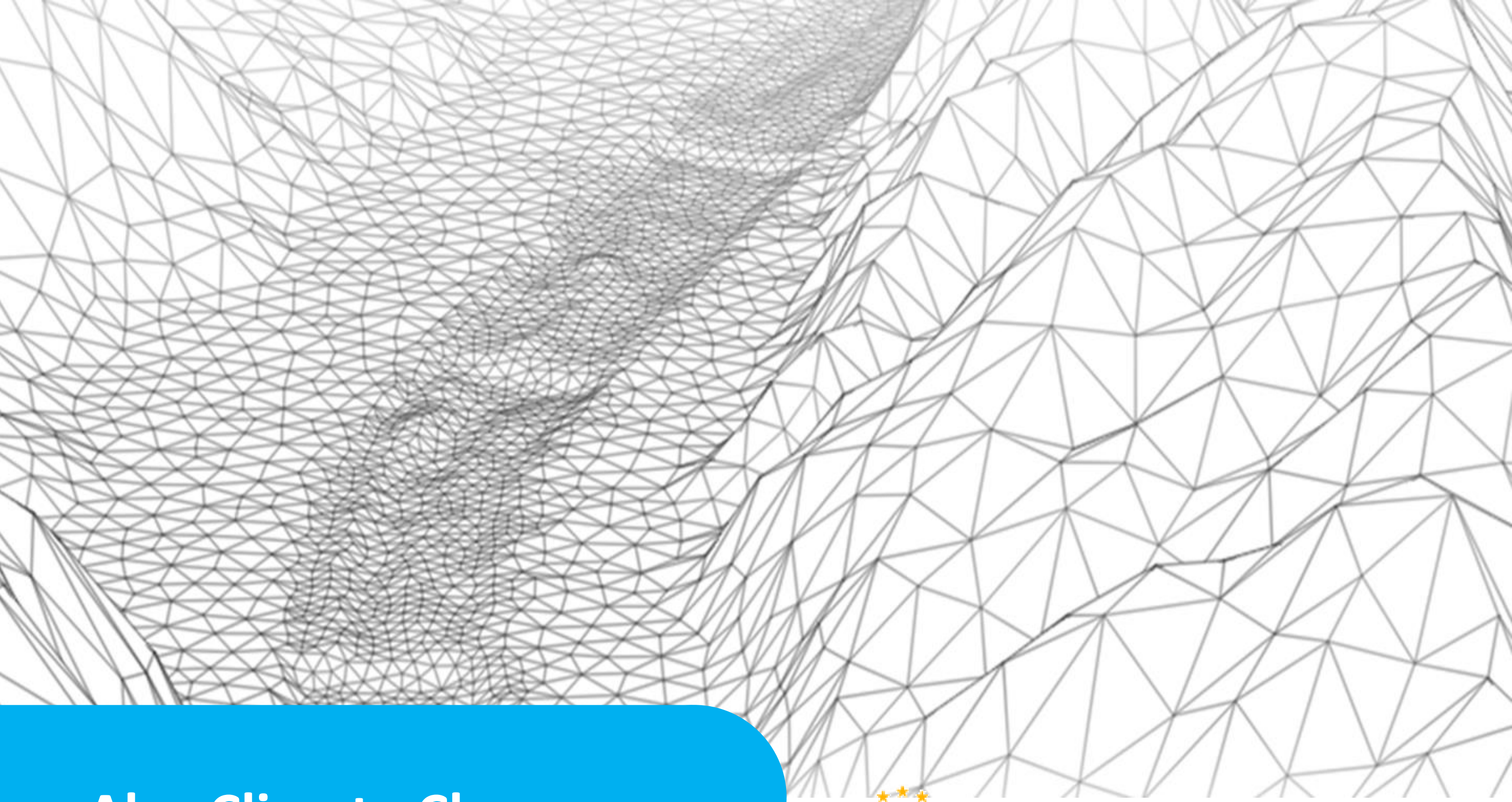

Ahr: Climate Change

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HydroEurope

WP2: Uncertainty in Advanced Hydrological and Hydraulic Modelling
WP3: Climate Change Impacts on Flash Floods
Case Study Ahr Catchment (Germany)

Climate Change Impacts on Flash Floods: Hydrological Modelling

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1. Introduction

Preface HydroEurope 2024

This teaching material is part of the teaching unit dealing with “Uncertainties in Advanced Hydrological and Hydraulic Modelling” and “Climate Change Impact Impacts on Flash Floods” for the case study River Ahr catchment in Rhineland-Palatinate (Germany). This tutorial deals with the preliminary consideration of climate change impacts on the hydrological situation in the Ahr catchment.

1.1. Prerequisites

The analysis on climate change impacts on flash floods is based on hydrological models describing the rainfall/runoff process in the Ahr catchment under heavy rainfall and related flash flood conditions. Prerequisite for this tutorial is the availability of suitable hydrological models. Three types of models can be considered:

- empirical, lumped model based con the CN method e.g. using HEC-HMS
- semi-distributed model e.g. SWAT
- distributed surface flow model e.g. 2D hydrodynamic models

1.2. Additional Catchment Data

This tutorial is using in addition to the provided catchment and 2021 flood event data in the other teaching units the KOSTRA-DWD data set. The German meteorological service (DWD) is providing this data set, defining precipitation patterns for planning and design activities. The data is based on historical data analysis and defines precipitation patterns by duration, intensity and probability (return period). Information on KOSTRA-DWD are available in the Web mainly in German language. Required data can be directly downloaded from the DWD CDC server or from the course platform. Descriptions to apply the data set are given in this tutorial.

- KOSTRA-DWD Web page
  https://www.dwd.de/DE/leistungen/kostra_dwd_rasterwerte/kostra_dwd_rasterwerte.html
- KOSTRA-DWD data sets
  https://opendata.dwd.de/climate_environment/CDC/grids_germany/return_periods/precipitation/KOSTRA/

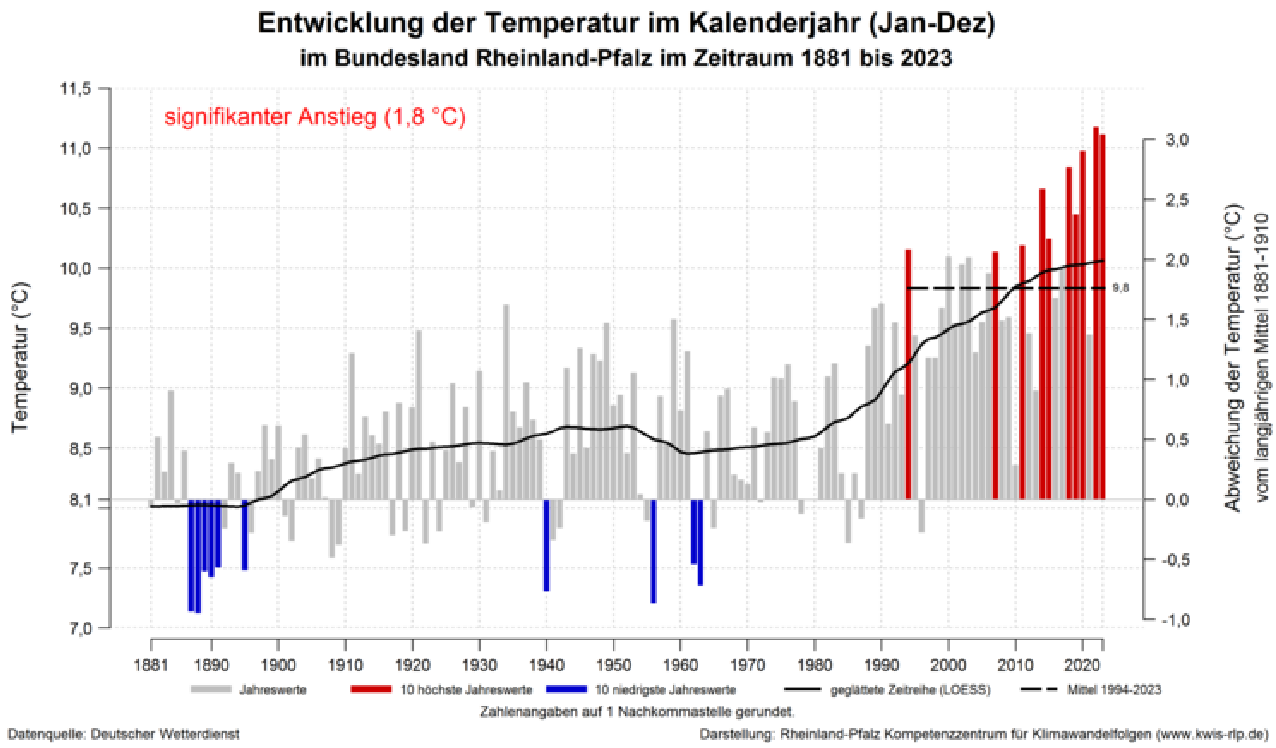
2. Climate Change

Climate change is an ongoing process of changing the climate system on Earth triggered by natural processes and events as well as anthropogenic interventions such as greenhouse gas emissions as one example. One result of the industrialisation in the last two centuries is an observe global warming. The global average temperatures to have impact to parts of the global water cycle. Consequently, an increase of the global average temperature has an impact to the water cycle as a whole as well as impact to local cycle parts such as regional (heavy) precipitation and related flood and flash floods. Understanding, analysis and modelling of the climate change impact to the water cycle on a global scale as well as on regional, local scale is an ongoing research activity. It is strongly recommended to participate in courses and modules about climate change in the home university to get a better understanding on the background in climate change processes, modelling approaches, scaling process (e.g. global to regional).

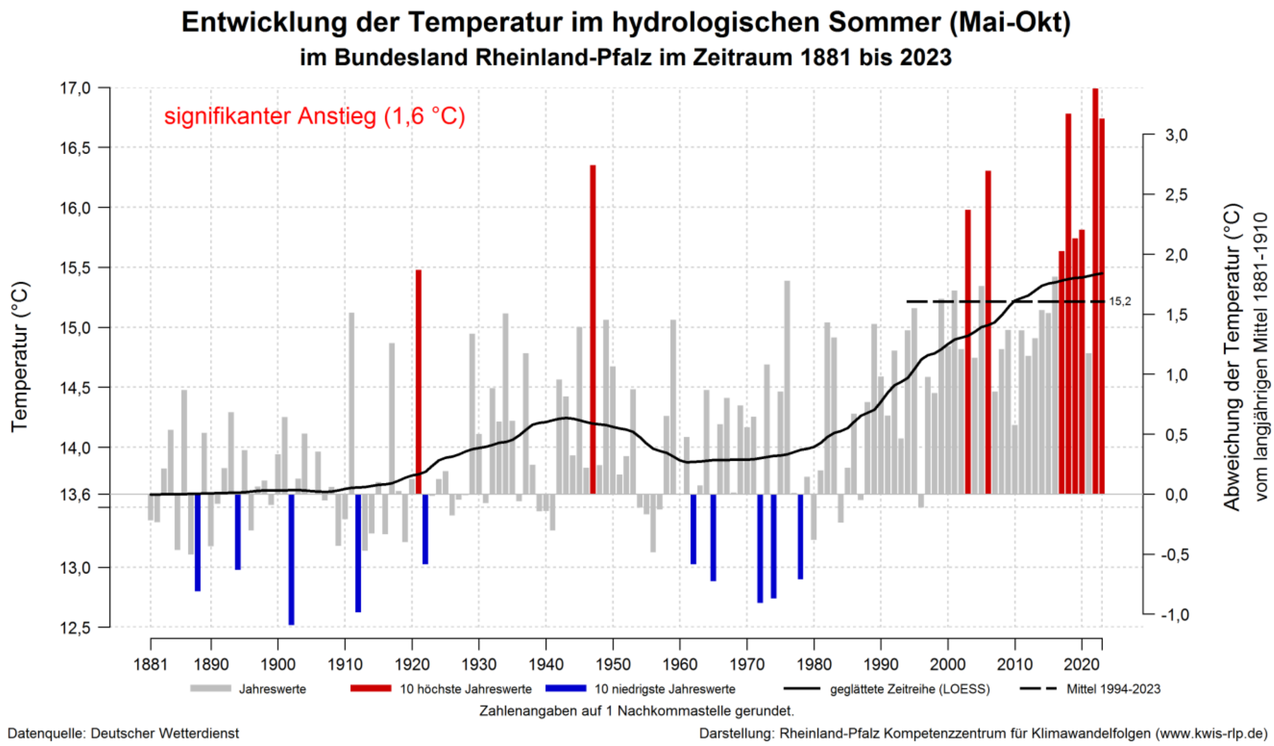
The climate change impact to the Ahr catchment has been and will be analysed by governmental institutions such as described on https://www.klimawandel-rlp.de/de/start/. The main conclusion from these activities will be summarized for the Ahr catchment case study in this teaching unit in respect to flash floods in the catchment.

2.1. Temperature Changes in Rhineland-Palatinate

The global warming in the state Rhineland-Palatinate was observed by a long-term annual average temperature increase of 1.8K for the last 30 years (1994-223) in comparison to the annual average temperature for the period 1881-1910.

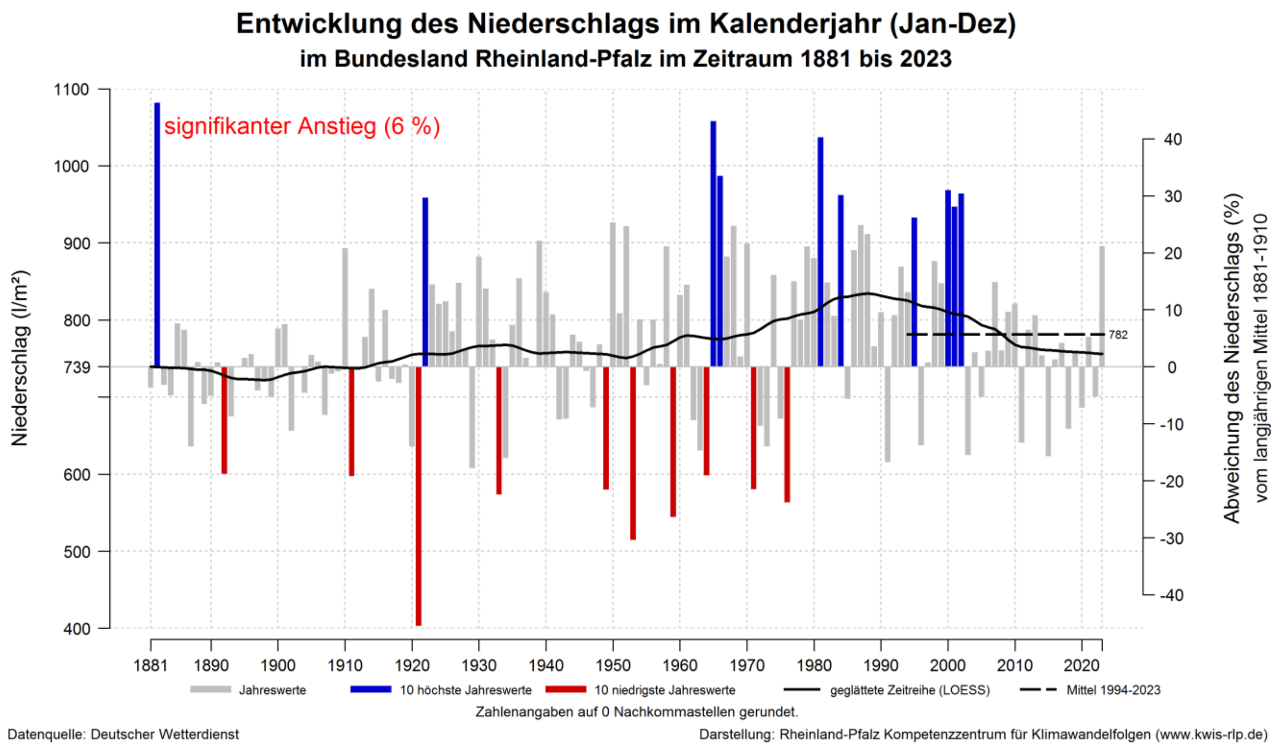


Climate change has a different impact to temperature in summer and winter period in the case study region. Heavy rainfall events (strong rainfall in short time windows) are more often seen in summer while in winter the average precipitation intensity is lower but the duration is longer. Therefore, the summer period is relevant for typical flash flood situations in this region. The temperature increase for the hydrological summer (May-October) has a similar trend by an increase of 1.6 K. The increase for the hydrological winter (Nov-Apr) is 1.9K (not shown here, diagrams are available on: https://www.klimawandel-rlp.de/de/daten-und-fakten/klimawandel-vergangenheit/).

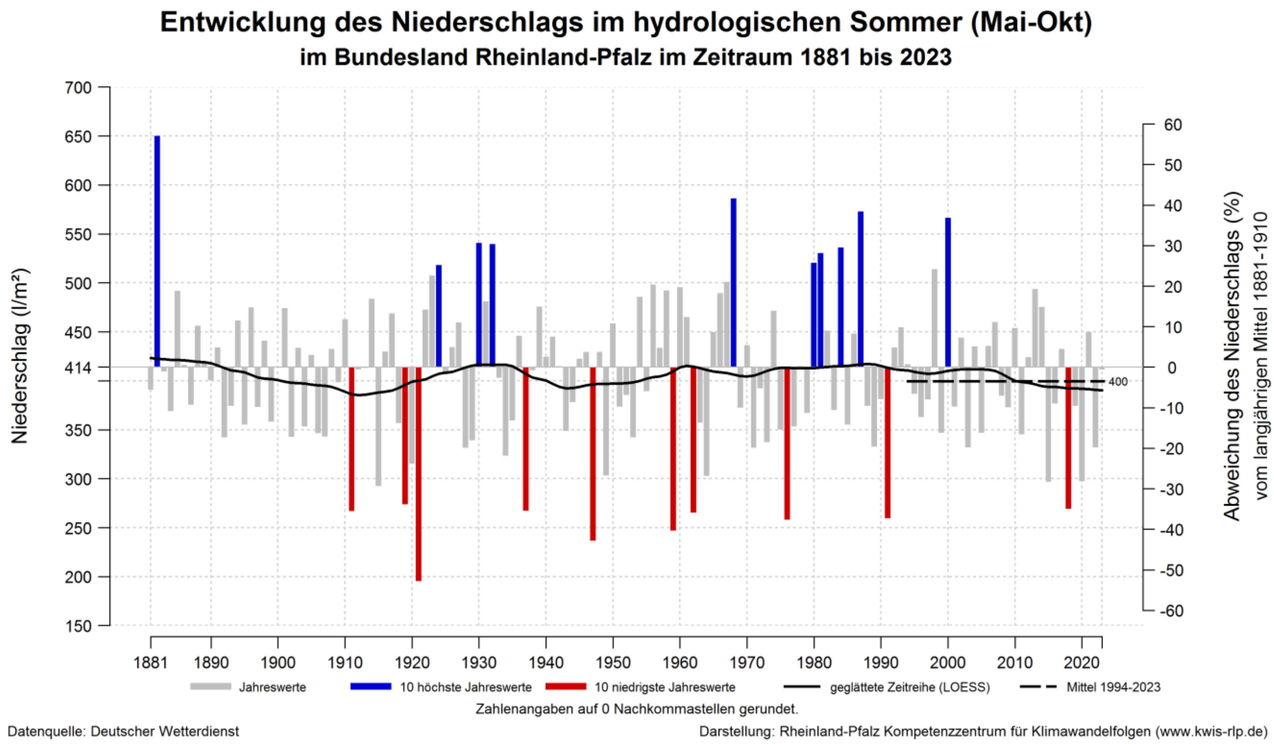


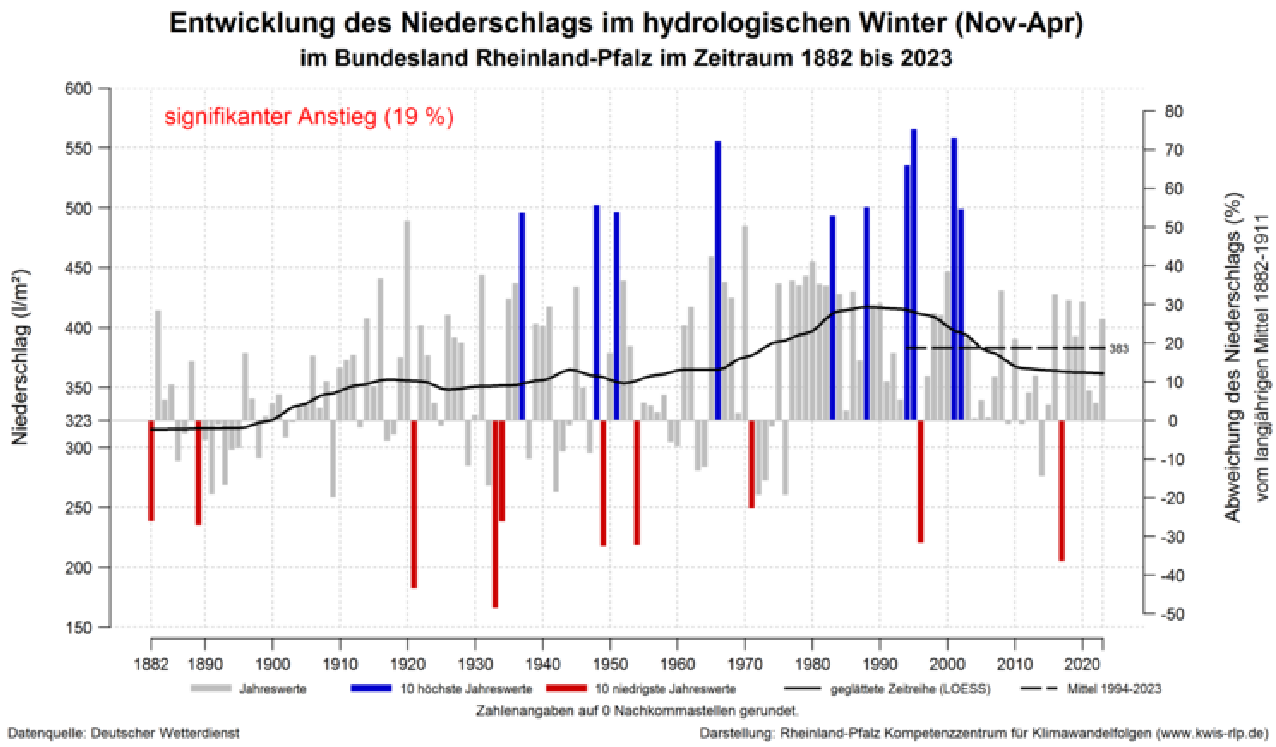
2.2. Precipitation Changes in Rhineland-Palatinate

This observed warming has also an effect on the precipitation. The annual precipitation in the state Rhineland-Palatinate has a positive trend (6% increase for the 30 year period 1994 to 2023 in comparison to the period 1881-1910).



Separated in hydrological summer and hydrological winter this trend is antithetical, in summer the annual precipitation has an overall stationary trend (slightly decreasing), while in winter the increase is significant with 19%.

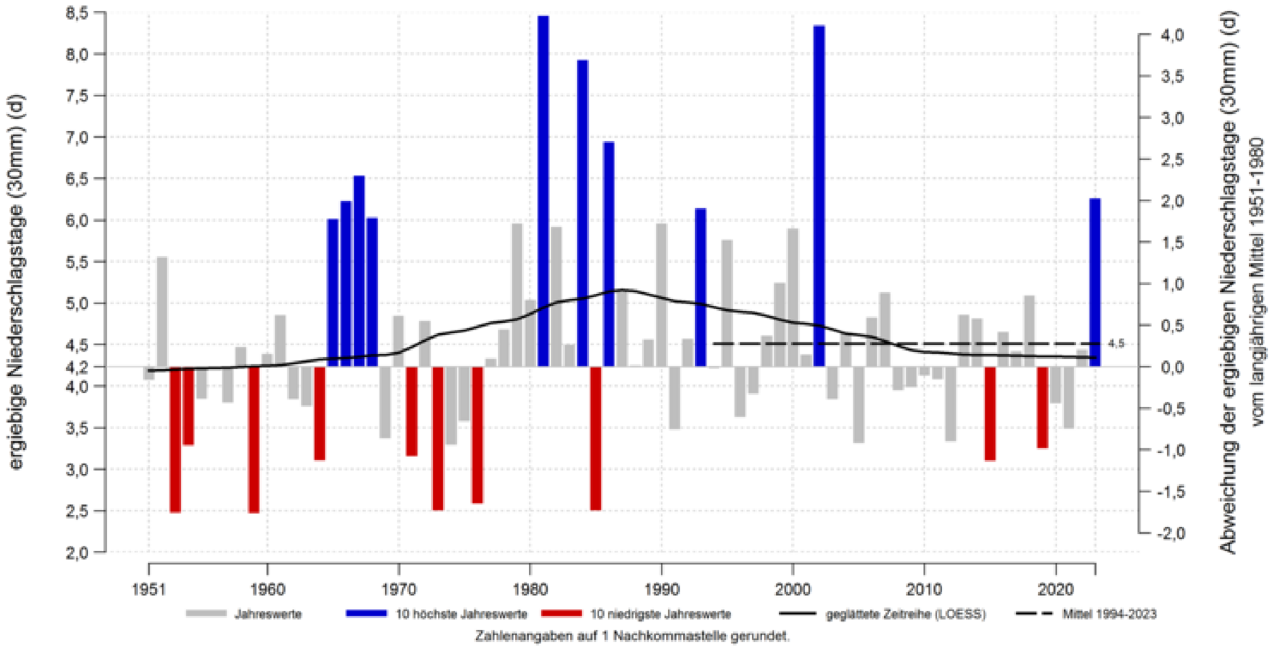




The annual precipitation is the sum of precipitation independent whether it is precipitation with longer duration and lower intensity (e.g. typical rainfall in winter) or short duration and high intensity (e.g. heavy rainfall generating flash floods in summer).

Relevant for the evaluation of the climate change impact on flash floods are intensive rainfall events. The number of days with min 30mm precipitation can used as indicator. These data are available for the whole year, not separated for summer and winter. A clear trend is not visible.

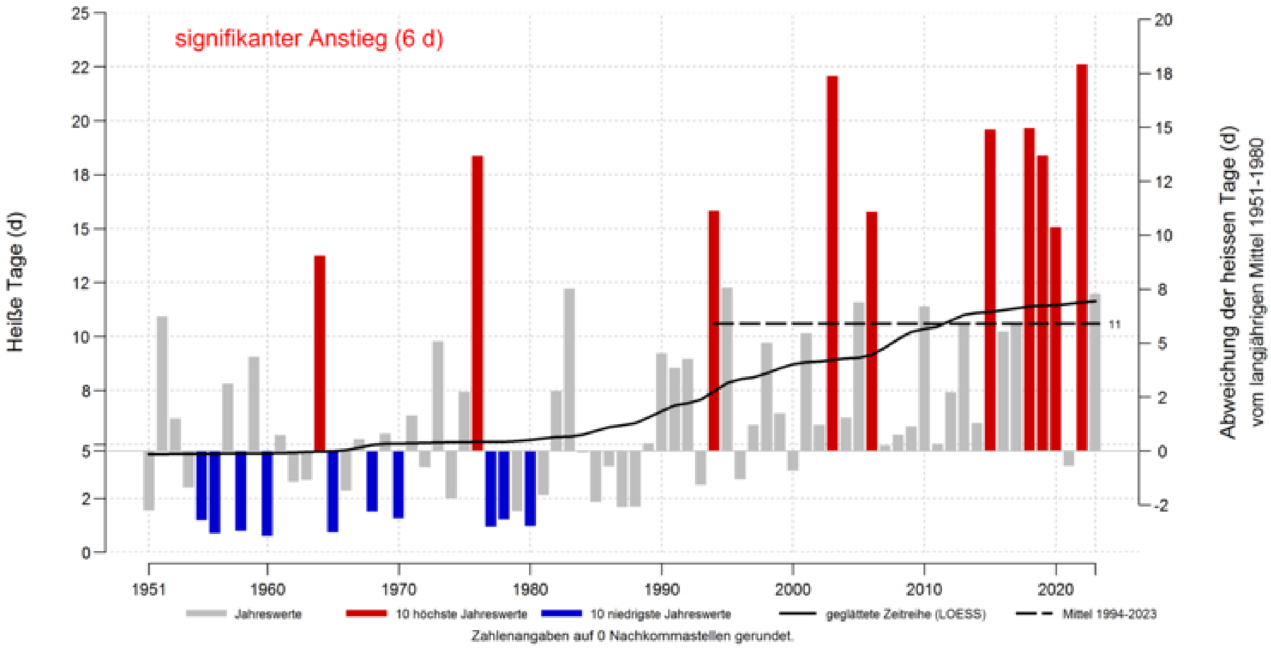
Entwicklung der ergiebigen Niederschlagstage (30mm) im Kalenderjahr (Jan-Dez)
im Bundesland Rheinland-Pfalz im Zeitraum 1951 bis 2023



Datenquelle: Deutscher Wetterdienst
Darstellung: Rheinland-Pfalz Kompetenzzentrum für Klimawandelfolgen (www.kwis-rlp.de)

As additional indicator the number of hot days (days with max T > 30°C), which naturally occurs during the summer period. There is a significant increase of 6 day for the 30 year period 1994 to 2023 (11d) in comparison to the period 1951 to 1980 (5d).

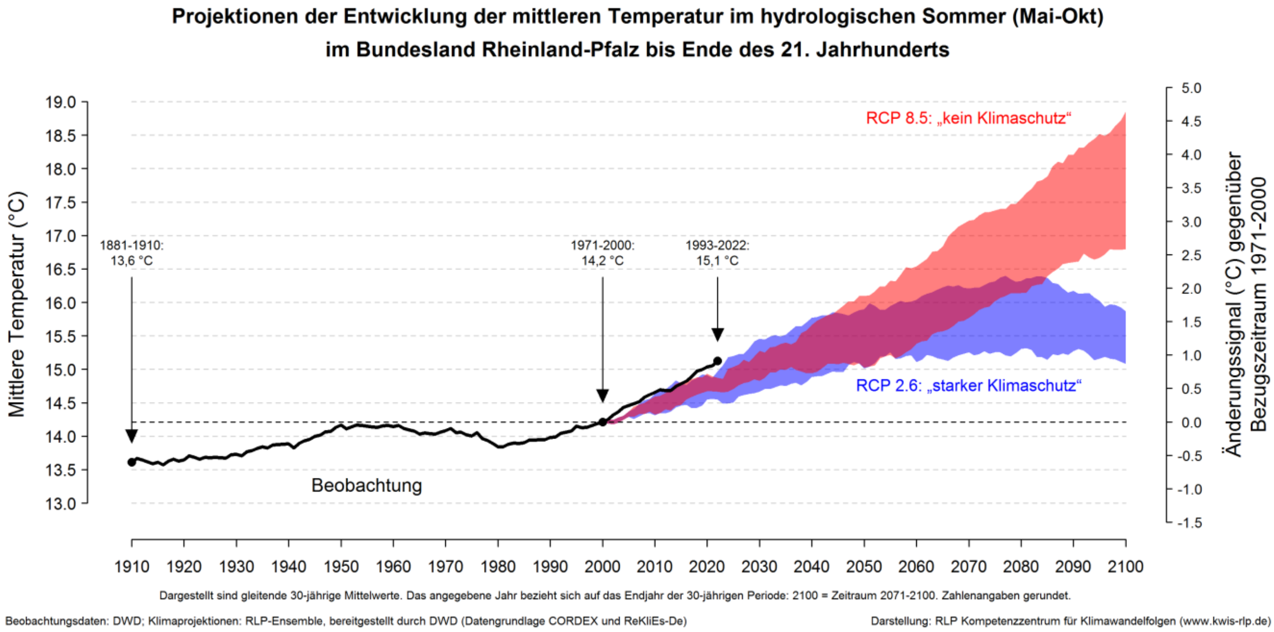
Entwicklung der heißen Tage im Kalenderjahr (Jan-Dez)
im Bundesland Rheinland-Pfalz im Zeitraum 1951 bis 2023



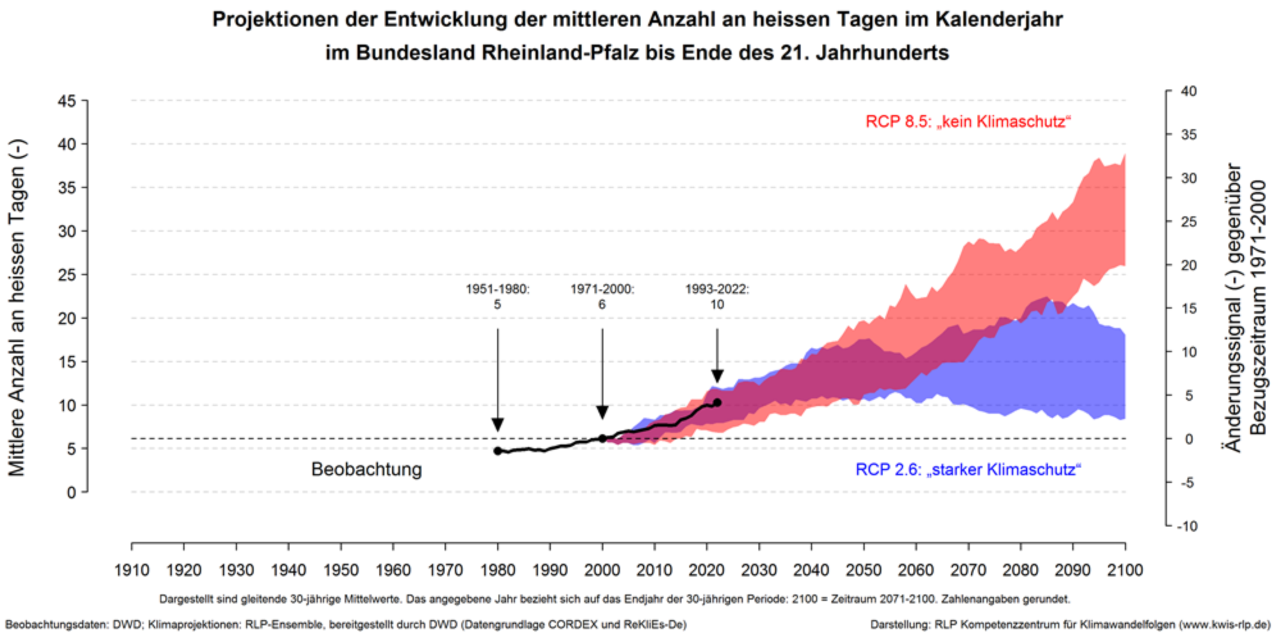
Datenquelle: Deutscher Wetterdienst
Darstellung: Rheinland-Pfalz Kompetenzzentrum für Klimawandelfolgen (www.kwis-rlp.de)

2.3. Climate Change Projection Scenarios for Flash floods

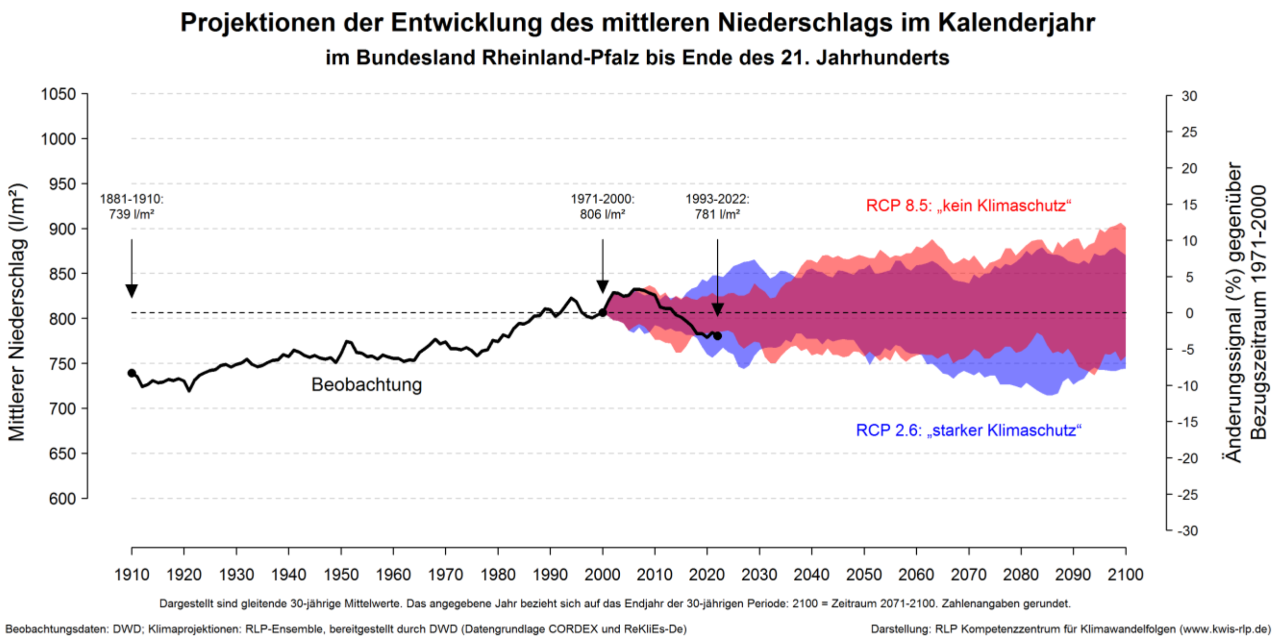
The observed climate change from the past until present can be forecasted for the future with different scenarios. The diagram below shows the range of temperature increase for scenarios RCP 3.5 and RCP 2.6 during hydrological summer (May to October). RCP (Representative Concentration Pathway) is a greenhouse gas (e.g. CO_2, CH_4, O_3, …) concentration trajectory adopted by the IPCC (Intergovernmental Panel on Climate Change https://www.ipcc.ch/). RCP 2.6 is defined as pathway assuming the CO_2 emissions start declining in 2020 and will be 0. in 2100 (as well as reductions of other greenhouse gas emissions). RCP 8.5 assumes an ongoing increase of greenhouse gas emission.



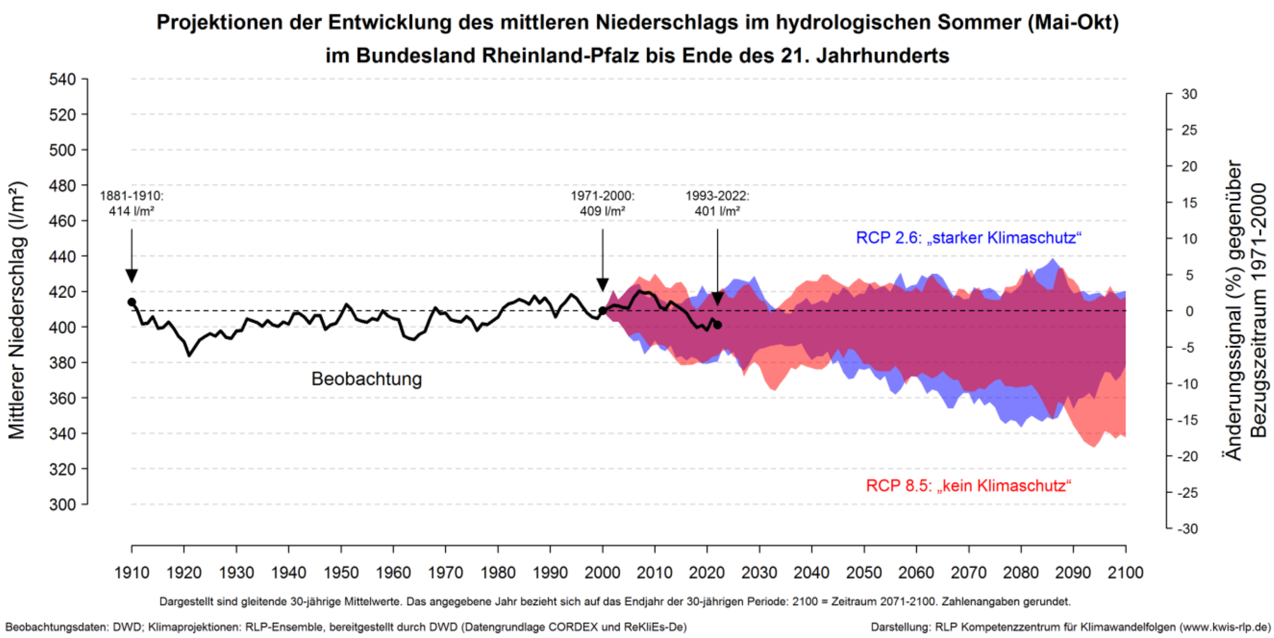
For summer an increase of 0.9 K within 22 years has been observed for the period 1993-2022 in comparison to the 1971-2022. Similar to the mean temperature the number of hot days during the year (occurring in summer) has increased and is also projected to increase for the next decades.



The projection of the annual mean precipitation did show a constant trend within the uncertainty from the scenario assumptions.

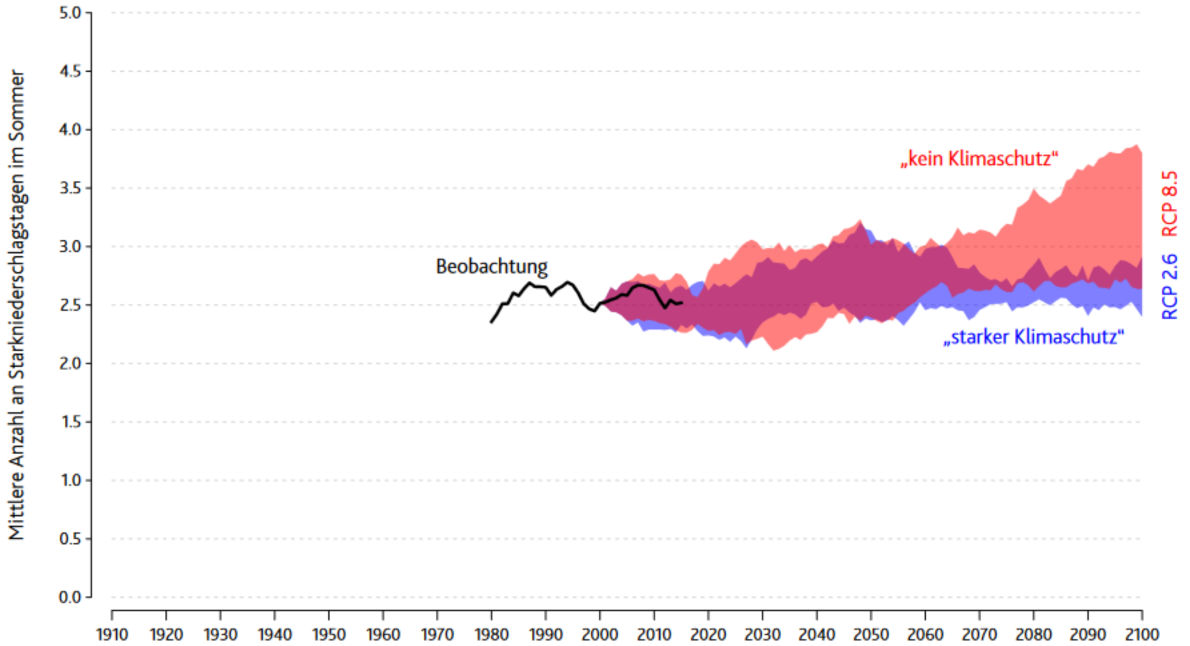


The trend for the mean annual precipitation for the hydrological summer is slightly negative in opposite to the observation of increasing heavy rainfalls in summer. Obviously as already mentioned the mean annual precipitation is not a suitable indicator for flash floods forced by heavy rainfall in summer.



The increase of temperature due to climate changed based global warming leads to the increase of the effective precipitable water, ~7% per 1 K. Theoretical Background is the Clausius-Clapeyron relation (see e.g. https://en.wikipedia.org/wiki/Clausius%E2%80%93Clapeyron_relation). Considering the convective rain contribution, the level of precipitation intensity might increase up to 14% per 1K. These physical basics explain the rise of heavy rainfall events potential in Germany as described in the study of the DWD in cooperation with the German Insurance Association (https://www.gdv.de/resource/blob/63746/ac53789625df198043ea0779329b42d9/fachbericht-data.pdf).

The projection of the mean number with heavy rainfalls during summer is shown below, showing for the two RCP scenario an increasing long-term (50-100 years) trend for RCP 8.5 and a constant trend for RCP 2.6 while for both scenarios the short-term (10-30 years) trend is increasing.



2.4. Climate Change Impact to the 2021 Ahr flood

The 2021 rainfall event in the Ahr catchment has been statistically evaluated (after the event in 2023) as a 400-year event under the actual climate conditions and can be classified as a rarely extreme event. However, a robust and reliable estimation of return periods for such large region in Europe between North Sea / Baltic Sea and the Northern Alp regions is out of the reliable application range of the known methods and still a demanding research challenge. (https://www.klimawandel-rlp.de/de/daten-und-fakten/flutkatastrophe-ahrtal/)

The impact of the climate change to the mean daily precipitation is estimated by an increase of 3% to 19% for two sequenced days like the 2021 event. This is based on a global warming by 1.2 K. This leads to an increase of the probability for a 1-day or a 2-day event by a factor of ~1.2 to 9.0 (increase of 20% - 800%) due to climate change. An expected future increase of temperature by 2.0 K would lead to an additional increase of the rainfall intensity by 1-6% for 1-day and 2-day events and to an increase of the probability by a factor of 1.2 to 1.4. These assumptions are based on analysis of observations/measurements as well as regional climate change models.

Damages and losses for rarely extreme events like the July 2021 cannot be avoided completely. However, the probability of such event has been increased and might increase further in the future. The society as a whole has to prepare itself to reduce vulnerability and hazard esp. within catchments with narrow river valleys used by humans and their settlements as for the river Ahr.

3. Analysis of Climate Change Impacts to Flash Floods – Ahr Catchment

The 2021 flash flood event in the Ahr catchment and surrounding catchments (Erft, Maas) was mainly triggered by strong rainfalls for a duration of 1 to 2 days as well as already wet / moistly initial conditions from earlier rainfalls. The climate change impact to such flash floods will be analysed for these scenarios on catchment level in the future as well as other scenarios e.g. extreme rainfalls in shorter periods such as few hours, concentrated locally in the catchment.

This academic course with limited time and work load resources cannot analyse all climate change impacts on flash floods in the Ahr catchments. To achieve at least some 1st new insight and experiences, three specific tasks has been selected and defined as team work to be studied.

- modelling possible rainfall/runoff scenarios based on design rainfall pattern
- estimation and classification of future flood risk ranges incl. uncertainties
- activities and actions for flash flood prevention

Task 1: Modelling Rainfall Pattern Scenarios

The available rainfall/runoff models can be used to evaluate the impact of design rainfall pattern scenarios to the discharges and related water levels in the Ahr catchment to estimate the climate change impacts. The KOSTRA-DWD data set is used to define suitable design rainfall pattern. The pattern can be applied for the whole catchment (esp. for durations of the level of hours and days) as well as for upstream sub-catchments with local extreme rainfall patterns for shorter durations (minutes to hours). Variations of the probability can be used to estimate actual and future risk levels.

Task 2: Estimation and Classification of Future Flood Risk Ranges incl. Uncertainties

The output of the rainfall/runoff models could be used to estimate the level of peak discharges at different location. The relationship of model input parameter (rainfall patters) as climate change indicators to the discharged incl. model uncertainties can be shown. The discharge values can be also used to estimate potential water levels via rating curves and flood dimension maps. A GIS based visualization might be demonstrate the local spatial hazard zones in the Ahr valley.

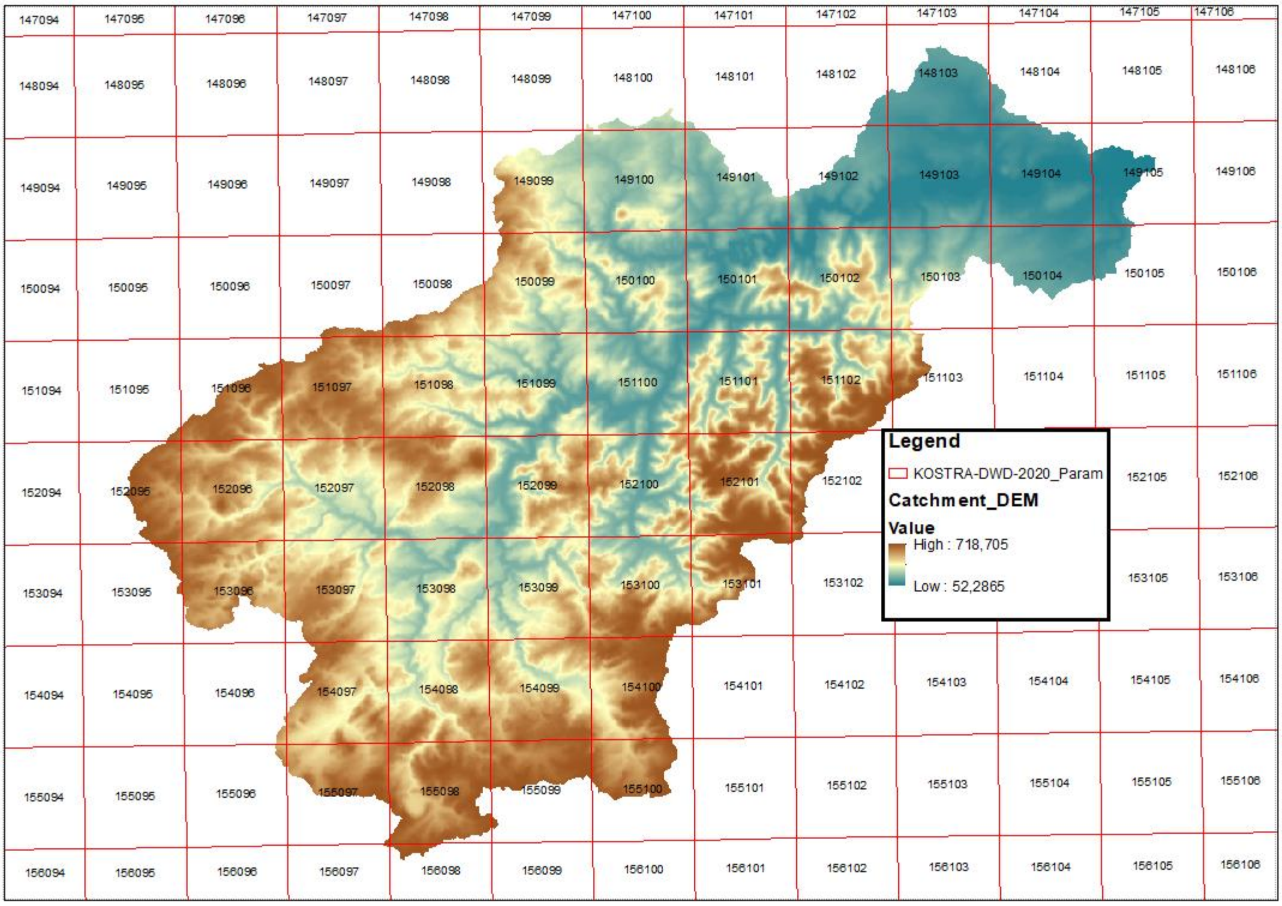
Task 3: Activities and Actions for Flash Flood Prevention

The climate change impact on flash floods will increase the probability of related future damages. Please analyse, discuss and present possibilities for activities and actions for flash floods preventions under the given specific constraints of the Ahr catchment. Besides the technical aspects of water engineering measures consider environmental, ecological, economic and social aspects in your proposals. Please propose a list of priorities and guideline drafts for decision makers and citizens in the region.

3.1. KOSTRA-DWD Data Set

The KOSTRA-DWD data set is defining heavy rainfall intensities in mm (Starkregenniederschlag) and rain yield rate in l/(s ha) (Regenspende) for different return periods T (Wiederkehrzeit) and duration levels D (Dauerstufe) for different parts of Germany. The actual version is valid since 2023 and based on data from 1951 to 2020. The spatial distribution of KOSTRA-DWD 2020 is considered by raster cells of 5 km x 5 km size. The range of tolerance / uncertainty is also part of the data set and differs depending on location, duration level and return period roughly from ~ +-10% to ~ +-20%. This values is also part of the data set.

The relevant raster cells (148100–148104, 149099-149105, 150097-150105, 151095-151103, 152095-152102,153095-153102, 154096-154100. 155096-155100, 156097-156098, in total 58) are shown for the Ahr catchment in the image below.



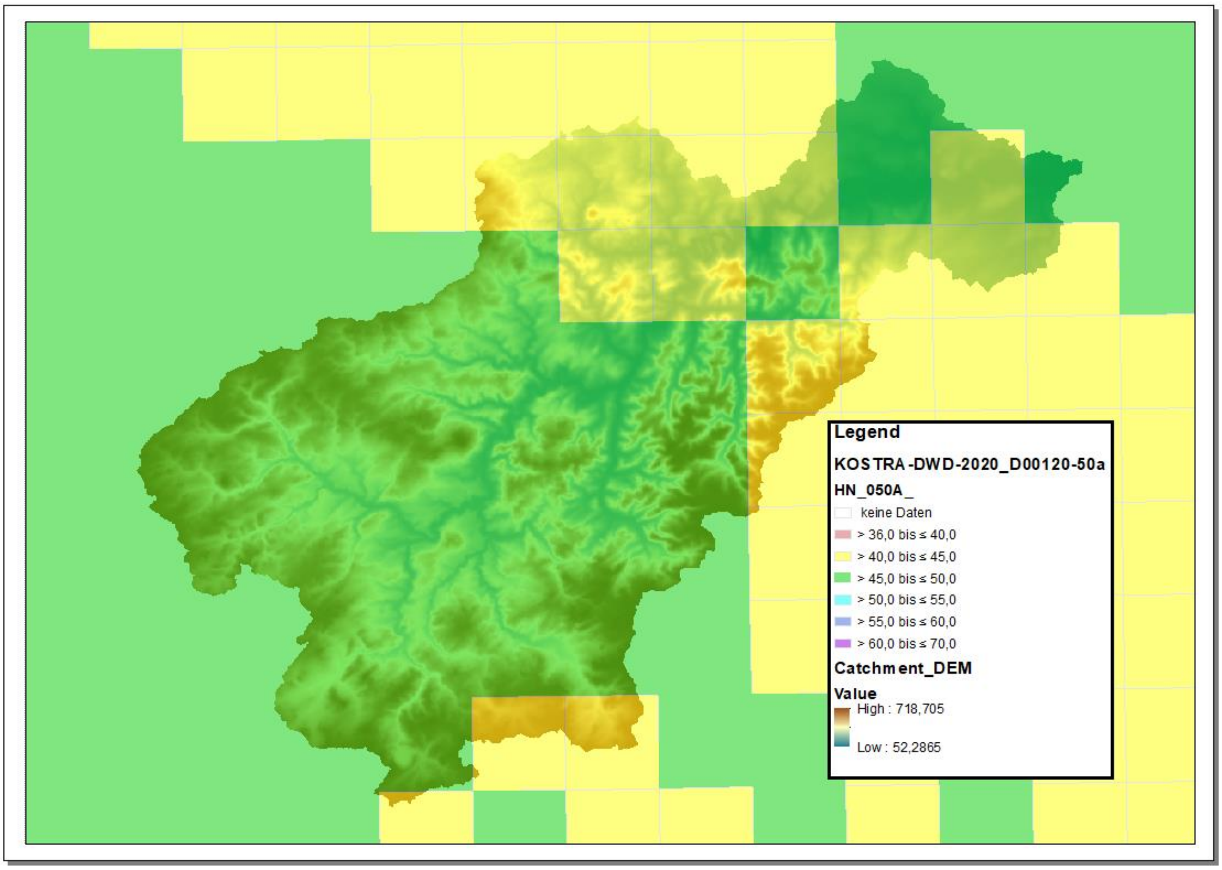
There are “older” data sets available: KOSTRA-DWD 2000 using data 1951-2019 and KOSTRA-DWD 2010R based on data from 1951-2010. These data sets can be used to evaluate the temporal change of these design rainfall intensities within the related 10 years. These data sets are using different raster cell sizes as KOSTRA-DWD 2020.

Raster cell 150101 are used as demonstration example to apply the data. The tables for these raster cells (Rasterfeld) have been downloaded and provided as csv files on the server.

		Wiederkehrzeit T																	
Dauerstufe D		1 a		2 a		3 a		5 a		10 a		20 a		30 a		50 a		100 a	
min	Std	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)
5		5,1	170,0	6,3	210,0	7,0	233,3	8,0	266,7	9,4	313,3	10,8	360,0	11,7	390,0	13,0	433,3	14,7	490,0
10		7,5	125,0	9,3	155,0	10,3	171,7	11,8	196,7	13,8	230,0	15,9	265,0	17,3	288,3	19,1	318,3	21,6	360,0
15		9,1	101,1	11,2	124,4	12,5	138,9	14,2	157,8	16,6	184,4	19,1	212,2	20,8	231,1	23,0	255,6	26,1	290,0
20		10,2	85,0	12,6	105,0	14,0	116,7	15,9	132,5	18,7	155,8	21,5	179,2	23,4	195,0	25,8	215,0	29,3	244,2
30		11,8	65,6	14,6	81,1	16,2	90,0	18,5	102,8	21,7	120,6	25,0	138,9	27,1	150,6	30,0	166,7	34,0	188,9
45		13,5	50,0	16,6	61,5	18,5	68,5	21,1	78,1	24,7	91,5	28,5	105,6	30,9	114,4	34,2	126,7	38,8	143,7
60	1	14,7	40,8	18,1	50,3	20,2	56,1	23,0	63,9	26,9	74,7	31,0	86,1	33,7	93,6	37,2	103,3	42,3	117,5
90	1,5	16,5	30,6	20,3	37,6	22,6	41,9	25,7	47,6	30,2	55,9	34,8	64,4	37,8	70,0	41,7	77,2	47,4	87,8
120	2	17,8	24,7	21,9	30,4	24,4	33,9	27,8	38,6	32,6	45,3	37,5	52,1	40,8	56,7	45,0	62,5	51,1	71,0
180	3	19,7	18,2	24,3	22,5	27,1	25,1	30,8	28,5	36,1	33,4	41,6	38,5	45,2	41,9	49,9	46,2	56,7	52,5
240	4	21,2	14,7	26,1	18,1	29,1	20,2	33,1	23,0	38,8	26,9	44,7	31,0	48,5	33,7	53,6	37,2	60,9	42,3
360	6	23,4	10,8	28,7	13,3	32,1	14,9	36,5	16,9	42,8	19,8	49,3	22,8	53,6	24,8	59,1	27,4	67,1	31,1
540	9	25,7	7,9	31,6	9,8	35,3	10,9	40,1	12,4	47,1	14,5	54,3	16,8	59,0	18,2	65,1	20,1	73,9	22,8
720	12	27,5	6,4	33,9	7,8	37,8	8,8	43,0	10,0	50,4	11,7	58,1	13,4	63,1	14,6	69,7	16,1	79,1	18,3
1080	18	30,2	4,7	37,2	5,7	41,5	6,4	47,2	7,3	55,4	8,5	63,8	9,8	69,3	10,7	76,6	11,8	86,9	13,4
1440	24	32,3	3,7	39,8	4,6	44,4	5,1	50,5	5,8	59,2	6,9	68,2	7,9	74,1	8,6	81,8	9,5	92,9	10,8
2880	48	37,9	2,2	46,7	2,7	52,1	3,0	59,2	3,4	69,4	4,0	80,0	4,6	86,9	5,0	96,0	5,6	109,0	6,3
4320	72	41,6	1,6	51,2	2,0	57,2	2,2	65,0	2,5	76,2	2,9	87,8	3,4	95,4	3,7	105,4	4,1	119,6	4,6
5760	96	44,4	1,3	54,7	1,6	61,0	1,8	69,4	2,0	81,4	2,4	93,8	2,7	101,9	2,9	112,5	3,3	127,8	3,7
7200	120	46,8	1,1	57,6	1,3	64,2	1,5	73,0	1,7	85,7	2,0	98,7	2,3	107,3	2,5	118,4	2,7	134,5	3,1
8640	144	48,8	0,9	60,0	1,2	67,0	1,3	76,1	1,5	89,3	1,7	102,9	2,0	111,8	2,2	123,5	2,4	140,2	2,7
10080	168	50,5	0,8	62,2	1,0	69,4	1,1	78,9	1,3	92,5	1,5	106,6	1,8	115,8	1,9	127,9	2,1	145,2	2,4

The table can be used to get the rainfall intensity for a specified duration (D) and a specified return period (T). E.g. is the rainfall intensity for a 60 min (=1h) duration and a 50-year return period 37.2 mm while the rain fall intensity for a 24-hour event duration and a 2-year return period is 39.8 mm.

For spatial analysis the data is also available as spatial raster data set to be used in GIS. An example (Return Period 50 years, Duration Level 2 hours) is shown below



3.2. Application of the KOSTRA-DWD data set

Potential future rainfall scenario generating flash floods in the Ahr catchment could be defined based on the KOSTRA-DWD data set. The design rainfall intensities can be used to compare the discharge for different rainfall pattern. As example: The 2-day duration level with a 10-year return period could be compared with a 2-day duration level with a 20 years period or 1-day duration level with a 10-year return periods. The different combination of duration level and return period can be additionally varied with a spatial distribution, e.g. local rainfall scenarios in upstream sub-catchments or by temporal shifts e.g. earlier rainfall in the West and later rainfall in the East. This range of variations requires a suitable strategy to generate the simulations and to analyse the results.

The KOSTRA-DWD data set has been defined to specify the design rainfall intensity at specific points as calculation base e.g. for storm water system. They could be used for sub-catchments size up to 25 km**2. The application in larger regions requires reductions, as in nature the intensity of rainfall is spatial distributed and the max. intensity might not represent the rainfall in the whole region of interest for a design storm. Reduction parameter might compensate this. One simplified approach without considering duration level is the equation:

$$f = 1 - (\, 0.04 \log A)$$

f -> reduction factor [ ]   A -> catchment area [km^2]

For the Ahr catchment with a catchment area of ~890 km2 the factor is 0.88.

The temporal distribution could be assumed as constant per time unit or using distribution such as Euler type 2 distribution (as used in the SCS – Unit Hydrograph method), where the intensity increases strongly towards the maximum after 1/3 of the time window duration and a strong decrease converging to zero at the end of the time window.

The outcome of the rainfall/runoff model are hydrographs (discharge time series). The discharges could be converted to water levels using rating curves (within the range of the rating curves). These water levels at the outflow points can be used for a basic interpolation in GIS, e.g. by a linear interpolation along the river valley between two gauge stations. The local governmental institutions provide flood extension lines for the 2021 event, these maps can be also used to estimate flash flood risk maps based on the KOSTRA-DWD data set. (see https://sgdnord.rlp.de/themen/wiederaufbau-ahr/hochwasseranschlaglinien)

The KOSTRA-DWD data set has been originally defined in 2010 and has been updated for 2020. The differences in rainfall intensities can be used as simple approach for future climate change estimations. E.g. the rainfall intensities for the villages Altenahr, a location in raster cell 150101 (2020 data set) resp. raster cell 61010 (2010R data set) for a 1-day duration and 50-year return period has been increased from 44.0 mm in 2010 to 81.8 mm in 2020. The return period of a 50 mm rainfall event for a 12-hour duration changed from a 50-year return period 2010 to a 20-year return period in 2020. These examples might help to estimate and evaluate climate change impacts to flash floods in the Ahr catchment.

4. References

Climate Change Rhineland-Palatinate

Rheinland-Pfalz Kompetenzzentrum für Klimawandelfolgen – Klimainformationssystem
https://www.klimawandel-rlp.de/de/start/

KOSTRA-DWD

Webpage with information for 2020 data set (in German)
https://www.dwd.de/DE/leistungen/kostra_dwd_rasterwerte/kostra_dwd_rasterwerte.html

Description of 2010 data set (in German)
https://www.dwd.de/DE/leistungen/kostra_dwd_rasterwerte/download/bericht_revision_kostra_dwd_2010.pdf

Data set download (2010R and 2020)
https://opendata.dwd.de/climate_environment/CDC/grids_germany/return_periods/precipitation/KOSTRA/

Related Maps Rhineland-Palatinate

WMS and WFS GIS Services
https://wasserportal.rlp-umwelt.de/kartendienste

Flood Hazard Map Rhineland-Palatinate
https://hochwassermanagement.rlp-umwelt.de/servlet/is/200041/

Flood Risk Map Rhineland-Palatinate
https://hochwassermanagement.rlp-umwelt.de/servlet/is/200042/

Flash Floods Maps Rhineland-Palatinate
https://wasserportal.rlp-umwelt.de/auskunftssysteme/sturzflutgefahrenkarten
https://wasserportal.rlp-umwelt.de/auskunftssysteme/sturzflutgefahrenkarten/sturzflutkarte

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