Integrated Overview of the effects of socio-economic scenarios on the discharge of the Rhine

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Title
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Summary

Climate change results into changes in precipitation and evaporation, as well as snow melt and glacier melt, and consequently also in changes in the discharge of the Rhine river. In addition, changes in socio-economic activities may lead to changes in water use and water consumption, and also influence the discharge of the Rhine river. In this study the possible effects of water use and water consumption of the public sector (domestic water), the industrial sector (production water), the energy sector (cooling water), the mining sector (pumping and filling of mines) and the agricultural sector (irrigation) are evaluated. The objective of the study is to integrate the available information and to evaluate the relevance of water use and consumption by the individual sectors.

The results of the study show that the water consumption of the public sector and the industry sector is relatively small compared to the discharge of the Rhine. Cooling water, lignite mining and irrigation are considered as the most important sectors with respect to the water consumption. However, the available information on cooling water consumption and irrigation in agriculture is limited, and it is recommended to study the water use and consumption of these two sectors in more detail.

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final

Content

1 Introduction

Due to climate change the precipitation, evaporation and temperature in the Rhine river basin are changing, and consequently this will affect the discharge of the Rhine as well. Although various climate change models and climate change scenarios indicate a range of values (see for instance the Rheinblick-2050 study of Görgen et al., 2010), in general hydrologists agree that:

- the winter extreme high discharges are likely to become higher;
- the summer low discharges might become lower (and might last longer); and
- the variability of the discharge will increase.

After the finalisation of the Rheinblick-2050 study the International Commission for the Hydrology of the Rhine river basin (CHR) started a research project on the contribution of snow melt and glacier melt on the discharge of the Rhine. The results of this study (ASG-Rhine, Stahl et al., 2017) provide new knowledge on low flows during summer time.

In addition to the effects of climate change on precipitation and evaporation (Görgen et al., 2010) and the effect of climate change on snow melt and glacier melt (Stahl et al., 2017), future changes in water use and consumption might also influence the discharge of the Rhine. CHR organised in 2014 a Seminar in Bregenz (see workshop website) on the socio-economic influences on the discharge of the Rhine river. Based on the results of the workshop, CHR asked Deltares to prepare an integrated overview of the effects of various Socio-Economic sectors and Scenarios on the discharge of the Rhine: the SES-Rhine project.

The objectives of the SES-Rhine project are:
- to integrate the available national information regarding the actual and future water use and consumption by various socio-economic sectors and generate an overview up to the level of the Rhine river basin,
- to evaluate the relevance of water use and consumption by individual socio-economic sectors on the discharge in the Rhine river basin,
- to compare the possible effects of socio-economic changes on the discharge of the Rhine with the effects of climate changes as studied in Rheinblick-2050 and ASG-Rhine, and
- to gather knowledge on concepts for impact assessment and feedback mechanisms between hydrology and socio-economic developments.

A top-down method is applied to identify first the most relevant socio-economic sectors for water use and water consumption. In a later stage these relevant sectors can be analysed in more detail.

The SES-Rhine project is implemented in close coordination with the Bundesanstalt für Gewasserkunde in Koblenz (BfG). At BfG the Wasserwirtschaft-project (WaWi) is being implemented simultaneously, and the intermediate results of both projects have been exchanged.

During the project two workshops were held in Koblenz, to discuss the water use and water consumption of various sectors with several selected experts. The results of these workshops are included in the Integrated Overview. A report of the Workshops is included in Annex A.

Water use and water consumption

In this report 'water use' and 'water consumption' are discussed for various socio-economic sectors and scenarios. Water use refers to the abstraction of water from surface water and groundwater, whereas water consumption takes into account the return flow and refers to the net water use of the sector. From the point of view of the discharge of the Rhine river, water consumption is most relevant.

Integrated Overview

The "Integrated Overview" of the effects of various socio-economic scenarios on the discharge of the Rhine river refers to an Excel-spreadsheet with all gathered data for the various sectors and scenarios.

The gathered data are described in Chapter 2 of this report, together with the calculation method to estimate the water use and water consumption by the various sectors in different parts of the Rhine river basin.

This report also describes the results of the Integrated Overview in Chapter 3, presenting the contribution of the various sectors on the total water use and water consumption in the Rhine river basin.

Conclusions and recommendations on the analysis of the water use and water consumption by economic sectors are included in Chapter 4.

The Excel spreadsheet (SES-Rhine.xlsx) with the Integrated Overview is available from https://www.chr-khr.org/.

2 Methodology

2.1 Spatial resolution

The overarching objective of the Integrated Overview is to analyse the effects of various socio-economic scenarios on the level of the Rhine river basin. For this reason, the spatial resolution of the Integrated Overview is set to the general level of the Alpen Rhein, the Hoch Rhein, Ober Rhein, Main, Neckar, Mittel Rhein, Mosel/Saar, Nieder Rhein and Delta Rhein. All data have been gathered for these 9 geographical entities. The geographical delineation of these 9 entities is presented in Figure 2.1.

On the scale of the entire Rhine river basin the approach with the 9 geographical entities is assumed to be sufficiently detailed. However, if the same approach would be applied to a more detailed analysis the exchange of water between the geographical entities should be taken into account in more detail.

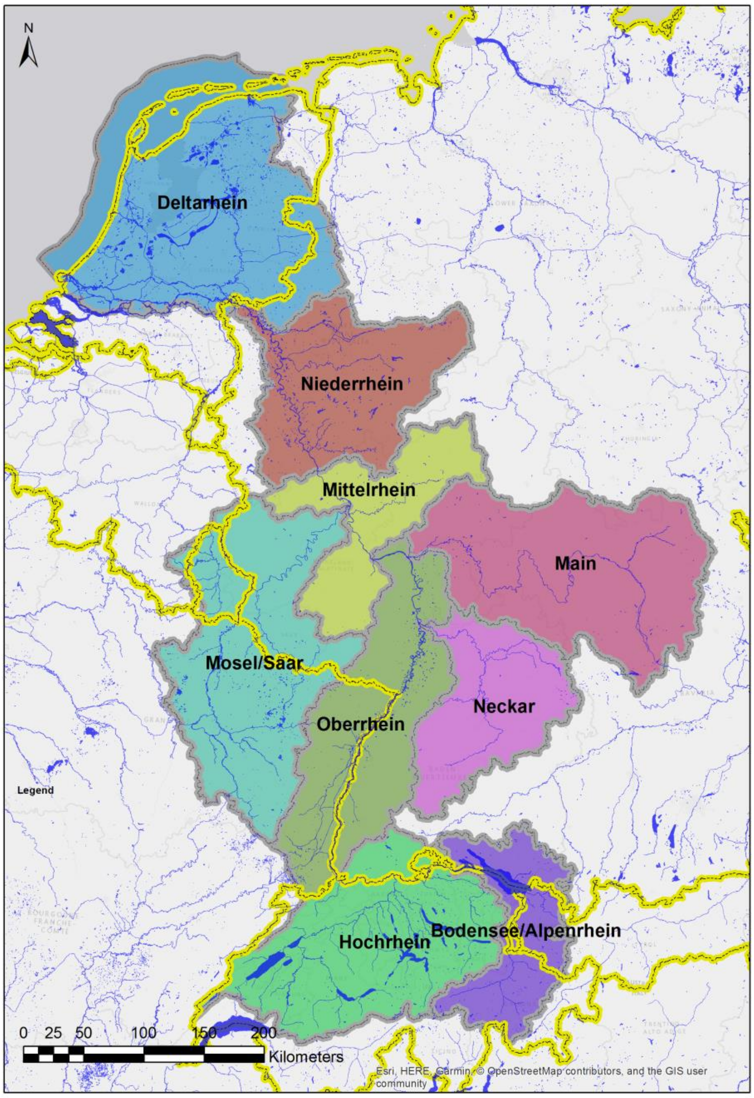

Figure 2.1 Geographical delineation of the Rhine river basin in the Integrated Overview.

Eurostat, the statistical office of the European Union situated in Luxembourg, developed the NUTS levels (Nomenclature of Units for Territorial Statistics) for the administration of information in Europe (see https://ec.europa.eu/eurostat). For each EU member country, a hierarchy of three NUTS levels is established, as presented in Table 2.1. Note that not all countries include every NUTS level, depending on their size. For instance, in Luxembourg and Lichtenstein the three NUTS divisions are equal and correspond to the entire country itself. The location of the NUTS1 and NUTS2 regions in the Rhine river basis are presented in Figure 2.2.

The Eurostat-database includes information on various statistical items that have been included in the present study, like the number of inhabitants, GDP and landuse. Some data are available on NUTS3 level (the most detailed level) and some data are only available on NUTS2 or NUTS1 level. As the boundaries of the NUTS regions do not coincide with the natural boundaries of the selected 9 sub basins in the Rhine river basin, the NUTS-information was translated to the 9 sub basins using GIS. The translation was based on the surface area of the NUTS regions and the 9 sub basins.

Countries		*NUTS 1*		*NUTS 2*		*NUTS 3*	
Austria	*AT*	*Groups of states*	*3*	*States*	*9*	*Groups of districts*	*35*
Belgium	*BE*	*Regions*	*3*	*Provinces (+ Brussels)*	*11*	*Arrondissements (Verviers split into two)*	*44*
Germany	*DE*	*States (Bundesland)*	*16*	*Government regions (Regierungbezirk) (or equivalent)*	*39*	*Districts (Kreis)*	*429*
France	*FR*	*Z.E.A.T. + DOM*	*9*	*Regions + DOM*	*27*	*Departments + DOM*	*101*
Liechtenstein	*LI*	*—*	*1*	*—*	*1*	*—*	*1*
Luxembourg	*LU*	*—*	*1*	*—*	*1*	*—*	*1*
Netherlands	*NL*	*Groups of provinces*	*4*	*Provinces*	*12*	*COROP regions*	*40*
Switzerland	*CH*	*—*	*1*	*Regions*	*7*	*Cantons*	*26*

Table 2.1 Number of NUTS regions for NUTS level 1, 2 and 3 in the countries of the Rhine river basin.

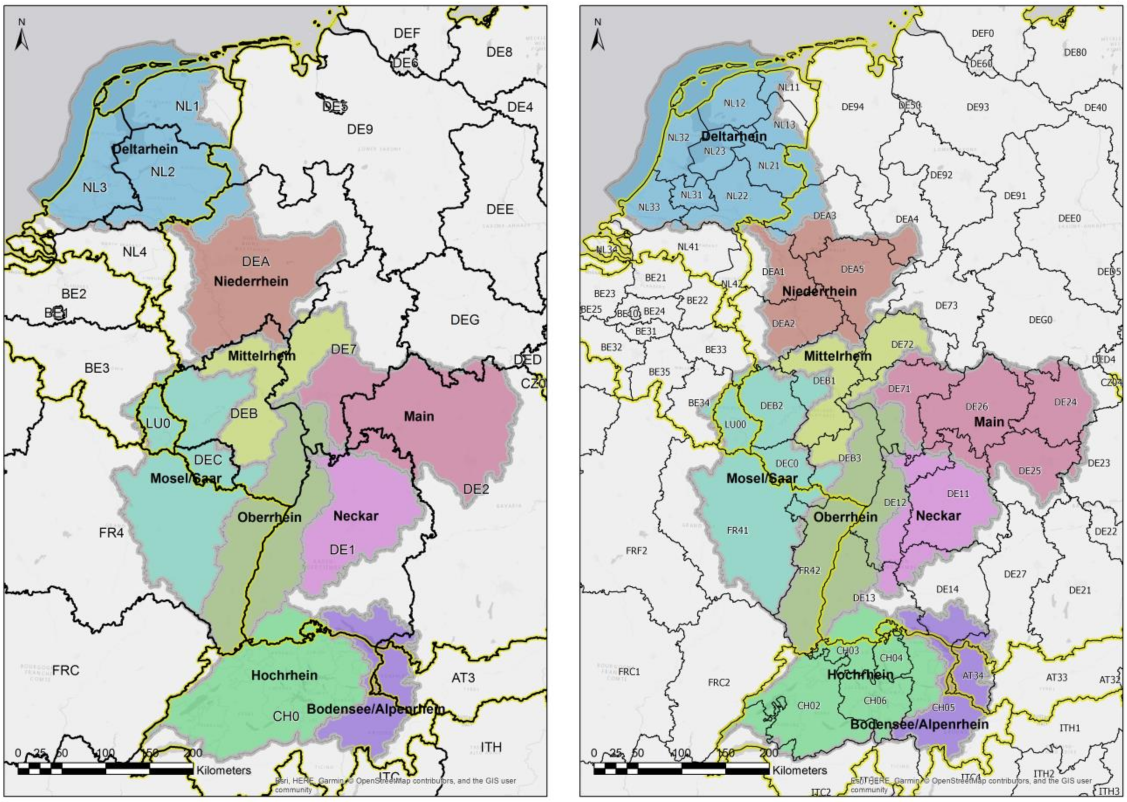

Figure 2.2 NUTS1 (left) and NUTS2 (right) areas in the Rhine river basin.

2.2 Temporal resolution

With respect to the temporal resolution a monthly approach was included, to cover seasonal variation. The monthly approach is considered sufficiently accurate to describe the seasonal variation of the water use and consumption in the Rhine river basin.

Please note that the Integrated Overview assumes that the river basin system is in balance and zero delta storage is taken into account in the calculations. Whereas groundwater storage is not included in the Integrated Overview, the net effect of storage should be included (manually) in the input data for discharge.

The objective of the Integrated Overview is to generate an overview of the water use and consumption by various economic sectors in the Rhine river basin. The effects on the water balance of the basin and the discharge of the Rhine are presented roughly. The results of the Integrated Overview could be included in a hydrological model for a more detailed analysis of the effects on the discharge of the Rhine.

2.3 Scenarios

In the Integrated Overview the actual situation and 3 scenarios are included:

- **Actual**
  The Actual situation includes the available data for the present situation. These data refer to 2017 or other recent years.

- **S1. Reduce**
  Compared to the Actual situation, S1. Adapt includes an estimate for the water use and consumption in case a reduction of the economic situation will occur in the Rhine river basin.

- **S2. Develop**
  An estimate for the increase in water use and consumption in the Rhine river basin is included in S2. Develop.

- **S3. Adapt**
  Technical measures to adapt the water use and consumption in the Rhine river basin is included in S3. Adapt.

The 3 scenarios refer to a possible future situation, without an exact time indication. Together, the 3 scenarios indicate more-or-less the possible range for the future water use and water consumption by each of the socio-economic sectors. At the same time this range indicates the uncertainty on the future water use and consumption.

In the sections below the data used in the 4 calculations are presented for the various sectors.

2.4 Natural discharge

The "natural discharge" of the Rhine river is defined here as the sum of the runoff from various types of land use, and runoff due to snow melt and glacier melt.

2.4.1 Runoff

For the calculation of runoff, it was decided to use the results from the Rheinblick-2050 project (Görgen et al, 2010) in this study. In the Rheinblick-2050 the projected discharge of the Rhine river under various climate change scenarios has been studied. The Rheinblick-2050 did not include an analysis of the effect of land-use change scenarios.

The land use area for each region was deduced from the EuroStat database (more specific: lan_lcv_ovw on https://ec.europa.eu/eurostat/data/database). These data include information on the land use for the NUTS1 and NUTS2 regions in 2015. Using GIS, the land use was translated spatially to the 9 geographical entities included in the Integrated Overview. Please note that the subdivision for cropland to various crops was only available for NUTS1 regions. The resulting land use data for 2015 are presented in Table 2.2. On average some 10% is indicated as 'urban', some 50% as 'agriculture' (25% cropland and 25% grassland), and some 40% as 'nature' (woodland, shrub/bareland, wetlands and water).

Values on land use for Switzerland are not available in the Eurostat database; the values mentioned in Table 2.2 for Alpine Rhein and Hoch Rhein have been interpolated from the total area within Switzerland and the relative distribution of land-use types in the rest of the Alpine Rhein and Hoch Rhein.

km²	Total	Urban area	Cropland	Wood land	Grass land	Shrub/ Bareland	Wetland	Water
Bodensee/AlpenRhein	*11374*	*763*	*1967*	*4415*	*2946*	*1022*	*223*	*31*
Hoch Rhein	*24742*	*2194*	*5506*	*10047*	*5819*	*669*	*425*	*74*
Ober Rhein	20364	1483	4580	8449	4950	575	273	38
Neckar	13938	1234	3105	5669	3271	376	236	41
Main	27229	1901	7366	10711	6093	672	407	60
Mosel/Saar	25784	1852	5611	10419	6731	690	245	32
Mittel Rhein	13516	1088	3025	5843	2991	431	117	0
Nieder Rhein	18940	2517	5846	5529	4303	505	230	0
Delta Rhein	28861	3216	6735	4078	10395	907	3024	266
Grand Total	184750	16247	43739	65160	47499	5848	5179	543

km²	Cropland	Cereals	Root crops	Industrial crops	Vegetables and flowers	Fodder crops	Fruit trees	Other
Bodensee/AlpenRhein	*1967*	*1392*	*59*	*190*	*57*	*178*	*65*	*25*
Hoch Rhein	*5506*	*3837*	*127*	*592*	*148*	*444*	*254*	*116*
Ober Rhein	4580	3169	129	632	126	279	130	116
Neckar	3105	2167	75	332	82	246	141	62
Main	7366	5518	382	666	189	512	80	19
Mosel/Saar	5611	3976	143	758	135	379	86	133
Mittel Rhein	3025	2022	175	388	108	146	50	136
Nieder Rhein	5846	4448	530	306	280	114	104	63
Delta Rhein	6735	3856	1913	65	417	429	43	13
Grand Total	43739	30385	3533	3929	1542	2727	953	683

Table 2.2 Land use data in km², as deduced from EuroStat for 2015. Upper table total area and main classes; lower table subdivision for cropland. Values for Alpen Rhein and Hoch Rhein were interpolated (see text).

2.4.2 Snow melt and Glacier melt

The detailed results of the ASG-study from Stahl et al (2017) provide information on the actual discharge from snow and glacier melt in the Rhine river basin. These results are also used in the present study. In the (ongoing) ASG-2 study more information will become available on the possible future discharge from snow and glacier melt, including the possible effects on the discharge of the Rhine river.

2.5 Socio-economic sectors

In the Integrated Overview the following 5 socio-economic sectors are included:

- private sector (domestic water use)
- industrial sector (industrial water use)
- energy production sector (cooling water use)
- mining sector (pumping water discharge and lake refilling)
- agricultural sector (irrigation water use)

The calculation methods and used input data are described in the sections below.

2.5.1 Domestic water use

Calculation method
The calculation of the domestic water use is based on the number of inhabitants multiplied by the (average) water use per inhabitant. The (net) domestic water consumption follows from the water use multiplied by (100% - the return flow rate).

Input data
The *number of inhabitants* for each region has been deduced from the EuroStat database (more specific: demo_r_pjangrp3 on https://ec.europa.eu/eurostat/data/database). These data include information on the population for the NUTS3 regions in 2017. Using GIS, the population for the NUTS3 regions was translated spatially to the 9 geographical entities included in the Integrated Overview.
The resulting population numbers for 2017 are presented in Table 2.3, together with the assumptions for the three scenarios. It was assumed under S1. Reduce that the population will reduced to 90%, whereas in S2. Develop and S3. Adapt the population is assumed to increase to 120% of the 2017 data.

The *water use per inhabitant (capita) per day (l/c/d)* has been assumed to be about 140 liter in the actual (2017) situation. For S1. Reduce and S3. Adapt it was assumed to be reduced to 120 l/c/d/, whereas in S2. Develop a domestic water use of 180 l/c/d is assumed.

Based on information from Luxemburg (Hansen, 2018) *seasonal variation* in the domestic water use has been included, showing 10% increase in June and 20% increase in July and August.

The *return flow rate* in the actual situation is assumed to be 95%, resulting in a net consumption of 5% compared to the water use (due to evaporation). The same value is being used in S1. Reduce as well as S2. Develop. In S3. Adapt the return flow rate is assumed to be increased (due to technical improvements) to 98%.

It should be noted that it is assumed that all domestic (drinking) water is abstracted from surface water (either direct abstraction or bank filtration), and the return flow is being discharged back to surface water. According to Eurostat data (env_watabs_rb) approximately one third of the domestic water is abstracted from surface water and two thirds from groundwater. In the present overview the changes in groundwater storage are not included (it is assumed to be constant over time), and an increase in groundwater abstraction is assumed to be related to a reduction of the baseflow of groundwater to the surface water system.

Geographical entity	Inhabitants 2017		S1. Reduce	S2. Develop	S3. Adapt
Bodensee/Alpen Rhein	1,565,779		1,409,201	1,878,935	1,878,935
Hoch Rhein	6,740,925		6,066,833	8,089,110	8,089,110
Ober Rhein	7,241,808		6,517,627	8,690,170	8,690,170
Neckar	5,456,522		4,910,870	6,547,826	6,547,826
Main	6,635,320		5,971,788	7,962,384	7,962,384
Mosel/Saar	4,541,365		4,087,229	5,449,638	5,449,638
Mittel Rhein	2,721,839		2,449,655	3,266,207	3,266,207
Nieder Rhein	12,605,961		11,345,365	15,127,153	15,127,153
Delta Rhein	12,989,901		11,690,911	15,587,881	15,587,881
Grand Total	**60,499,421**		**54,449,478**	**72,599,304**	**72,599,304**

Table 2.3 Number of inhabitants per geographical entity, as deduced from EuroStat for 2017 and under the 3 scenarios.

2.5.2 Industrial water use

Calculation method

The calculation of the industrial water use is based on the gross domestic product (GDP) multiplied by the (average) specific water use per unit of GDP. The (net) domestic water consumption follows from the water use multiplied by (100% - the return flow rate).

Input data

The *gross domestic product* *(GDP)* for each region has been deduced from the EuroStat database (more specific: nama_10r_3gdp on https://ec.europa.eu/eurostat/data/database). These data include information on the gross domestic product for the NUTS3 regions in 2015. Using GIS, the GDP data for the NUTS3 regions was translated spatially to the 9 geographical entities included in the Integrated Overview. For GDP the 2015 values were used (instead of 2017) as these were the most recent available data for NUTS3 regions.
Values on GDP for Switzerland where not available in the Eurostat database; the values for Alpine Rhein and Hoch Rhein (from Germany and Austria) were interpolated from the total area within Switzerland and the GDP in the rest of the Alpine Rhein and Hoch Rhein.

The resulting GDP data (in Million Euro) for 2015 are presented in Table 2.4, together with the assumptions for the three scenarios. It was assumed under S1. Reduce that the GDP will reduce to 90%, whereas in S2. Develop and S3. Adapt the GDP is assumed to increase to 120% of the 2015 data.

Data for the *specific industrial water use* (m^3/y/Million Euro) are rather scarce. Based on the data provided in Katz (2015) a value of 500 m^3/y/Million Euro was estimated. For S1. Reduce and S3. Adapt it was assumed to be reduced to 400 m^3/y/Million Euro, whereas in S2. Develop a specific industrial water use of 600 m^3/y/Million Euro is assumed.

No seasonal variation is assumed for the industrial water use and consumption.

The *return flow rate* in the actual situation is assumed to be 95%, resulting in a net consumption of 5% compared to the water use. The same value is being used in S1. Reduce as well as S2. Develop. In S3. Adapt the return flow rate is assumed to be increased (due to technical improvements) to 98%.

Geographical entity	GDP 2015		S1. Reduce	S2. Develop	S3. Adapt
Bodensee/Alpen Rhein	*87,773*		*78,996*	*105,328*	*105,328*
Hoch Rhein	*472,972*		*425,675*	*567,566*	*567,566*
Ober Rhein	276,090		248,481	331,308	331,308
Neckar	245,161		220,645	294,193	294,193
Main	283,127		254,814	339,752	339,752
Mosel/Saar	84,853		76,368	101,824	101,824
Mittel Rhein	166,535		149,882	199,842	199,842
Nieder Rhein	473,986		426,587	568,783	568,783
Delta Rhein	516,799		465,119	620,159	620,159
Grand Total	**2,607,296**		**2,346,566**	**3,128,755**	**3,128,755**

Table 2.4 Gross domestic product (in Million Euro) per geographical entity, as deduced from EuroStat for 2015 and under the 3 scenarios. Values for Alpen Rhein and Hoch Rhein were interpolated (see text).

2.5.3 Energy sector

The energy sector influences the discharge of the Rhine river in three different ways:

- mining activities
- reservoir management
- cooling water use

The influence of *mining activities* by the energy sector on the discharge of the Rhine is described in section 2.5.4.

The energy sector is responsible for (most of the) *reservoir management* in the Rhine river basin. Over time, variations in the prices of energy have become more important in the management of the reservoirs. The influence of reservoir management on the discharge distribution of the Rhine river is discussed in a separate memo, as included in Annex B. In the memo it was concluded that possible future changes in reservoir management could influence the discharge distribution of the Rhine river.

In the production of electricity two types of power plants are being distinguished from the point of cooling water: “closed loop” power plants and “open loop” power plants.

- In the closed loop power plants the water taken from the Rhine river is being used for cooling and discharged back into the Rhine with higher temperature. The closed loop power plants do not influence the discharge of the Rhine (although they influence the temperature of the Rhine).
- The open loop power plants use the water taken from the Rhine river for cooling by evaporation. As a consequence the discharge of the Rhine is reduced (without a direct influence on the temperature of the Rhine).

Calculation method
The calculation of the cooling water use for closed loop power plants and open loop power plants is based on the energy production (in GW/y) multiplied by the specific water use per GW.

Input data
A proper source of information on the *energy production per geographical unit* has not been localized up to now. To estimate the energy production the specific energy use per inhabitant was multiplied with the number of inhabitants per geographical unit. At https://www.iea.org data are available on the electricity consumption per inhabitant (per country). Data for the riparian states of the Rhine river show a value of about 7 MWh/year per capita on average for the actual situation. In the calculation for S1. Reduce a value of 6 MWh was used and in S2. Develop a value of 8 MWh was used, whereas in S3. Adapt the value of 7 MWh/y/capita was used.

The *specific water use* and consumption for closed loop power plants is estimated to 2 m^3/MWh of energy production. For open loop power plants the specific water use is estimated to 100 m^3/MWh and the specific water consumption to 1 m^3/MWh. These data are based on FAO (2011). We assumed 50% of the energy production based on closed loop and 50% on open loop techniques.

2.5.4 Mining

The lignite mines in Nord Rhein Westphalen (Nieder Rhein) currently pump water out to allow for mining, and discharge the water to the Rhine. In future, once the mining activities will be stopped, water will be taken from the Rhine to fill the lakes.

During the CHR Workshop of March 2018 (see Annex A) Dr. Forkel of RWE presented the volumes of water involved. At present about 300 Mm^3 per year is being discharged to the Rhine, corresponding with about 10 m^3/s. It is expected that between 2045 and 2080 some 10 m^3/s will be taken from the Rhine to fill the new lakes.

The actual discharge of 10 m^3/s is included in the calculations for the Actual situation (and represented as a “negative abstraction”). The future abstraction of 10 m^3/s is included in each of the three calculations for the Scenarios.

2.5.5 Irrigation water use

Calculation method
The calculation of the irrigation water use is based on the total irrigated area of cereals and other cropland multiplied by the (average) irrigation in mm/month. No return flow is taken into account, as all irrigated water is assumed to be evapo(transpi)rated.

Input data
The *total area* of cereals and other cropland has been deduced from the EuroStat database (more specific: lan_lcv_ovw on https://ec.europa.eu/eurostat/data/database), for each region as presented in Table 2.2. It is being assumed that irrigation in agriculture is only implemented at cereals and other cropland.
In EuroStat also information is available on the share of irrigable and irrigated areas in the utilized agricultural area (aei_ef_ir on https://ec.europa.eu/eurostat/data/database). These data show that 1% (Alpine areas and south Germany) up to 70% (parts of the Netherlands) of the utilized agricultural area is irrigable, whereas 0% up to 20% of the irrigable area is being irrigated (values strongly vary per year and location).

The “utilized agricultural area” (tai05 on https://ec.europa.eu/eurostat/data/database) includes grassland and arable land (and permanent crops; the latter is only 1-2% within the Rhine river basin and is assumed to account for cropland together with arable land). As only cropland is assumed being irrigated, the available data on irrigation are to be translated to the areas cropland, as presented in Table 2.5. Please note that these data have to be considered as educated guestimates of the actual irrigated areas.

km^2	Grassland	Cropland	Irrigated area (%)	Irrigated area (km^2)	Irrigated Cereals (km^2)	Irrigated Other crops (km^2)
Bodensee/AlpenRhein	*2946*	*1967*	*1%*	*49*	*35*	*14*
Hoch Rhein	*5819*	*5506*	*1%*	*113*	*79*	*35*
Ober Rhein	*4950*	*4580*	*1%*	*95*	*66*	*29*
Neckar	3271	3105	2%	128	89	39
Main	6093	7366	2%	269	202	68
Mosel/Saar	6731	5611	2%	247	175	72
Mittel Rhein	2991	3025	3%	180	121	60
Nieder Rhein	4303	5846	3%	304	232	73
Delta Rhein	10395	6735	10%	1713	981	732
Grand Total	47499	43739		3099	1978	1121

Table 2.5 Translation of data on area (km^2) grassland and cropland with % of irrigated area to educated guestimates of the irrigated area of cereals and other crops.

It is assumed under S1. Reduce that the irrigated area will reduce to 80% of the actual situation. For S2. Develop and S3. Adapt the irrigated area is assumed to increase to 300% of the actual data. The relatively large assumed increase for S2 and S3 is also representing the relative large uncertainty on the irrigated area.

The *specific irrigation (in mm/y)* is estimated to 200 mm/y for cereals and 100 mm/y for other crops, based on expert judgement. For S1. Reduce and S3. Adapt it was assumed to be reduced to 150 mm/y (cereals) and 75 mm/y (other crops), whereas in S2. Develop a specific water use for irrigation of 250 mm/y and 150 mm/y is assumed.

The assumed *seasonal variation* of the irrigation on cereals and other crops for the actual situation is presented in Figure 2.3, and is assumed not to change in the future scenarios.

The return flow of water use for irrigation is set to 0%: it is being assumed that all water applied for irrigation will evaporate (or evapotranspirate) and will not return back into the water cycle of the Rhine river basin.

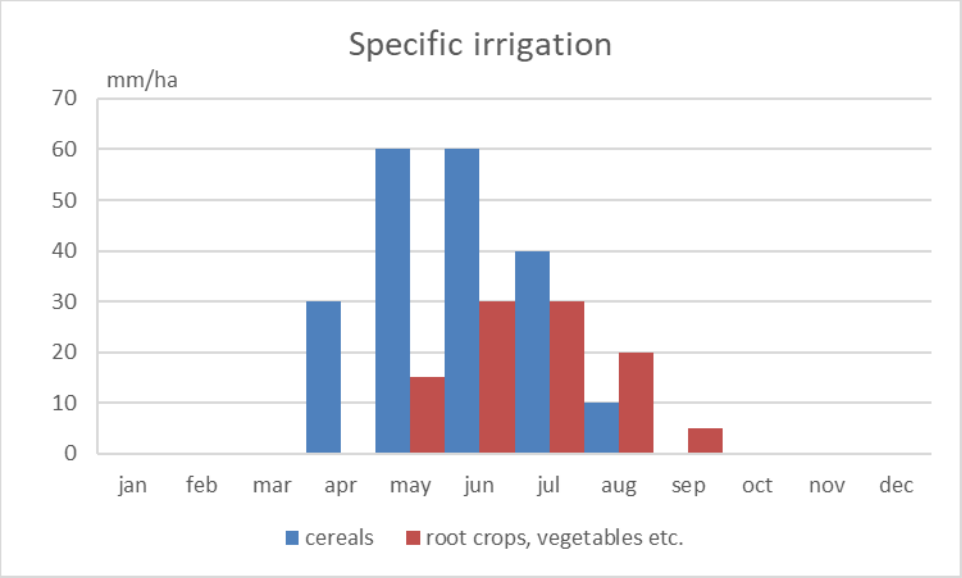

Figure 2.3 Seasonal variation of specific irrigation of cereals and other crops (mm) as assumed for the actual situation, as well as the scenarios.

3 Results

3.1 Natural discharge

The “natural discharge” of the Rhine river is defined here as the sum of the runoff from various types of land use, and runoff due to snow melt and glacier melt. In the Rheinblick-2050 project Görgen et al (2010) saw with respect to low flows *“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 far 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).”*

The yearly average contribution (1901-2006) from snow and glacier melt to the total discharge was modelled by Stahl et al (2017), see Figure 3.1, and amounts to 34% and 1 % respectively. During low flows, like 2013, the relative contribution from ice (glaciers) is be higher, as presented in Figure 3.2 (also copied from Stahl et al (2017).

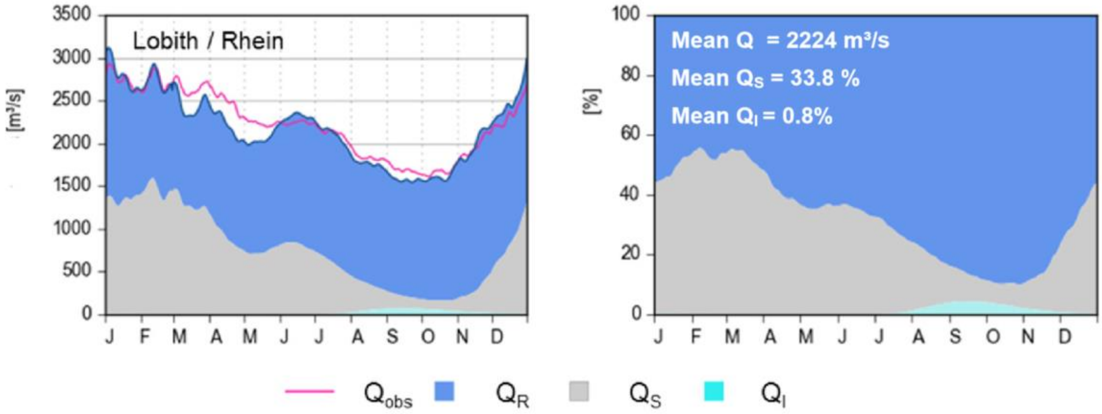

Figure 3.1 Observed and modelled discharge at Lobith originating from rain (Q_R), snow (Q_S) and ice (Q_I). Annual averages for the periode 1901-2006. Copied from Stahl et al, 2017 (Figure 6.12)

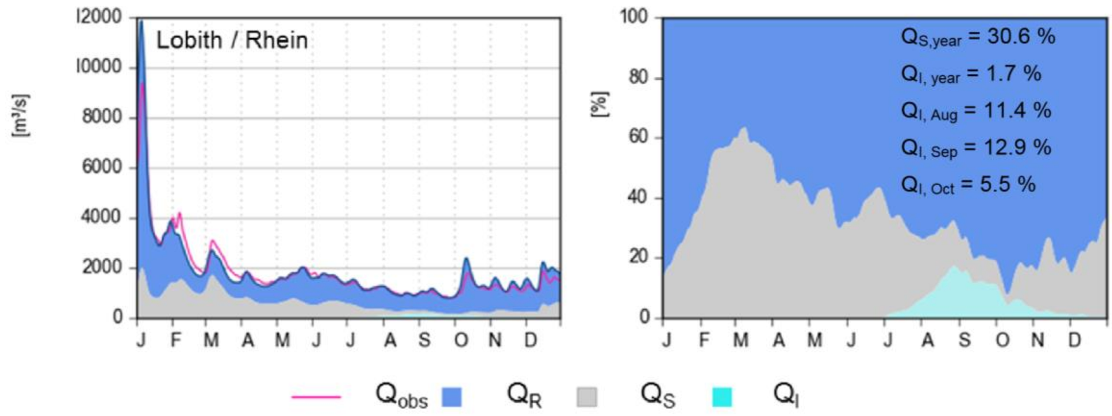

Figure 3.2 Observed and modelled discharge at Lobith originating from rain (Q_R), snow (Q_S) and ice (Q_I) for the low flow year 2003. Copied from Stahl et al, 2017 (Figure 6.16)

For the analysis of the effects of climate change and land-use change on the discharge of the Rhine river the present approach is not applicable; a hydrological model needs to be applied, in combination with climate change scenarios (eg. Görgen et al, 2010, and Stahl et al, 2017). In the ASG-2 study the climate change effects of the shift from precipitation in snow to rainfall due to changing temperatures and the consequential effects on the changing discharge distribution of the Rhine river will be studied in combination with the effects of the reduced discharge from glaciers.

Evaporation from open water surfaces
Increased evaporation from open water due to higher temperatures could also contribute to a reduction of the discharge of the Rhine river. According to the data presented in Table 2.2 the total open water surface in the Rhine river basin amounts to 543 km^2. If the evaporation from open water would increase (eg. due to climate change) with - for instance - 100 mm in 3 months in summer, this would imply $543 \cdot 10^5$ m^3 in total or 6,9 m^3/s during the 3 summer months. Compared to possible changes in precipitation and snow (melt) the contribution from an increase in evaporation from open water surfaces seems to be negligible within the context of the Rhine river basin.

3.2 Water use and water consumption

The calculated yearly water use and water consumption by various sectors in the Rhine river basin upstream of Basel and Lobith is presented in Figure 3.3 and Figure 3.4 for the actual situation and 3 scenarios.

These results are to be considered as indications – estimates or guestimates – of the real water use and water consumption by the various sectors, as the calculations are based on very general data, as will be discussed also in section 3.3. Having said that, these results indicate that:

- The actual water use for cooling (in electricity production) in the Rhine river basin is estimated at almost 700 m^3/s.
- With respect to the possible future yearly average water consumption in the Rhine river basin, cooling water (15-25 m^3/s), lignite mining (10 m^3/s) and irrigation (10-65 m^3/s) are considered the most important sectors in this study. Given the uncertainties in the underlying data for cooling water and irrigation, those estimates should be updated though.
- The contribution of public water supply (2-8 m^3/s) and industry (1-3 m^3/s) on the possible future water consumption in the Rhine river basin is small compared to the other sectors.
- Possible future scenarios show considerable variation in water consumption for irrigation, merely due to uncertainty in the future irrigation patterns.
- The estimated possible increase of water consumption in future scenarios ranges from 0 to 70 m^3/s on annual basis (taken into account the mentioned uncertainty in water consumption for irrigation).

The seasonal variation of the water consumption by the various sectors in the Rhine river basin is presented in Figure 3.5 for the actual situation. The seasonal variation of water consumption by irrigation is substantial; the other sectors show zero or limited seasonal variation.

In Figure 3.6 the seasonal variation of the total water consumption in the Rhine river basin of the various scenarios is presented. The estimated water consumption in the summer period increases from 50-75 m^3/s in the actual situation up to some 250 m^3/s following the S2. Develop scenario. This means the water consumption in the Rhine river basin might increase by 200 m^3/s during the low flow season.

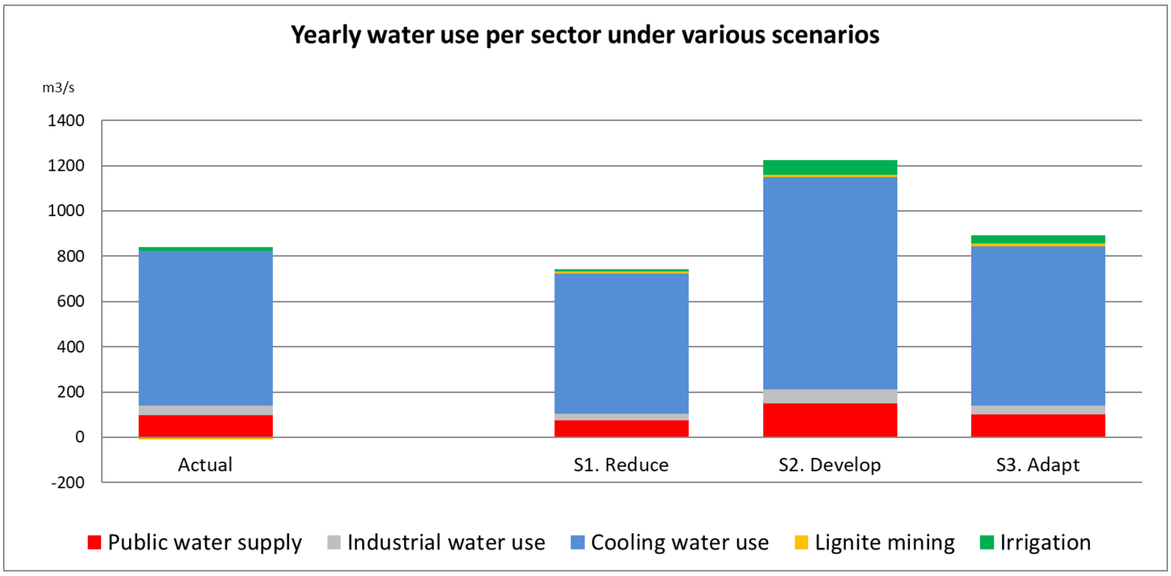

Figure 3.3 Calculated yearly water use upstream in the Rhine river basin for various scenarios.

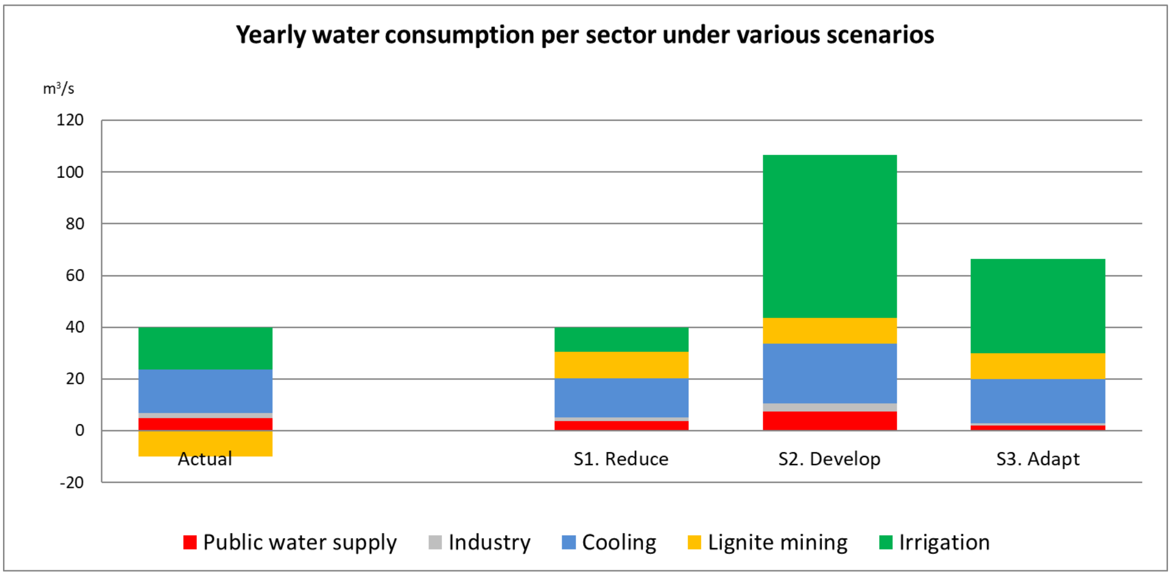

Figure 3.4 Calculated yearly water consumption upstream in the Rhine river basin for various scenarios.

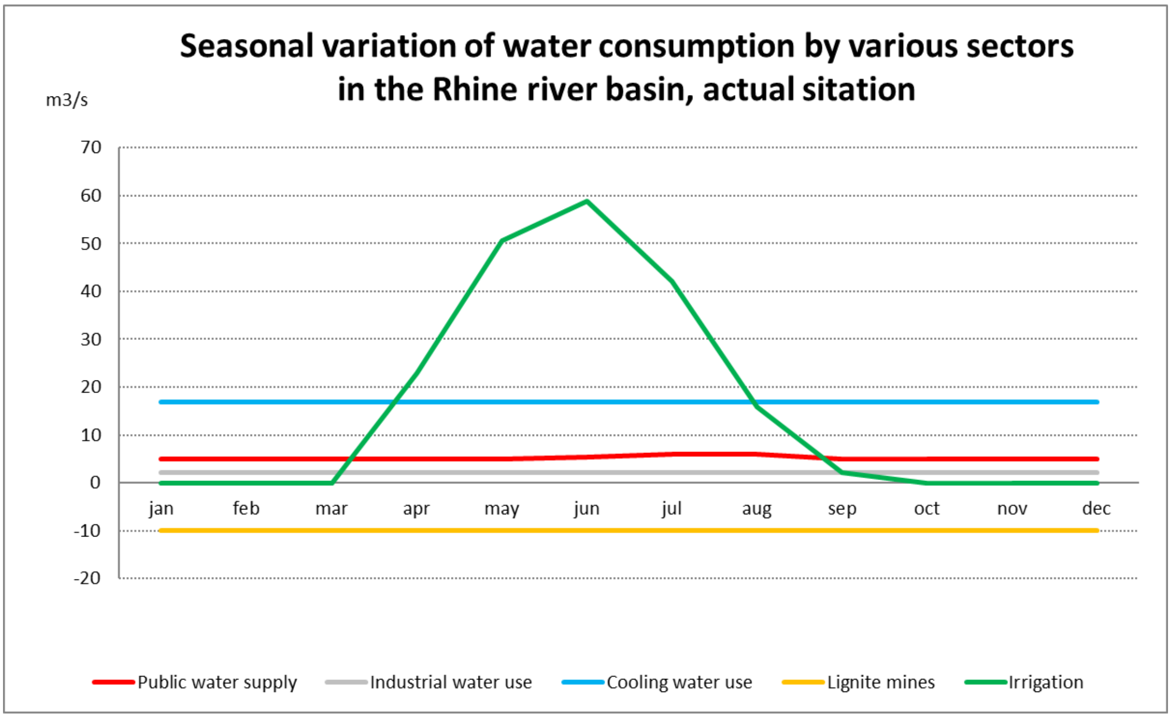

Figure 3.5 Calculated seasonal variation of the water consumption upstream in the Rhine river basin for various sectors in the actual situation.

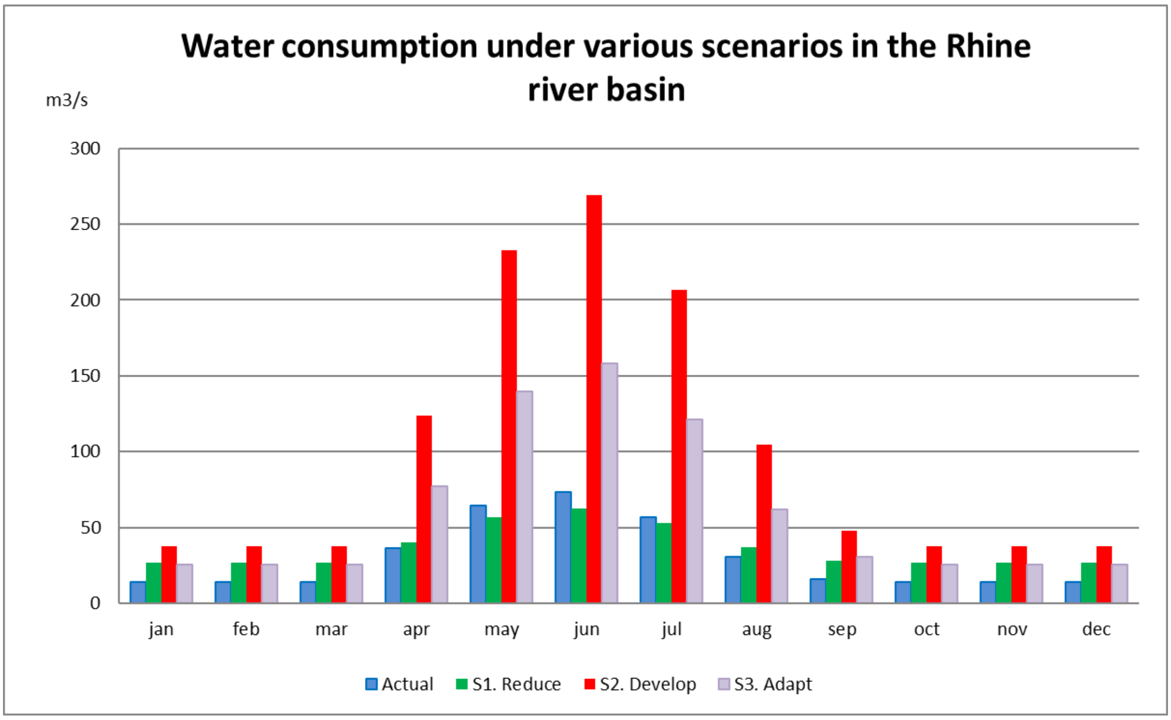

Figure 3.6 Calculated seasonal variation of the water consumption upstream in the Rhine river basin for various sectors in the actual situation.

3.3 Accuracy of the estimates

With respect to the calculation results for public water supply the input data are relatively well defined. The calculation method is straightforward and commonly applied. Only minor improvements are expected with more detailed analysis on the level of the Rhine river basin. On a local or regional level improvements are possible by using more detailed data, including water transfers.

Industrial water use is estimated based on the GDP in combination with an estimate on the (average) specific water use per unit of GDP. Although the values for GDP are generally well known, the applied value for the specific water use per unit of GDP should be considered as a rough estimate and could be improved. It should be noted though that the return flow rate (95%-98%) from industry is high, and the calculated water consumption by industry will only change slightly with improved values for the specific water use. As the share of industrial water consumption in the total water consumption is limited, the accuracy of the present estimates is considered sufficient for the present study on the level of the Rhine river basin.

The estimated water use and consumption for cooling purposes in the energy sector dominates to the total water use and consumption in the Rhine river basin. The input data used to estimate the water use and consumption for cooling purposes are based on very general assumptions. Given the relatively large contribution of water use and consumption for cooling to the total water use and consumption in the Rhine river basin, these data should be updated with more detailed information. Please note that the effects of water use for cooling on the temperature of the Rhine are not considered in this study.

Information on the water discharge and use from the lignite mines is based on direct communication with RWE, and can be considered as accurate.

Although the estimated water use for irrigation is small compared to the water use of other sectors (merely cooling water), the estimated water consumption by irrigation is very relevant, specifically during the summer season and under the S2. Development scenario. However, the input data used for the calculation of the water consumption by irrigation are not considered to be very reliable. Both the data on the extent of the irrigated areas (km^2) and the data on the specific water use (mm per crop type) could be updated with more accurate information, leading to a more accurate estimation of the actual and future water consumption by irrigation.

4 Conclusions and recommendations

4.1 Conclusions

Based on the analysis of the results of the Integrated Overview on water use and consumption of socio-economic scenarios the following conclusions are formulated:

- The yearly average actual water <u>use</u> for cooling (in electricity production) in the Rhine river basin is estimated at almost 700 m^3/s.
- With respect to the possible future yearly average water <u>consumption</u> in the Rhine river basin, cooling water (15-25 m^3/s), lignite mining (10 m^3/s) and irrigation (10-65 m^3/s) are considered the most important sectors in this study. Given the uncertainties in the underlying data for cooling water and irrigation, those estimates should be updated though.
- The contribution of public water supply (2-8 m^3/s) and industry (1-3 m^3/s) on the possible future water consumption in the Rhine river basin is small compared to the other sectors.

- Possible future scenarios show considerable variation in water consumption for irrigation, merely due to uncertainty in the future irrigation patterns.
  The estimated possible increase of water consumption in future scenarios ranges from 0 to 70 m^3/s on annual basis (taken into account the mentioned uncertainty in water consumption for irrigation).

- The estimated water consumption in the summer period increases from 50-75 m^3/s in the actual situation up to some 250 m^3/s following the S2. Develop scenario. This means the water consumption in the Rhine river basin might increase by some 200 m^3/s during the low flow season.

Based on these results it can be concluded that the possible effects of changes in various socio-economic sectors in water use and water consumption on the discharge of the Rhine river during low flows are within the same order of magnitude as the effects of climate change (precipitation) and changes in snow and glacier melt.

4.2 Recommendations

In addition, the following recommendations are formulated based on the present analysis:

- Investigate in more detail the actual water consumption for <u>irrigation</u> as well as the possible effects of irrigation scenarios on the discharge of the Rhine river in future. Information on the irrigated area and the specific water use for irrigation should be updated.
- Investigate in more detail the actual and possible future <u>cooling water</u> consumption. Information on the electricity production and the water use and return flows should be updated.
- Include the water consumption by socio-economic sectors in the hydrological models to describe the low flow conditions.

Following the memo included in Annex B, it is also recommended to:

- Investigate in more detail the effect of reservoir management on the discharge distribution of the Rhine river.
- Include the (natural) lakes and (the management of artificial) reservoirs in the hydrological models.

Referring to the impact assessment of changes in hydrology with respect to socio-economic developments, it is notified that:

- Changes in cooling water use and changes in the discharge (distribution) of the Rhine river may influence the temperature of the Rhine (in relation to changes of the temperature due to climate change). It is recommended to address the issues related to the temperature in a separate study, eg. in close cooperation with the IKSR.
- In addition to water temperature, water quality in general is influenced by the changing discharge of the Rhine as well (eg. De Rijk et al, 2010). It is recommended to address the issue of water quality as well in close cooperation with the IKSR.
- Low flow conditions are very relevant for the navigation on the Rhine river. It is recommended to cooperate with IKSR in the discussion on the impact assessment of low flow conditions on navigation with CCNR.

5 Literature

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Katz, David, 2015. Water use and economic growth: considering the Environmental Kuznets Curve relationship. Journal of Cleaner Production 88 (2015) 205-213.

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Rijk, S. de, O. de Keizer, M. de Wit, F.H.M. van de Ven, 2010, Invloed van steden en klimaatverandering op de Rijn en de Maas. Deltares, 1201196.

A Workshops

During the project two Expert Workshops were held in at BfG in Koblenz, to discuss the water use and water consumption of various sectors with several selected experts. The results of these Expert Workshops are included in the Integrated Overview.

First (Kick-off) Expert Workshop, March 30/31 2017 in Koblenz

March 30/31 a successful Expert Workshop was organised in Koblenz in the framework of the Socio-Economic-Scenarios project SES-Rhine. This Expert Workshop is considered as a follow-up of the Bregenz workshop in 2014. Participants are listed in below.

The objectives of the SES-Rhine project are:

- to integrate the available national information on actual and future water use by various socio-economic sectors and generate an overview up to the level of the Rhine river basin,
- to evaluate the relevance of water use by individual socio-economic sectors for the flow in the Rhine river basin,
- to compare the possible effects of socio-economic changes on the discharge of the Rhine with the effects of climate changes as studied in Rheinblick-2050 and ASG, and
- to gather knowledge on concepts for impact assessment and feedback mechanisms between hydrology and socio-economic developments.

During the workshop a number of recent relevant national projects (CH, DE, NL) were presented by the various participants, including the results of the Bregenz workshop. The (draft) Integration Platform (the anticipated overview of socio-economic sectors on the Rhine river basin level) was presented and discussed. Information was exchanged on effects of land-use change and climate change, water use for irrigation, role of reservoirs in water management, industrial water use, and socio-hydrology.

The participants of the workshop appreciated the (draft) Integration Platform to create an overview of the contribution of the various socio-economic sectors to the water balance. During the workshop a number of adaptations to the Integration Framework were discussed. These will be included and presented during the next workshop.

The selected temporal resolution of 12 months was agreed upon. As no “storage” is included in the speadsheet, the included variation on time in the input data should carefully be taken into account.

The present project focusses on the effects of socio-economic scenarios on the *discharge* of the Rhine river. During the Expert workshop it was discussed that *water temperature* might prove to be a relevant item for further discussions in a next phase of the project, possibly in cooperation with the initiatives of ICPR. Temperature of surface water is a key issue during low flows (hydrology) in relation to cooling water discharge (industry), threatening ecological standards. Moreover, temperature might prove to be an excellent case study to evaluate the possible implementation of new developments in the field of socio-hydrology.

Participants:

- Ute Menke (Secretariat CHR)
- Enno Nilson (BfG, Germany)
- Peter Krahe (BfG, Germany)
- Christina Maus (BfG, Germany)
- Karina Meyerholz (BfG, Germany)
- Olivier Overney (FOEN, Switserland)
- Marc Scheibel (Wupperverband, Germany)
- Dennis Lemke (EVONIC, Germany)
- Linda Kuil (TU Vienna, Austria)
- Ulrich Ostermann (Kreisverband der Wasser und Bodenverbände, Uelzen, Germany)
- Erik Ruijgh (Deltares, the Netherlands)
- Willem van Verseveld (Deltares, the Netherlands)

Second (Intermediate) Expert Workshop, March 30/31 2018 in Koblenz

The Intermediate Workshop for the CHR/KHR project on Socio-Economic-Scenarios SES-Rhine was organised on March 1st, 2018, and kindly hosted by BfG in Koblenz on behalf of CHR/KHR. During the Kick-off Workshop (in 2017) we discussed on the domestic, industrial and land-use / irrigation water use. The main focus of the Intermediate Workshop was on the use of water from the energy sector.

Dr. Thomas Maurer opened the Workshop and welcomed the participants. He underlined the relations of the present workshop with the ongoing activities of BfG.

The objectives and present status of the CHR/KHR project SES-Rhine was presented by Erik Ruijgh, and Dr. Enno Nilson presented the motivation and present status of the ongoing projects in this field within BfG.

Then Dr. Christian Forkel (RWE) gave an informative presentation on the water use of the lignite mines in Nordrhein-Westphalia. He explained the actual situation with respect to water use of the mines and presented the planned water use in the upcoming 100 years.

Finally, Mr. Guido Federer (BFE, Switzerland) kindly explained in his presentation on the water use by hydropower plants in Switzerland. He addressed the motivation of the electricity companies to discharge water on a short time basis, the actual yearly distribution of the discharge from the reservoirs and the projected developments in the upcoming 30 years.

The presentations triggered the participants to start interesting and vivid discussions during the Workshop. The Workshop allowed for an in depth exchange of information among the participants.

Participants:
- Thomas Maurer (BfG, D)
- Enno Nilson (BfG, D)
- Peter Krahe (BfG, D)
- Christina Maus (BfG, D)
- Karina Meyerholz (BfG, D)
- Thomas Recknagel (BfG, D)
- Christian Forkel (RWE, D)
- Guido Federer (Bundesamt fur Energie BFE, CH)
- Erik Ruijgh (Deltares, Nl)

B Memo ”The influence of reservoirs on the discharge distribution of the River Rhine” – November 30, 2017

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Memo

To
Eric Sprokkereef, CHR

Date	**Reference**	**Number of pages**
30 November 2017	11201722-002-ZWS-0001	15
From	**Direct line**	**E-mail**
Erik Ruijgh, Mark Hegnauer, Frederiek Sperna Weiland, Willem van Verseveld	+31(0)88 335 8135	Erik.Ruijgh@deltares.nl

Subject
The influence of reservoirs on the discharge distribution of the River Rhine

1 Introduction

Climate change studies (like Görgen et al., 2010; Van Pelt et al., 2012; Sperna Weiland et al., 2015) indicate that in future the discharge of the Rhine River will show more extreme events, the maximum discharge in winter will increase and the summer discharge might decrease.

The hydrological models used in these studies do include the effect of climate change on precipitation and evaporation, as well as the effects on snow melt (higher temperatures in spring result into a shift in time of the snowmelt, and thus in a change in the discharge distribution). The hydrological models also include a basic representation of the effect of climate change on glacier melt. The contribution of glacier melt on the actual river discharge has been studied in the CHR-project ASG (Abflussanteile aus Schnee- und Gletscherschmelze im Rhein und seinen Zuflüssen vor dem Hintergrund des Klimawandels) (Stahl et al., 2017). From this study is clear that the remaining glaciers will diminish further in future and may eventually disappear completely. The effect of climate change on glacier melt will be studied in detail in the next phase of ASG.

Both the effect of climate change on discharge from snow melt and from glacier melt result into a change in the discharge distribution in time, leading to higher discharges in the wet season and lower discharges in the dry season. The redistribution of discharge is related to the reduction of the volume of water in snow cover and glaciers: two large (natural) reservoirs of water.

In this memo we evaluate the contribution of present (artificial) reservoirs on the discharge distribution in the Rhine river basin. We try to evaluate whether a change in the operation rules of the present reservoirs could possibly contribute to counterbalance the change in discharge distribution due to climate change.

The results of this memo will be incorporated in the SES-Rhine project (Socio-economic scenarios).

2 Droughts and climate change

2.1 Discharge distribution

In 2014 / 2015 Deltares conducted a climate change analysis for the rivers Rhine and Meuse. This assessment focused on the quantification of the impacts of climate change on the flow of the river Rhine and Meuse based on the KNMI'14 scenarios and the CMIP5 datasets used by the Interngovermental Panel of Climate Change (Sperna Weiland et al., 2015). This report includes a discharge change assessment for Lobith. The new projections were compared with earlier analysis based on the KNMI'06 scenarios and analysis done for the international RheinBlick2050 project (Görgen et al., 2010). In general the scenario sets and studies agree upon:

- Decrease of late summer discharge (see Figure 2.1);
- Decrease of the annual minimum 7-day low flow value (see Figure 2.2).

This indicates that discharges in the summer, especially the late summer, are likely to decrease at Lobith due to climate change, whereas mean and especially maximum discharge in winter and spring will likely increase.

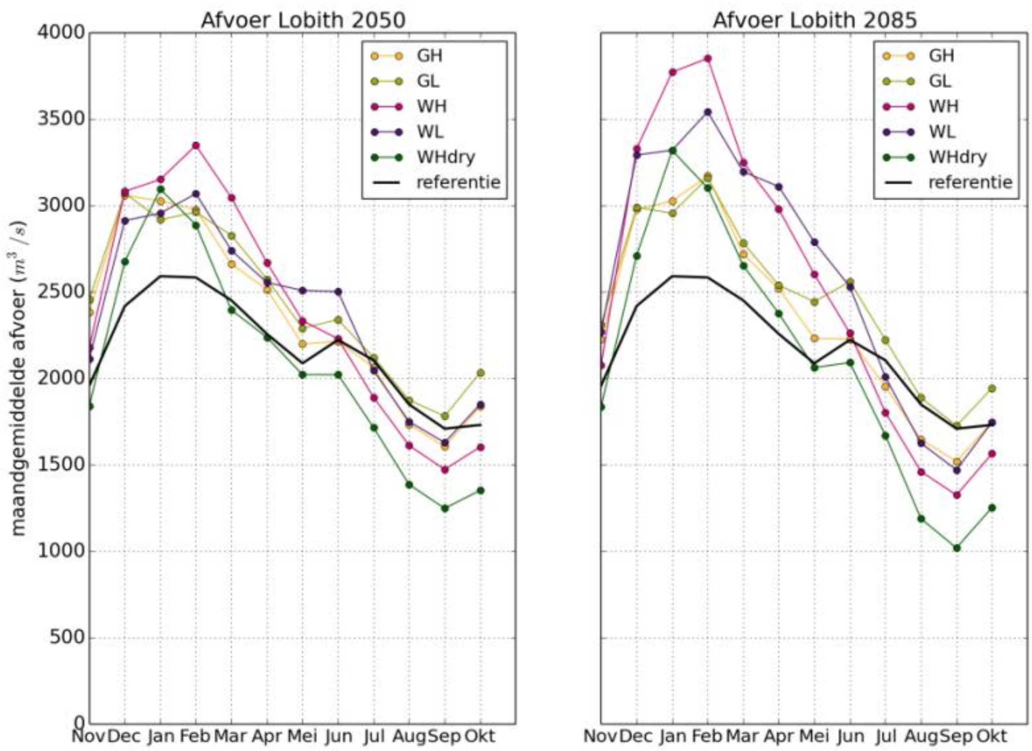

Figure 2.1: Discharge climatology for the Rhine at Lobith for the KNMI'14 scenario's (source Sperna Weiland et al., 2015.)

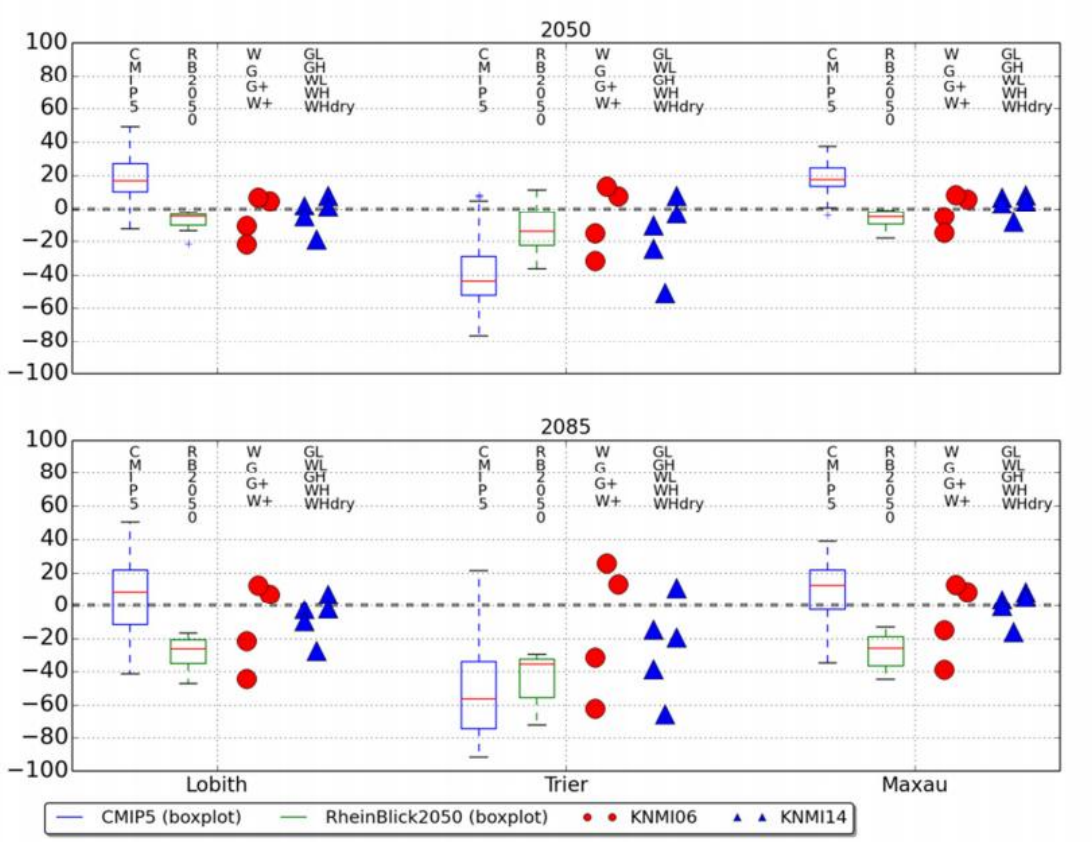

Figure 2.2: Percentage change in given7-day minimum flow (NMQ7) for the Rhine for all climate model / scenario sets. The color / symbol coding and boxplots represent the scenario sets. On top of the graphs the ordering of scenarios is given.

2.2 Minimum flow and discharge deficit

Maintaining a minimum river discharge at Lobith is extremely relevant for agricultural production, salt management and navigation in the Netherlands [1)]. The “Landelijke Coördinatiecommissie Waterverdeling” (LCW) in the Netherlands formulated discharge thresholds that trigger action once the discharge of the Rhine falls below this value. These low flow discharge thresholds are presented in Figure 2.3.

[1)] Flood protection is also an issue of droughts in the Netherlands, as the strength of some dikes may be weakened due to water shortage.

Navigation thresholds [m³/s]								
	Lobith		Andernach	Cochem	Frankfurt	Rockenau	Rekingen	Untersiggenthal
Jan	1000	Q96	799	118	63	40	159	215
Feb	1000	Q97	823	124	83	44	153	220
Mar	1000	Q98	969	128	73	59	149	218
Apr	1000	Q99	986	79	75	47	200	286
May	1000	Q99	966	65	58	44	243	348
Jun	1000	Q99	903	46	25	34	327	376
Jul	1000	Q98	863	45	28	33	304	360
Aug	1000	Q96	855	45	36	31	297	359
Sep	1000	Q91	867	52	52	35	286	300
Oct	1000	Q87	858	69	63	37	248	260
Nov	1000	Q87	868	83	72	40	217	249
Dec	1000	Q93	843	108	77	42	180	228
Growing season thresholds [m³/s]								
May	1400	Q89	1270	104	86	62	350	472
Jun	1300	Q97	1170	65	57	45	389	465
Jul	1200	Q96	1070	54	48	38	360	422
Aug	1100	Q92	966	52	46	34	323	400

Figure 2.3: Low flow discharge thresholds for Lobith (with corresponding exceedance percentage) and other locations along in the Rhine River (copied from Kersbergen, 2016).

Based on the thresholds in Figure 2.3 and the discharge projections of the climate change models, a discharge deficit can be calculated. This is calculated from the difference between the actual discharge and the low flow criteria for the period that the actual discharge is below the discharge criteria. This difference is multiplied with the duration to obtain a discharge deficit volume. The results for Lobith are presented in Figure 2.4. The discharge deficit will likely increase by 2085.

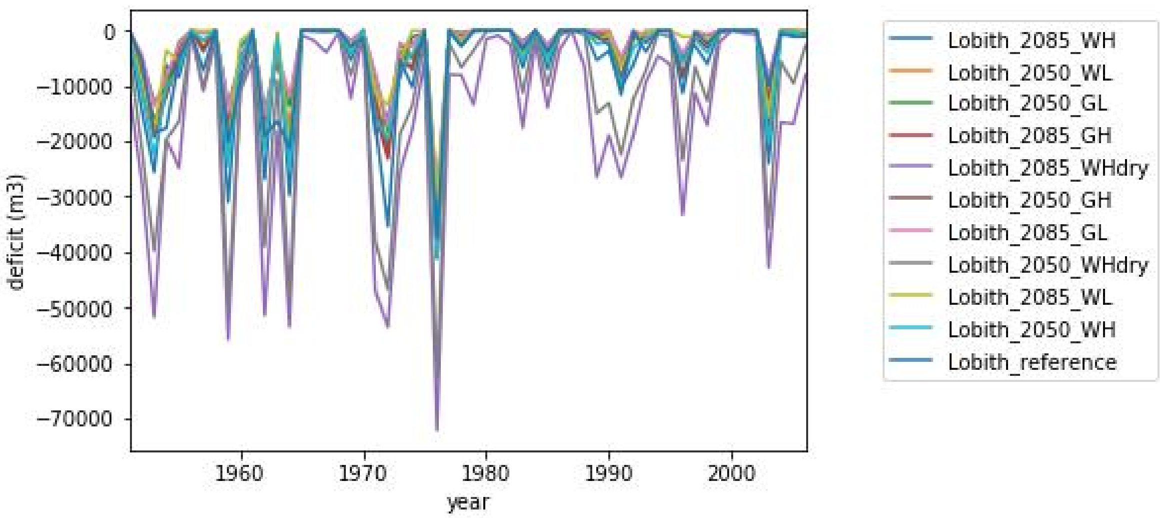

Figure 2.4: Discharge deficits for Lobith for the reference situation and the KNMI14 scenarios.

2.3 Cumulative discharge

Whereas the discharge distribution is changing due to climate change, the low flows are decreasing and the discharge deficit in summer will likely increase, the projected total annual discharge volume increases (see Figure 2.5, Sperna Weiland et al., 2015). So, on an annual basis the total volume of water available in the Rhine river basin will increase. The low flows are reduced due to the change in the discharge distribution, not due to a lack of water on an annual basis.

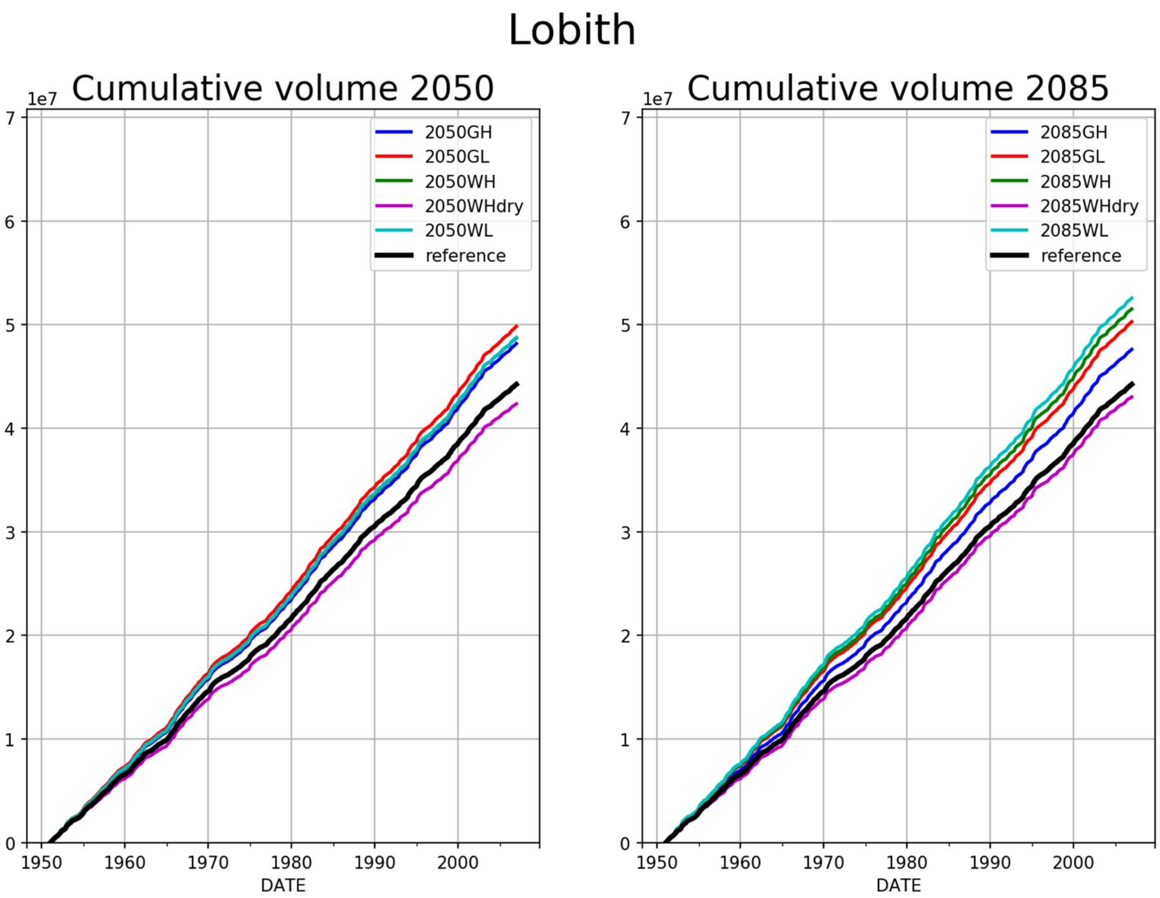

Figure 2.5: Cumulative yearly discharge volume for Lobith for the reference situation and the KNMI14 scenarios at 2050 and 2085 (Sperna Weiland et al., 2015).

3 Discharge from glaciers

3.1 Glaciers

The ASG-project (Stahl et al., 2017) has studied the contribution of snow melt and glaciers in the Alpes on the discharge of the Rhine river. Table 6.4 of Stahl et al. (2017) summarizes the results for the contribution of glacier melt on the discharge of the Rhine river. The table is copied in Figure 3.1. Based on this information the total volume of water originating from the glaciers (along the Rhine and) at Lobith is calculated in Figure 3.2, together with the calculation for Basel as a consistency check. The total volume of water amounts to some 900 Mm^3 water during the months July - October. These four months are presented here as these months show very low flows (see also Figure 2.1), and the highest discharge from glacier melt.

Table 6.4: Average modelled Q_I values (absolute values in m³/s and relative fractions in % of Q) for the months July, August, September, and October in the drought and low flow year 2003 for selected Rhine gauges (location for the gauges see Figure 6.11).

Gauge	July		August		September		October	
	(m³/s)	(%)	(m³/s)	(%)	(m³/s)	(%)	(m³/s)	(%)
Brienzwiler/Aare	23.7	32.9	42.9	65.5	21.5	52.7	5.9	22.6
Basel	49.0	5.5	126.9	17.3	109.2	16.9	64.1	7.0
Maxau	43.6	4.6	122.1	16.0	113.2	16.5	68.3	6.8
Worms	42.2	4.2	120.8	15.1	114.9	15.9	70.0	6.4
Mainz	40.7	3.8	119.5	14.0	116.7	15.0	71.8	6.2
Kaub	39.3	3.6	118.5	13.8	117.8	14.9	73.0	6.2
Andernach	37.7	3.2	117.1	12.7	119.0	13.6	74.4	5.8
Köln	36.1	3.0	116.0	12.3	120.6	13.5	76.1	5.7
Düsseldorf	34.6	2.8	114.8	12.1	121.6	13.4	77.3	5.7
Lobith	30.7	2.4	112.0	11.4	124.0	12.9	80.2	5.5

Figure 3.1: Average modelled discharge values of contribution of meltwater from the glaciers in the Alpes on the discharge of the Rhine in 2003 (copied from Stahl et al., 2017)

GLACIER	July	Aug	Sep	Oct	
Basel (m3/s)	49	126.9	109.2	64.1	
Lobith (m3/s)	30.7	112	124	80.2	
days/month	31	31	30	31	
seconds/day	86400	86400	86400	86400	Cumulative:
Basel (Mm3)	131	340	283	172	926
Lobith (Mm3)	82	300	321	215	918

Figure 3.2: Calculation of discharge at Basel en Lobith, originating from the glaciers in the Alpes on the discharge of the Rhine in 2003 (based on data from Stahl et al., 2017)

3.2 Glaciers in hydrological models used in climate change studies

The hydrological models that are being used at present in climate change studies do include (both snow melt and) a basic representation of the effect of climate change on glacier melt. The volume of glaciers is included in the models as an initial value, and the melting process is calculated based on the temperature as included in the meteorological forcing data. Typically, the effect of climate change on the river discharge is calculated for one typical year in the future (“zichtjaar”), using different meteorological forcing data (scenarios) representing the climate change.

Consequently, a hydrological calculation for (for instance) 2085 uses the meteorological data (including precipitation, evaporation and temperature) related to the selected climate change scenario and the actual (!) initial values, for instance the soil moisture content, groundwater levels, storage in lakes and artificial reservoirs as well as snow cover and glacier volume, corresponding to the actual state. As the glacier volume in 2050 and 2085 is likely to be smaller than the actual volume, the present hydrological models overestimate the volume of water from glacier melt. This is illustrated in Figure 3.3.The higher glacier melt rate (due to increased temperature) results in higher flow contribution from glacier melt. In other words, the present climate change studies are likely to overestimate the projected low flows, and thus underestimate the effect on river discharge.

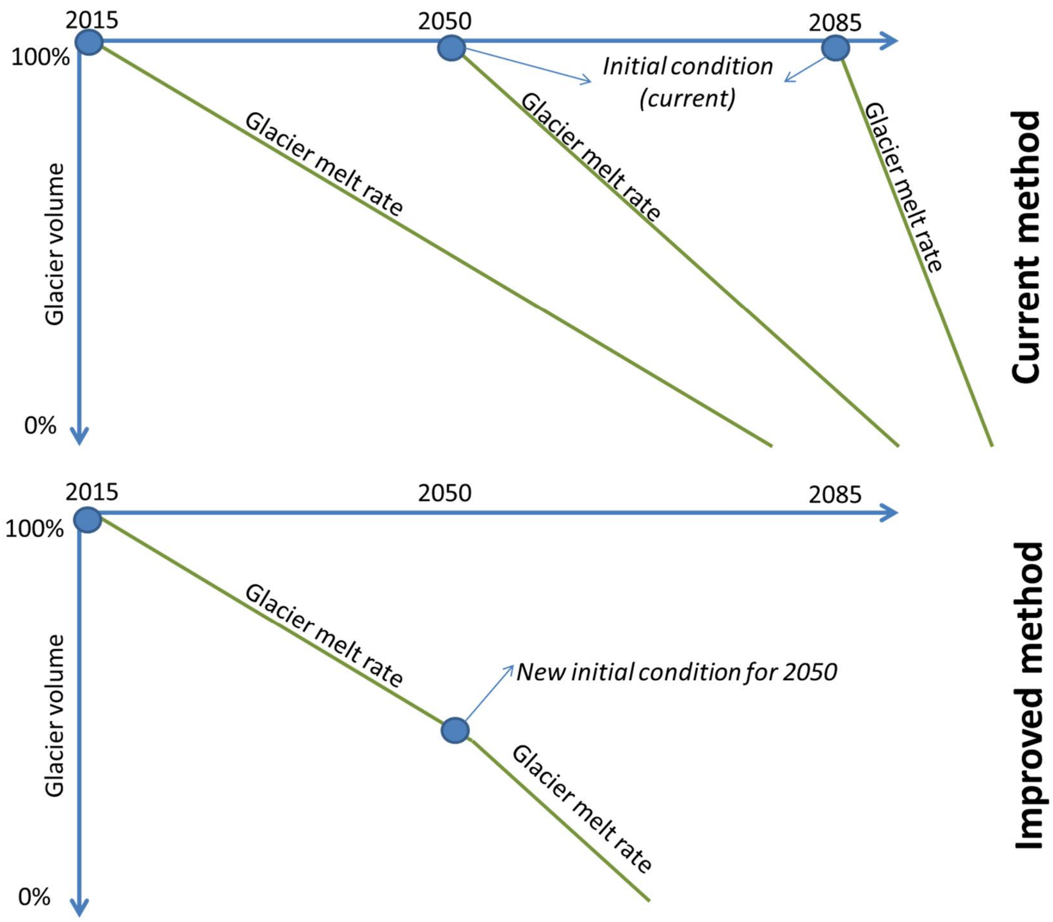

Figure 3.3: Method of using initial glacier conditions in current studies (top) and proposed improved method (bottom)

4 Reservoirs

4.1 Overview of volume of reservoirs in Rhine river basin

CHR report II-10 (Wildenhahn and Klaholz, 1996) provides an overview of all artificial reservoirs in the Rhine river basin. The summarized results are copied below in Figure 4.1 and Figure 4.2. As presented in Figure 4.1 and Figure 4.2, the total volume of the reservoirs in the Rhine river basin reported in CHR-II-10 amounts to 3121 hm^3 (=3121 Mm^3).

It should be noted that only the artificial reservoirs are included in this overview; the natural lakes (eg. Lake Constance) are not included.

Another source of information on the volume of reservoirs in the Rhine river basin is provided by the AQUASTAT database (FAO, 2016). This source shows a total reservoir volume in the Rhine river basin of 2683 Mm^3.

The difference between the values from Wildenhahn and Klaholz (1996) and FAO (2016) has not been studied here in detail; FAO (2016) might not have included all reservoirs, or the difference in volumes could be related to sedimentation in the reservoirs during the 20 years in between. Within the framework of the present analysis, we conclude that the order of magnitude of these two sources correspond rather well. The total (present) volume of reservoirs in the Rhine river basin is estimated to approximately 3000 Mm^3.

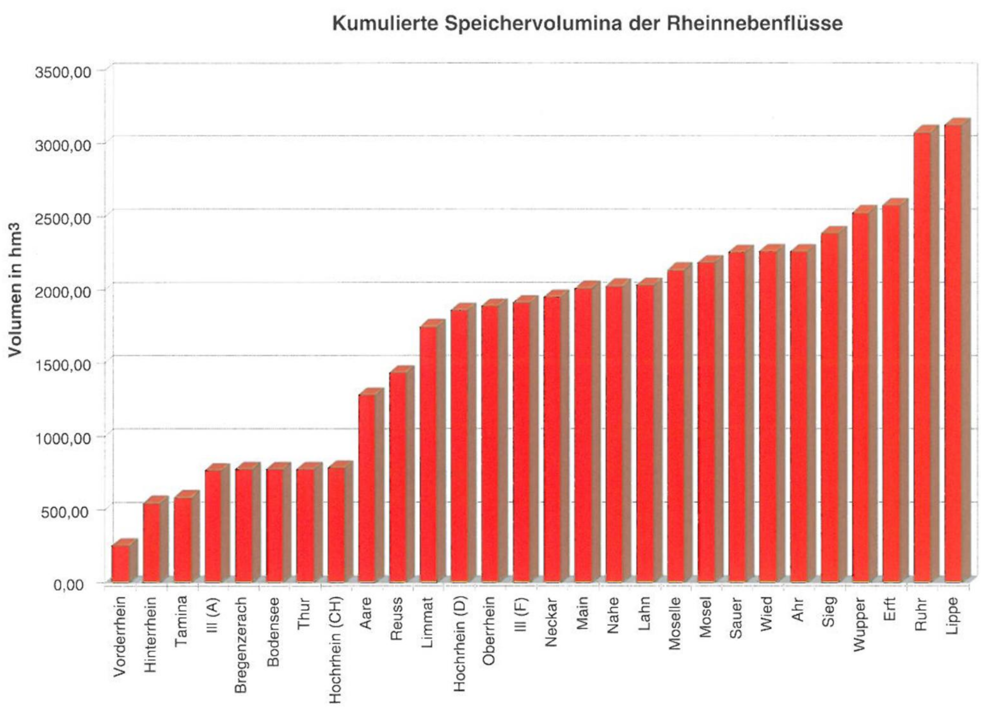

Figure 4.1: Cumulated storage volume of reservoirs in the tributaries of the Rhine river (copied from CHR II-10).

Nebenfluß	Volumen in hm³	Summe d. Volumens (hm³)
Vorderrhein	253,14	253,14
Hinterrhein	289,36	542,50
Tamina	38,50	581,00
Ill (A)	183,40	764,40
Bregenzerach	8,40	772,80
Bodensee	1,40	774,20
Thur	0,60	774,80
Hochrhein (CH)	7,26	782,06
Aare	496,95	1279,01
Reuss	153,19	1432,20
Limmat	314,86	1747,06
Hochrhein (D)	112,85	1859,91
Oberrhein	27,63	1887,54
Ill (F)	24,29	1911,83
Neckar	37,99	1949,82
Main	59,64	2009,46
Nahe	14,05	2023,51
Lahn	6,63	2030,14
Moselle	103,58	2133,72
Mosel	50,53	2184,25
Sauer	71,40	2255,65
Wied	4,45	2260,10
Ahr	0,73	2260,83
Sieg	123,10	2383,93
Wupper	140,43	2524,36
Erft	51,00	2575,36
Ruhr	496,06	3071,42
Lippe	50,01	3121,43

Figure 4.2: Cumulated storage volume of reservoirs in the tributaries of the Rhine river (copied from CHR II-10).

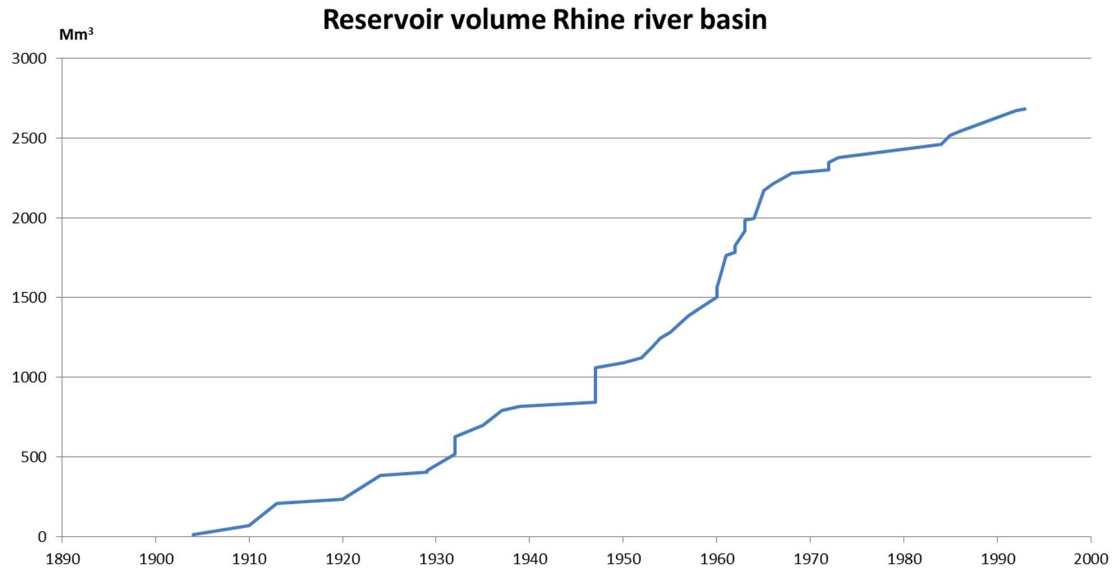

Figure 4.3: Increase of total volume in reservoirs in the Rhine river basin between 1900 and 2000 (from FAO, 2016).

Figure 4.3 also shows the increase of the reservoir volume over the last century. As presented in Figure 4.3 the increase in volume has been reduced significantly since 1970 (although still some more reservoirs have being constructed after 1970). Information from the ASG-report (Stahl et al., 2017) confirms the reduction in increase of reservoir volume since 1970 for the upper reaches of the tributaries of the Rhine in the Alpes (see Figure 4.4).

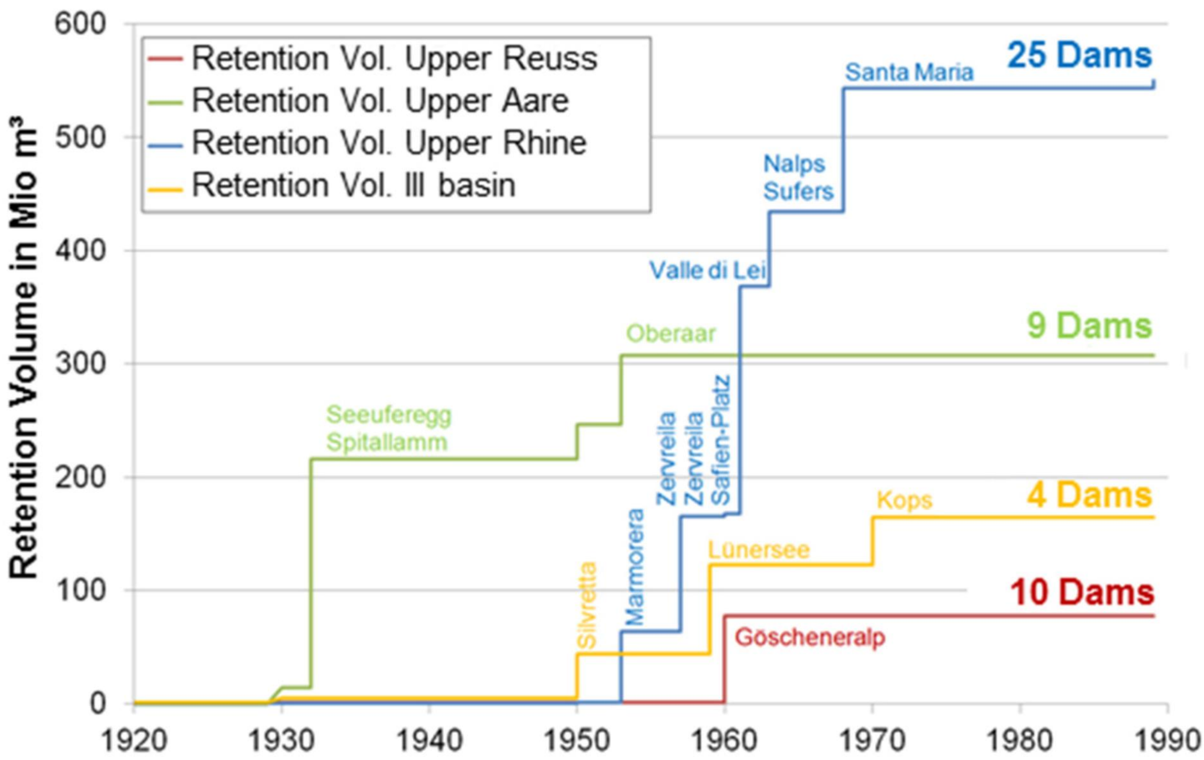

Figure 4.4: Development of the reservoir volume since 1920 for the upper reaches of the rivers Reuss (red), Aare (green) and Rhine (blue), and Ill (orange) (copied from Stahl et al., 2017).

4.2 Effect of reservoirs on the discharge distribution

The effect of reservoirs on the discharge distribution is nicely presented in the ASG report (Stahl et al., 2017), and copied in Figure 4.5. Another example for the River Rhone (EAWAG, 2011) is presented in Figure 4.6.

As can be seen from these graphs, the construction of reservoirs results in less high values in the downstream discharge, as the peak discharges are partially used to fill the reservoir whereas during low flows water is being released from the reservoir.

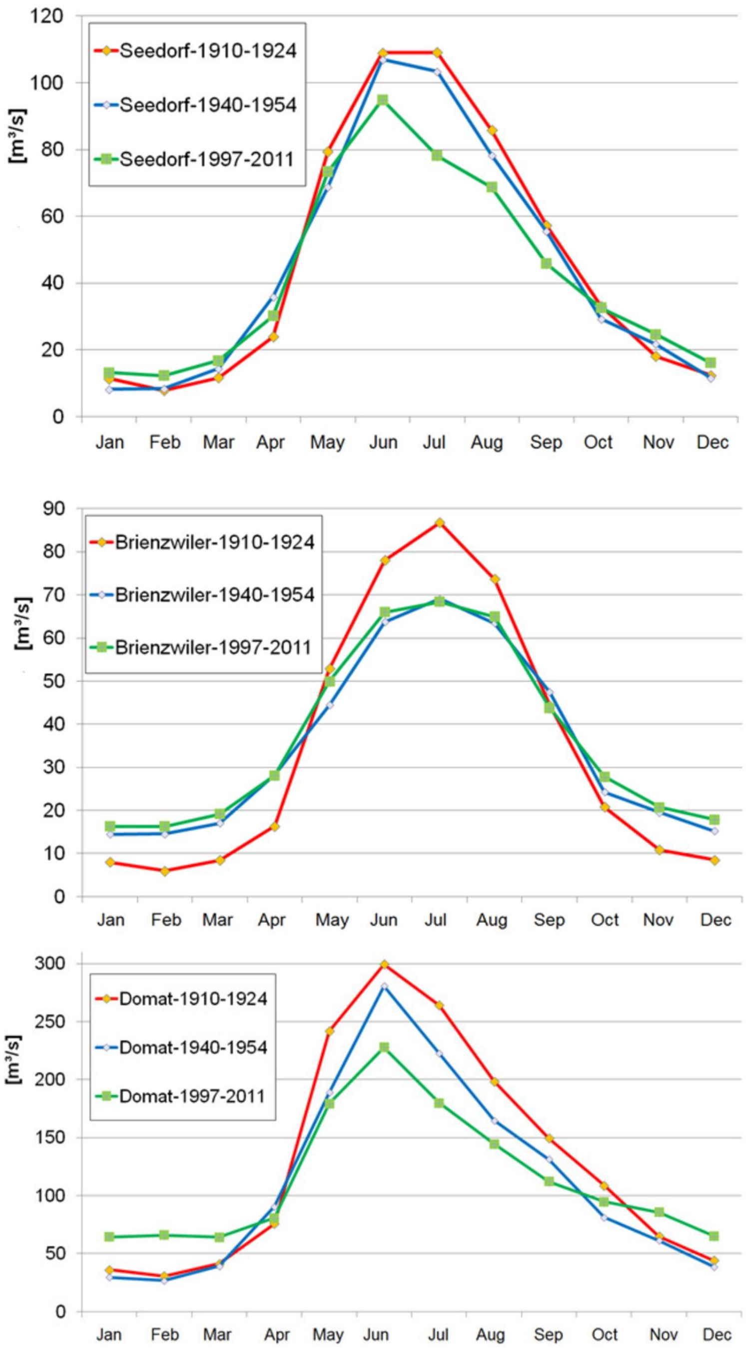

Figure 4.5: Average observed monthly streamflow (in m³/s) at the gauges Seedorf/Reuss (upper), Brienzwiler/Aare (middle) and Domat-Ems/Rhein (lower) for the time periods 1910–1924 (red), 1940–1954 (blue), and 1997–2011 (green). (Copied from Stahl et al., 2017).

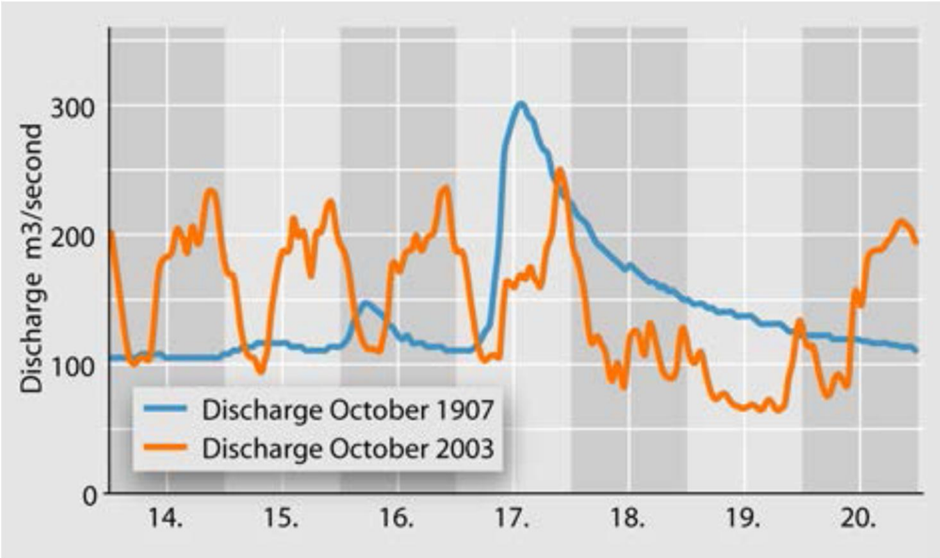

Figure 4.6: Discharge of the Rhône at Vouvry before and after the construction of large dams. (copies from EAWAG, 2011)

5 Discussion and conclusions

Climate change studies on the discharge of the Rhine show an increase of the total annual discharge, in combination with an increase of the seasonal variation. The discharge in the wet season is projected to increase whereas the discharge in the dry season is projected to decrease. The projected reduced flow during late summer (July-October) at Lobith is resulting from the change in the seasonal discharge distribution, rather than from a reduction of the annual total discharge.

Meteorological climate change models provide projections on the future precipitation, evaporation and temperature. These projections include changes in the total annual values as well as the seasonal (and geographical) variation. The precipitation excess is partly and temporarily stored in glaciers, as well as snow cover, groundwater, soil moisture and natural and artificial lakes, and subsequently discharged to the rivers. These “storages” influence the redistribution of the precipitation excess in time, and thus the seasonal variation of the river discharge.

The contribution of glacier melt on the discharge of the Rhine at Lobith during the dry late summer of 2003 (July-October) is calculated (based on Stahl et al., 2017) to have been some 900 Mm^3. If, due to the melting of the glaciers, the contribution of the glaciers disappears, the future low flows might decrease further.

The present volume of (artificial) reservoirs in the Rhine river basin amounts to approximately 3000 Mm^3. Similarly to the glaciers, water is (net) stored in the reservoirs during the (cold) wet season and (net) released during the (hot) dry season. Consequently, the reservoirs also contribute to the redistribution of the discharge. Judging from the estimated volumes of the glaciers and reservoirs, the effect of the reservoirs on the discharge distribution of the Rhine River might be in the same order of magnitude as the effect of the glaciers. The exact effect of the reservoirs on the discharge distribution depends on the operation rules of the artificial reservoirs.

The artificial reservoirs are not taken into account explicitly in the actual hydrological model(s) used for climate change studies in the Rhine basin. The effect of the reservoirs on the discharge distribution is more or less taken into account in the parameters of the lumped model. The consequence of this approach on the calculated discharge distribution has not been studied yet. Particularly for low flow situations, this approach might result in an underestimation of the discharge.

Moreover, it is recognized that the operation rules of reservoirs might change in future to manage the variability in energy production from wind and sun due to the energy transition. The possible effects of these changes (and possibly even the construction of new reservoirs) due to socio-economic changes in the basin on the discharge distribution of the Rhine River could well be relevant in projections on the future low flows. As the reservoirs are included in the parameters of the lumped model, it is quite difficult to study the effect of a change of the operation rules of the reservoirs on the discharge distribution.

6 Recommendations

(Natural) lakes and (artificial) reservoirs
Hydrological models of the Rhine river basin that are used in climate change studies (e.g. Sperna Weiland et al, 2015) include the following natural lakes in the Swiss part of the Rhine basin: Boden See, Zurich See, Vierwaldstättersee See, and Neuenburger See (Hegnauer and van Verseveld, 2013). Perwitasari (2015) also illustrated the importance of including these lakes in the hourly HBV model configuration of the operational forecasting system RWsOS Rivieren. Including these lakes resulted in a performance increase during low flow conditions.

While including these lakes in the Swiss part of the Rhine basin proves to be important, we recommend for the evaluation of the contribution of present (hydropower) reservoirs on the discharge distribution in the Rhine river basin, to also include the (largest) artificial reservoirs of the Rhine basin in the hydrological model. This way, the influence of these artificial reservoirs on (low) flow conditions is not hidden in hydrological model parameters, and thus gives a more realistic result of the present contribution of reservoirs on the discharge distribution in the Rhine basin. By including the reservoirs in the model, also the effect of different reservoir optimization strategies (as might result from socio-economic developments) on the (low) flows of the Rhine could be investigated.

Initial glacier storage
As a further improvement we recommend to include the effect of climate change also on the initial glacier storage in the hydrological models. Currently, the effect of climate change on the initial glacier storage is not included in the hydrological models. The initial glacier storage is valid for the reference climate period, and not for climate scenarios. This means that the contribution from glacier melt is overestimated for the climate scenarios. Additional hydrological model runs for transient periods with a good representation of the glacier melting processes are required to simulate the development of the glacier storage in time under influence of different climate scenarios. Based on these results, an improved estimate of the initial glacier storage can be included for hydrological model runs for specific years and climate scenarios.

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