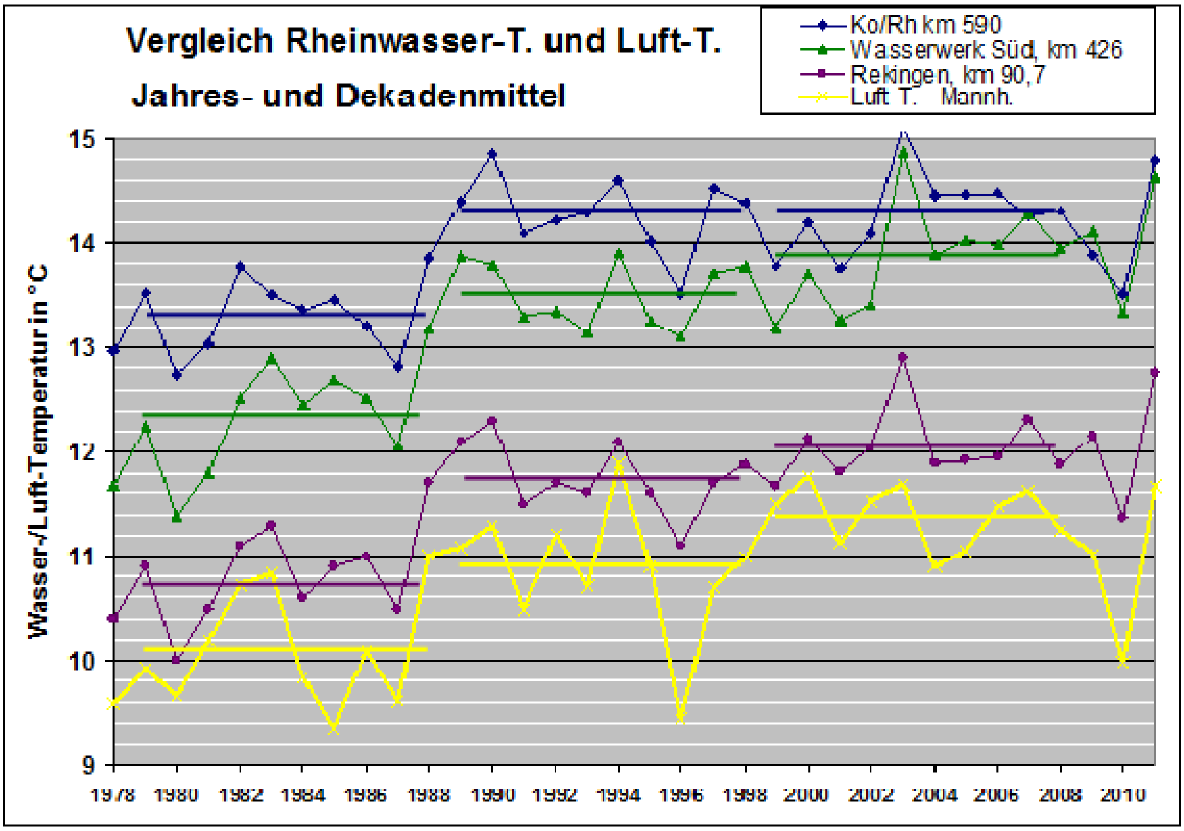

Fig. 5.5-1: Comparison of average annual and decennial Rhine water temperatures and air temperatures (average decennial beginning with decade 1979-1988; coloured horizontal lines).

A direct comparison of the water temperatures at the BASF waterworks south with the neighbouring air monitoring station of the German meteorological service (DWD) in Mannheim reveals that, within the longstanding average, water temperatures are 2 to 2.3 °C above the air temperatures. This completely corresponds to evaluations known from literature.

Greis [Greis 2007] also examines monitoring stations in the Rhine area with respect to the correlation between air and water temperatures at monitoring locations close to one another. For the water temperature monitoring stations Koblenz and Karlsruhe, correlation coefficients of 0.898 and 0.900 have been determined. That means that, in these cases, air and water temperatures correlate well.

Table 5.5-1: Correlation coefficient between data of the water and air temperature monitoring stations (source: Greis 2007)

Water temperature - monitoring station	**Air temperature - monitoring station**	**Period of investigation**	**Correlation coefficient**
Koblenz	Koblenz-Horchheim	1978 to 2007	0.898
Karlsruhe	Karlsruhe	1988 to 2007	0.900

The additional cross-correlation showed a maximum correlation of air and water temperatures at the different stations with a deferral of one to three days.

On the rivers Rhine and Neckar, maximum correlation coefficients were detected with a deferral of two (Koblenz/Rhine, Besigheim/Neckar and Poppenweiler/Neckar) and three days (Rockenau/Neckar and Karlsruhe/Rhine).

5.6 Influence of major tributaries on the Rhine water temperatures

A comparison of the seasonal average water temperatures of the Rhine and the Moselle at Koblenz for the past 20 years shows that, during fall and winter the average difference amounts to 1.7 resp. 1.8 °C, while, in summer, the average water temperatures of the Rhine and the Moselle are within the same range. During the period concerned, the average temperature of R. Moselle is 1 °C below that of the Rhine. These means that considering the average discharge relationship of 1:5 between the Rhine and the Moselle at Koblenz, the cooling effect of the Moselle on the Rhine after mixing can be calculated to 0.2 °C (Fig. 5.6-1).

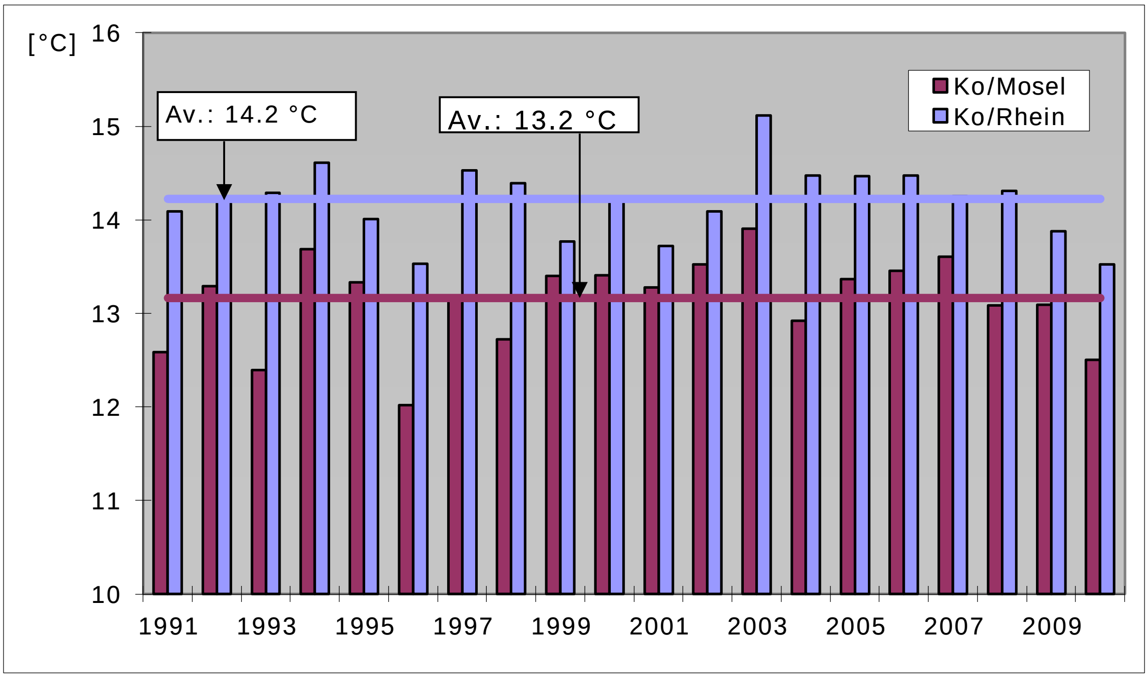

Fig. 5.6-1: Comparison of annual average water temperatures of the Rhine and the Moselle at Koblenz between 1991 and 2010.

The same comparison has been made for Rhine water temperatures at Mainz (left bank) with Main water temperatures at Bischofsheim - Fig. 5.6-2a. In this case, too, a temperature difference of 1 °C was stated which is seasonally distinct during the fall and winter but which does not exist in summer.

A comparison of water temperatures of R. Rhine and Neckar at Mannheim reveals a change of R. Neckar temperatures from higher to lower annual averages (Fig. 5.6-2b). The reason is the decommissioning of the Obrigheim nuclear power plant in May 2005. On average, between 2006 and 2010, the Neckar too contributed to a slight cooling of the Rhine (about 0.1 °C for MQ-Worms).

WT in °C Average 2000-2010	Main Bischofs-heim	Rhine-km 498 le. bank	delta T
Annual average	13.7	14.7	-1.0
Spring	12.4	13.1	-0.7
Summer	22.4	22.2	0.2
Fall	14.7	16.0	-1.3
Winter	5.0	7.4	-2.3

WT in °C	Mannheim Neckar	Rhine -km 426	delta T
Average 2000- 2004	14.8	13.8	0.93
Average 2006-2010	13.2	13.9	-0.72

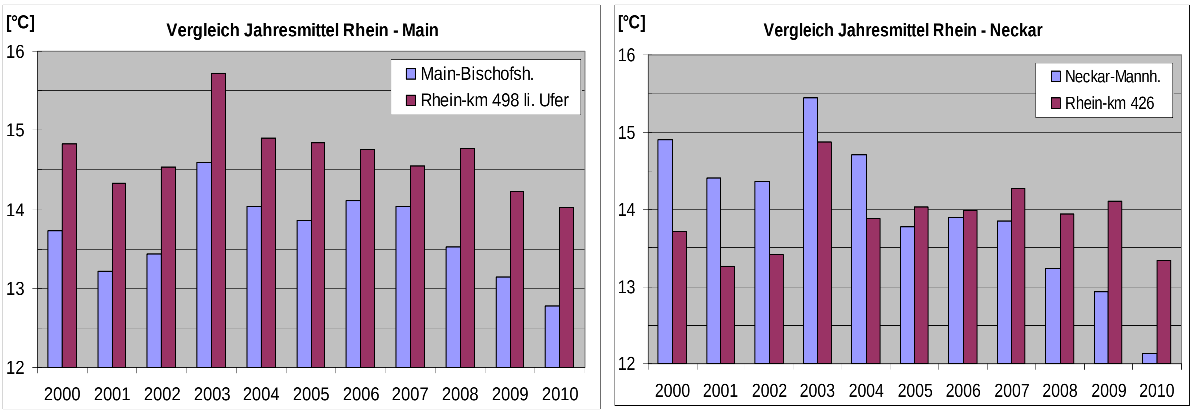

Fig. 5.6-2a/b: Comparison of the annual average water temperatures of R. Rhine and Main resp. Rhine and Neckar between 2000 and 2010 including a tabular evaluation

Contrary to the Rhine, the tributaries to the Upper and Middle Rhine often reach minimum temperatures around 0 °C, partly, severe ice formation is observed. As explained in chapter 5.3, between 1978 and 2011, in the Rhine at Koblenz (daily average) water temperatures below 2 °C were only measured during 7 years.

5.7 Influence of major thermal dischargers on the Rhine water temperatures

Considering the thermal discharges of existing and planned power plants, the ICPR treated issues related to the thermal load of the Rhine already in the 1970s. Following the extreme situation of the summer of 2003, and as already indicated above, the ICPR updated the survey of thermal discharges of 1989 in 2004 [ICPR 2006]. Given the rise in water temperature due to climate change (of about 1-2 °C), Table 5.7.1 represents a comparison with the theoretically possible rise in water temperatures due to thermal discharges concerning the average discharge at Worms (1,400 m^3/s). Until 2010, approximately 60 % of the major authorized thermal discharges into the Rhine concerned a short section of the Upper Rhine between Karlsruhe and Worms. Presuming that all dischargers entirely use their permitted capacities at the same time, and without taking into account natural processes, these could contribute to a theoretical rise in temperature of 2.6 °C at maximum in the average discharge at Worms, once thermal discharges have completely mixed with the Rhine water. On the other hand, the measurable rise in temperature at Mainz (related to MQ) amounts to about 1.4 °C and continues to fall to 1°C at Koblenz. Largely, this small difference can be explained by the fact that the permitted discharges are not completely exhausted and, on the section to Mainz, resp.

Koblenz, there is a heat exchange (evaporation and convection) with the atmosphere. The rise in temperature at Mainz is presumed to be mainly caused by thermal discharges in the Mannheim/Ludwigshafen region and by the Biblis nuclear power plant, to a lesser extent by natural warming in the course of the 50-60 km long reach of the river. The influence of the thermal discharges of the Philippsburg nuclear power plant at a distinctly greater distance should however hardly be measurable in Mainz. More precise statements can be expected to result from the modelling of water temperatures of this reach of the Rhine.

A reduction of low water discharges in summer below half of MQ or less, such as in 2003, might bring about a critical situation as, when discharges are low and cooling capacities are thus reduced, unchanged thermal discharges result in higher temperatures (Webb 2006).

Therefore, for cooling procedures, depending on the location of the power plant and the type of water body, limit values for abstracting and discharging cooling water are fixed in the German Water Act. They are based on recommendations of the Länderarbeitsgemeinschaft Wasser. Once these limit values are reached, the production of the power plant must be reduced, in order to reduce the heat discharge into the receiving waters [UBA 2010, p. 141].

Similar measures have been taken in the other Rhine bordering states.

Table 5.7-1: Compilation of major permitted thermal discharges between Karlsruhe and Mainz, the average discharge at Worms and the resulting theoretical rise in Rhine water temperatures

Thermal discharger	MW*	MQ [m³/s]	Theoret. rise in temp. [°C]
Philippsburg nuclear power plant	4265	1400	0.7
Biblis nuclear power plant	4940	1400	0.8
Total Karlsr. - Worms	15000	1400	2.6
delta T: Mainz-Karlsruhe 2010			1.4

* Permissions for thermal discharges according to the survey of thermal discharges 2004 of the ICPR report no. 151 [ICPR 2006]

Furthermore, the possible effects of the point source thermal discharges of the Fessenheim nuclear power plant in Alsace on water temperature measurements 130 km downstream at Karlsruhe are being considered. Since 1977, Fessenheim is the most important thermal discharger of anthropogenic origin (with a thermal discharge permission of 3520 MW [ICPR 2006]) along the river section between Basel and Karlsruhe. To this effect, the published monthly average [Umwelt & Strahlenschutz] rise in temperature in the immediate vicinity of the Grand Canal d'Alsace has been evaluated for the period March 2010 to March 2012. A monthly rise in temperature between 0 °C (during revision of the power plant) and 2.3 °C (April 2010) was registered. In the same period, the average rise in temperature of the Grand Canal d'Alsace amounted to 0.9 °C. For all discharge situations, the discharge regime of the Grand Canal d'Alsace is ruled by a Franco-German convention. Up to a discharge of 1500 m³/s, the major part of the discharge flows through the Grand Canal d'Alsace and only a small amount remains in the so-called "Restrhein" - the old bed of the Rhine. This means that, for most days of the year, the warming of the Grand Canal d'Alsace does not correspond to the natural rise in temperature of all the Rhine water in the transverse section.

Representations of the monthly average differences in temperature between Karlsruhe and Weil am Rhein in Figure 5.7-1 show that water temperature increases during most months and can only fall during the fall and winter months. Along the more than 130 km long impounded section leading to the Karlsruhe monitoring station, largely, natural heat exchange levels between water and atmosphere are registered. As shown in chapter 4, no temperature gradient is detected in the transverse profile at the Karlsruhe monitoring station. The heat discharges represented (monthly average 2010-2011) in the Grand Canal d'Alsace at Fessenheim can however not be correlated to the temperature development. The influence of thermal discharges seems to be overlapped by natural processes (warming up and cooling) and is no longer detectable. Along the more than 130 km long impounded section leading to the Karlsruhe monitoring station, largely, natural heat exchange levels between water and atmosphere are registered. A modelling of water temperatures will permit more detailed statements.

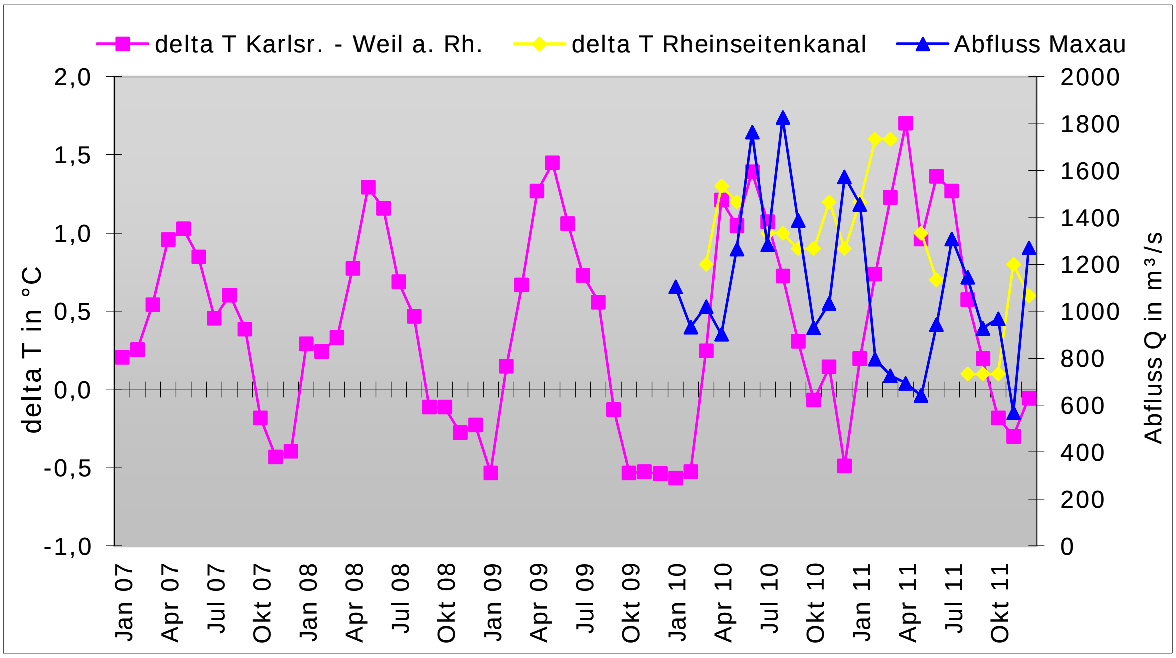

Fig. 5.7-1: Monthly average differences in temperature between Karlsruhe and Weil am Rhein, monthly discharge averages at Karlsruhe-Maxau and rise in temperature of the Grand Canal d'Alsace at Fessenheim 2010-2011

As a matter of principle and considering the results presented in Fig. 5.7-2 as well as those of the investigations conducted by Glaser [Glaser 1975] it can be stated that, given comparable discharges, such a thermal discharge at 20 °C water temperature results in the double heat dissipation due to evaporation and convection than the same thermal discharge at a water temperature of 5 °C.

Heat dissipation related to the dissipation at a surface temperature of 10 °C

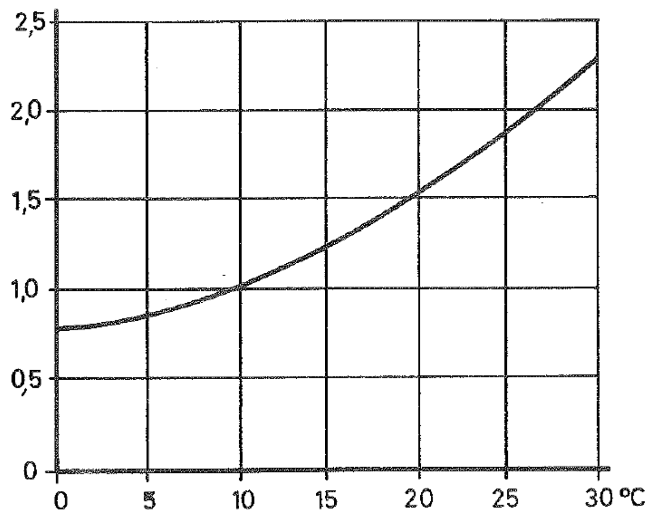

Fig. 5.7-2: Heat dissipation depending on the temperature at the water surface (source: Glaser 1975)

6. Development of Rhine water temperatures since 2011

In March 2011, and following the nuclear disaster in Fukushima/Japan, the German government decided a three months moratorium for eight nuclear power plants which started operating before 1981. With the entry into force of the 13th amendment to the Atomic Energy Act in 2011, the production of these installations was definitely stopped. In the Rhine area between Karlsruhe and Mainz this concerned the reactors Biblis I and Biblis II and Philippsburg, on the R. Neckar the unit Neckarwestheim I. About half of the thermal discharges figuring in the survey (according to ICPR report no. 151) originated from these installations. Thus, the difference in temperature between the monitoring stations Mainz and Karlsruhe, the long-term average (1989-2010) of which is 1.5 °C should have significantly fallen. Fig. 6-1 represents the monthly averages of temperature differences for 2011 compared to the monthly averages of the period 2001-2010. Since the power operation of the reactors stopped mid-March 2011, the difference in temperature during the second half year seems to be half of that of the 1st half year resp. of the longstanding average. The German deterministic model on a physical basis which is under development along the Rhine should confirm this order of magnitude. This development will be further observed during the years to come and will be statistically demonstrated. The merely statistical approach will be able to give more precise information on the reduction of thermal pollution, as long as thermal discharges from other power plants along the Rhine and its tributaries will not rise again.

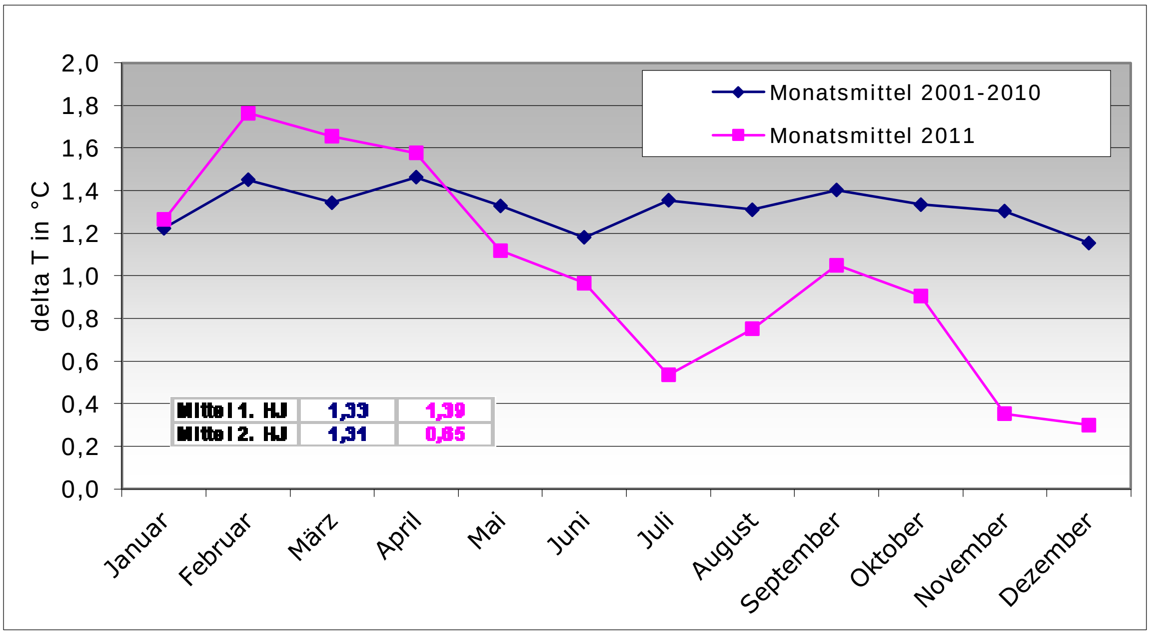

Fig. 6-1: Difference in temperature between the monitoring stations Karlsruhe and Mainz, comparison of the development of the monthly averages 2011 with those for 2001-2010.

7. Outlook

The results presented in the report at hand confirm the increase in water temperatures in the Rhine area by 1 °C during the past 3 decades, caused by climate change and which has so far been presented in the bibliography for individual regions of the Rhine area. It is clear that this rise in temperature is not a continuous development but mainly results from the effect of climate since the 1980s. For the past two decades, no significant trends towards a rise in water temperature were found for the High Rhine, the Upper Rhine or the Middle Rhine. So far, this is particularly true of the summer period, for which climate experts forecast rising air temperatures.

According to a Swiss report [BAFU 2012], between 1912 and 2011, average annual air temperatures have risen by more than 1.5 °C, a trend which has accelerated during the last 30 years (Fig. 7-1).

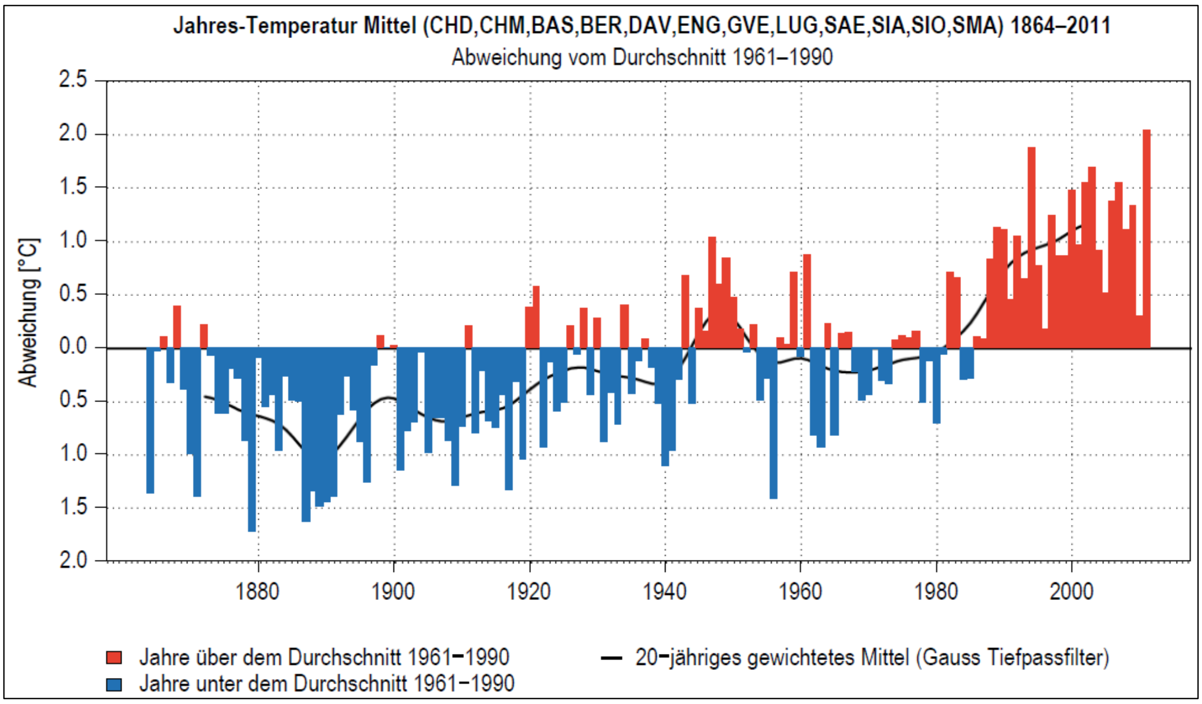

Fig. 7-1: Deviation of the average annual air temperature from the average of the period 1961-1990. (Source: BAFU 2012, average for Switzerland)

Between 1901 and 2006, the average air temperature in Germany rose by just under 0.9 °C, in the southwest of Germany even by 1.2 °C [DAS 2008]. According to recent results of the KLIWA project (Climate Change and Consequences for Water Management), there are significant positive trends of the annual air temperature averages for the time series 1941-2010 in the High and Upper Rhine regions showing 1.0 °C in the region R. Nahe and Middle Rhine and 1.2 °C in the R. Neckar region [KLIWA 2012]. Compared to the time series 1931-2000, the warming trend has increased during the past 10 years.

If this trend continues, water temperatures should also be affected to a certain degree. This is all the more true, if the discharge regime of the Rhine will change, leading to an increase of low water periods particularly in summer [Belz 2010]. The ICPR is working on a study concerning the development of Rhine water temperatures during the decades to come.

Further investigations within the KLIWA project show that climate change affects the physical-chemical relationship in water and the composition of aquatic biocoenosis [UBA 2010]. In particular, the considerable influence of a rise in temperature is pointed out which might detrimentally impact the self-cleaning processes.

Shutting down some nuclear power plants within the turnaround in German energy policy in 2011 distinctly improved Rhine water temperatures of the Upper Rhine detectable in Mainz (Fig. 6-1). It remains to be seen whether this corresponds to a sustainable development of Rhine water temperatures. Therefore, apart from selected climate scenarios, the above mentioned on-going study on future water temperature developments should take into account variants of "scenarios of thermal discharges".

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AKW	**Atomkraftwerk / nuclear power plant**
BAFU	**Swiss Environmental Agency**
BfG	**German Federal Institute of Hydrology**
BUWAL	**Swiss Ministry for Environment, Forestry and Agriculture**
BWG	**Swiss Agency for Water and Geology**
DWD	**German Meteorological Service**
HLUG	**Federal Hessian Agency for Environment and Geology (D)**
ICPR	**International Commission for the Protection of the Rhine**
KLIWA	**Cooperation project "Climate change and consequences for water policy" of the Länder Baden-Württemberg, Bavaria, Rhineland-Palatinate and the DWD**
LANUV	**Federal Agency for Nature, Environment and Consumer Protection, North Rhine Westphalia (D)**
LUBW	**Federal Agency for Environment, Monitoring and Nature Protection, Baden-Württemberg (D)**
LUWG	**Federal Agency for Environment, Water Management and Labour Inspection Rhineland-Palatinate (D)**
Meteo Schweiz	**Federal Agency for Meteorology and Climatology (CH)**
WT	**water temperature**
WW	**waterworks**