Simulation of the effects of climate change scenarios on future Rhine water temperature development

– update IPCC AR5 –

International Commission for the Protection of the Rhine

Technical report no. 302

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Imprint

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Simulation of the effects of climate change scenarios on future Rhine water temperature development – update IPCC AR5 –

1 Summary

This report is an update of the assessment of the effects of climate change on future Rhine water temperatures (ICPR, 2014). The study is carried out by the EG STEMP as part of the ICPR working plan 2022-2027 (task III.2) and under the mandate of the working group water quality (WG S). The previous assessment was based on the 4th assessment report of the IPCC (assessment report: AR4, 2007). An update is relevant as the IPCC has updated its assessment of climate change in AR5 (2014). Also, less heat is discharged into the Rhine due to changes in the powerplant network. Next to that, the water temperature modelling framework now has higher spatial and temporal resolution and better options to include climate variability. Moreover, the geographical coverage is extended, including the Swiss Rhine and Dutch Rhine delta branches.

Method

The future scenarios in this study relate to the climate scenario study of the IPCC AR5 (IPCC, 2014) with future horizons around 2050 and 2100. All climate chains in this study are based on the highest emission scenario RCP8.5. This scenario is frequently referred to as "business as usual". In this scenario, the representative concentration pathway has equivalent CO_2 concentrations of 1200 ppm in 2050 and 2100. The current study is based on a 20-year period where the selected reference period (1991-2010) is projected into the near future (2045-2065) and the far future (2081-2100). Heat inputs are not included in the scenarios, motivated by the fact that future heat inputs are unknown and strongly dependent on the socio-economic and energy situation in the Rhine riparian countries. Socio-economic influences are also not included in the scenario simulations.

In this study, two approaches were chosen to present the results. On a national level, each participating member state (CH, D, NL) uses its national model approach, including different model chain(s) to simulate climate change. For a first time towards a basin-wide approach, a selection of the national simulation results was made and presented as a common result. For this, the national models were forced with one common combination of a global circulation model (ECEARTH, run 1) and a regional climate model (KNMI-RACMO).

The projections of future water temperatures are based on available national hydrological models (PREVAH, LARSIM, HYDRAX and SOBEK) for the simulation of river discharge, in combination with national water temperature models that simulate the associated water temperature (air2water, QSim and SOBEK). In this study, the national model chains were validated using water temperature measurements and actual heat inputs for the period 2018-2020. The comparison of the validation results of the three water temperature models showed good agreement between simulated and measured water temperatures, which certifies all model formulations are valid for future projections.

For a first time towards a basin-wide approach, the national model chains were coupled offline at the national boundaries at Basel and Lobith.

Remarks

The approach followed was harmonised to the extent possible. Due to practical constraints, the overlap in climate change ensembles used by the three countries was limited. Also, methodologies and model concepts and formulations were different.

Expected results

Compared to the assessment made in 2014 (based on AR4, 2007), the current assessment in 2024 (based on AR5, 2014) expects that air temperatures are (slightly) higher in 2100, there is less influence of heat inputs, winter discharges are increased and summer discharges are decreased in the near and far future as a result of a shift from snow- and glacier-fed to a more rain-fed flow regime of the Rhine (ICPR, 2024).

Findings

The validation study for 2018-2020 shows that the influence of heat input is still significant in parts of the German Rhine resulting e. g. in an average anthropogenic heating of 1.33 ºC at Worms and 0.47 ºC at Lobith at the German-Dutch border. This contribution is not included in the scenario runs.

The study shows that in all sections of the Rhine, warmer water temperatures (wT) are projected for the near and far future. In the near future basin-wide the mean annual wT increase varies from +1.1 °C to +1.8 °C, in the far future the basin-wide mean annual wT increase varies from +2.9 °C to +4.2 °C. Summer and autumn warm faster than the annual average and winter and spring warming is slower. The number of days per year the 25 °C threshold is exceeded varies between 1-2 weeks in the near future. In the far future the number of days 28 °C is exceeded varies between 1 ± 0.5 week per year. The > 30 °C threshold is not exceeded in the scenarios.

Compared to the previous study, annual average warming results are similar for the near future and somewhat cooler for the far future. In the near future the number of days < 3 °C has increased in the current study. In the far future the number of days < 3 °C has deceased in the current study.

It was demonstrated that the common ensemble member ECE-R1_RAC_RCP85 in the 20-year runs used is less "mainstream" when comparing its position to the one in a comparable 30-year run at Lobith. Projections for the near future are therefore colder (estimated -0.1 °C to -0.6 °C, chapter 6.3).The reference period used here (1990-2010) is colder compared to the previous STEMP study (2000-2010) but e. g. warmer compared to what is normally used in the Germany where even older (and thus colder) years are used as a reference.

Harmonisation of the national boundaries was a significant methodological improvement. Only after coupling of the national models, a consistent basin-wide temperature profile with plausible seasonal patterns along the Rhine was simulated. So, the basin-wide approach in its current implementation is still not ideal yet but is nevertheless preferred to the method of combining the three national approaches to a Rhine wT profile (as done in chapter 5).

Recommendations

Current findings are based on AR5 GHG emissions (2014) which was issued 10 years ago. Time was too short to use the latest AR6 (2021) findings. It is suggested to change the update frequency in such a way that the ICPR has access to projections based on climate models using the latest AR GHG emissions (within 2-3 years should be possible). Furthermore, the aim should be to update discharge and temperature projections simultaneously for which a closer cooperation between EG HCLIM and EG STEMP may be considered.

Scenario periods used in the previous assessment (10 years) as well as the current assessment (20 years) were based on pragmatic choices that had to be made after national studies were already finished. Periods shorter than the desirable standard 30 years in climate studies introduce bias in the results. Upfront harmonisation of scenario periods may prevent this.

Rather than simulating one climate chain as done in this study, a better coverage of uncertainty is obtained by simulating multiple climate chains as is done in the national approaches, in a basin-wide model too. Riparian states should make sure to include climate chains representative for the scale of the Rhine catchment in their national analysis. Focus on the national scale only does not serve transboundary modelling of water temperature (and hydrology). During the national analysis, countries could consider the performance of their climate chain selection on a basin-scale, too.

Zusammenfassung

Dieser Bericht ist eine Aktualisierung der Bewertung der Auswirkungen des Klimawandels auf die künftigen Wassertemperaturen des Rheins (IKSR, 2014). Die Studie wurde von der EG STEMP im Rahmen des IKSR-Arbeitsplans 2022-2027 (Aufgabe III.2) und unter dem Mandat der Arbeitsgruppe Wasserqualität (AG S) durchgeführt. Die letzte Bewertung basierte auf dem vierten Sachstandsbericht des Weltklimarates IPCC (Assessment Report AR4, 2007). Eine Aktualisierung ist relevant, da der IPCC seine Bewertung des Klimawandels im AR5 (2014) aktualisiert hat. Zudem wird weniger Wärme in den Rhein abgegeben aufgrund von Änderungen im Kraftwerksnetz. Darüber hinaus verfügt der Rahmen für die Modellierung der Wassertemperatur nun über eine höhere räumliche und zeitliche Auflösung und bessere Möglichkeiten zur Berücksichtigung der Klimavariabilität. Hinzu kommt, dass die geografische Reichweite erweitert wurde und nun den Rhein in der Schweiz und die Rheinarme im niederländischen Delta umfasst.

Methode

Die Zukunftsszenarien in dieser Studie beziehen sich auf die Klimaszenariostudie des IPCC AR5 (IPCC, 2014) mit Zeithorizonten für die Zukunft um 2050 und 2100. Alle Klimaketten in dieser Studie beruhen auf dem höchsten Emissionsszenario RCP8.5. Dieses Szenario wird häufig als „business as usual" bezeichnet. Der repräsentative Konzentrationspfad hat in diesem Szenario äquivalente CO_2-Konzentrationen von 1200 ppm in den Jahren 2050 und 2100. Die aktuelle Studie basiert auf einem 20-Jahres-Zeitraum; der gewählte Referenzzeitraum (1991-2010) wird in die nahe Zukunft (2045-2065) und die ferne Zukunft (2081-2100) projiziert. Die Szenarien enthalten keine Wärmeeinleitungen, da die Wärmeeinleitungen in der Zukunft nicht bekannt sind und stark von der sozioökonomischen und energetischen Situation in den Rheinanliegerstaaten abhängen. Die sozioökonomischen Einflüsse werden ebenfalls nicht in den Szenariosimulationen berücksichtigt.

In dieser Studie wurden zwei Ansätze gewählt, um die Ergebnisse zu präsentieren. Auf nationaler Ebene nutzt jeder teilnehmende Mitgliedstaat (CH, D, NL) seinen nationalen Modellansatz, einschließlich unterschiedlicher Modellketten zur Simulation des Klimawandels. In einem ersten Schritt hin zu einem einzugsgebietsweiten Ansatz wurden nationale Simulationsergebnisse ausgewählt und als gemeinsames Ergebnis präsentiert. Dazu wurden die nationalen Modelle mit einer gemeinsamen Kombination aus einem globalen Zirkulationsmodell (ECEARTH, Lauf 1) und einem regionalen Klimamodell (KNMI-RACMO) betrieben.

Die Projektionen der zukünftigen Wassertemperaturen basieren auf verfügbaren nationalen hydrologischen Modellen (PREVAH, LARSIM, HYDRAX und SOBEK) zur Simulation der Abflüsse in Kombination mit nationalen Wassertemperaturmodellen, die die zugehörige Wassertemperatur simulieren (air2water, QSim und SOBEK). In dieser Studie wurden die nationalen Modellketten anhand von Wassertemperaturmessungen und tatsächlichen Wärmeeinleitungen für den Zeitraum 2018-2020 validiert. Der Vergleich der validierten Ergebnisse der drei Wassertemperaturmodelle zeigte eine gute Übereinstimmung zwischen simulierten und gemessenen Wassertemperaturen; dies bestätigt, dass alle Modellformulierungen für künftige Projektionen gültig sind.

Zum ersten Mal wurden in Richtung eines einzugsgebietsweiten Ansatzes die nationalen Modellketten offline an den Landesgrenzen bei Basel und Lobith gekoppelt.

Bemerkungen

Der gefolgte Ansatz wurde so weit wie möglich harmonisiert. Aufgrund praktischer Probleme war die Überlappung bei den Klimawandelensembles, die von den drei Ländern genutzt wurden, begrenzt. Auch die Methoden und Modellkonzepte und -formulierungen waren unterschiedlich.

Erwartete Ergebnisse

Im Vergleich zur Bewertung aus dem Jahr 2014 (auf der Grundlage von AR4, 2007) geht die aktuelle Bewertung 2024 (auf der Grundlage von AR5, 2014) von einer (leichten) Erhöhung

der Lufttemperaturen im Jahr 2100, einem geringeren Einfluss der Wärmeeinleitungen, einer Zunahme der Winterabflüsse und Abnahme der Sommerabflüsse in naher und ferner Zukunft aus, da sich das Abflussregime des Rheins von einem schnee- und gletschergespeisten zu einem mehr pluvialem Regime verschiebt (IKSR, 2024).

Erkenntnisse

Die Validierungsstudie für 2018-2020 zeigt, dass der Einfluss der Wärmeeinleitung in Teilen des deutschen Rheins immer noch signifikant ist, was z. B. zu einer durchschnittlichen anthropogenen Erwärmung von 1,33 ºC in Worms und 0,47 ºC in Lobith an der deutsch-niederländischen Grenze führt. Dieser Beitrag ist nicht in den Szenarienläufen berücksichtigt.

Die Studie zeigt, dass in allen Rheinabschnitten wärmere Wassertemperaturen (wT) für die nahe und ferne Zukunft prognostiziert werden. In der nahen Zukunft schwankt die jährliche mittlere wT-Zunahme für das gesamte Einzugsgebiet zwischen +1,1 °C und +1,8 °C und in der fernen Zukunft zwischen +2,9 °C und +4,2 °C. Sommer und Herbst erwärmen sich schneller als das Jahresmittel und Winter und Frühjahr erwärmen sich langsamer. Die Anzahl Tage im Jahr, an denen der Schwellenwert von 25 °C überschritten wird, schwankt zwischen 1-2 Wochen in der nahen Zukunft. Die Überschreitung der Anzahl Tage im Jahr von 28 °C in der fernen Zukunft variiert zwischen 1 ± 0,5 Woche im Jahr. Der Schwellenwert von > 30 °C wird in den Szenarien nicht überschritten.

Im Vergleich zur vorangegangenen Studie sind die Ergebnisse der jährlichen mittleren Erwärmung für die nahe Zukunft ähnlich und für die ferne Zukunft etwas kühler. Die aktuelle Studie zeigt einen Anstieg der Anzahl der Tage < 3 °C für die nahe Zukunft und eine Abnahme der Anzahl der Tage < 3 °C für die ferne Zukunft.

Es wurde z. B. gezeigt, dass das Ensemblemitglied ECE-R1_RAC_RCP85 in den 20-Jahres-Läufen weniger "mainstream" ist, wenn man dessen Position mit der im 30-Jahres-Lauf in Lobith vergleicht. Die Projektionen für die nahe Zukunft sind daher kälter (schätzungsweise -0,1 °C bis -0,6 °C, Kapitel 6.3). Der hier verwendete Bezugszeitraum (1990-2010) ist kälter als der in der vorherigen STEMP-Studie (2000-2010), aber z. B. wärmer als der Zeitraum, der in Deutschland normalerweise genutzt wird und bei dem sogar ältere (und damit kältere) Jahre einbezogen werden.

Die Harmonisierung der nationalen Grenzen war eine wesentliche methodische Verbesserung. Erst nach der Kopplung der nationalen Modelle wurde ein konsistentes einzugsgebietsweites Temperaturprofil mit plausiblen saisonalen Mustern entlang des Rheins simuliert. Daher ist der einzugsgebietsweite Ansatz in seiner derzeitigen Umsetzung immer noch nicht ideal, aber dennoch der Methode, die drei nationale Ansätze zu einem Rhein-wT-Profil kombiniert (wie in Kapitel 5 geschehen), vorzuziehen.

Empfehlungen

Die aktuellen Ergebnisse beruhen auf dem AR5 zu den Treibhausgasemissionen (2014), der vor 10 Jahren veröffentlicht wurde. Die Zeit war zu knapp, um die neuesten Erkenntnisse des AR6 (2021) zu nutzen. Es wird vorgeschlagen, die Aktualisierungshäufigkeit so zu ändern, dass die IKSR Zugang zu Projektionen auf der Grundlage von Klimamodellen hat, die auf den neuesten AR-Treibhausgasemissionen beruhen (innerhalb von 2-3 Jahren sollte dies möglich sein). Zudem sollte das Ziel darin bestehen, die Abfluss- und Temperaturprojektionen gleichzeitig zu aktualisieren, wofür eine engere Zusammenarbeit zwischen den Expertengruppen HCLIM und STEMP in Betracht gezogen werden könnte.

Die in der vorangegangenen Bewertung (10 Jahre) wie auch in der aktuellen Bewertung (20 Jahre) verwendeten Szenariozeiträume beruhten auf pragmatischen Entscheidungen, die getroffen werden mussten, nachdem die nationalen Studien bereits abgeschlossen waren. Kürzere Zeiträume als die erwünschten 30 Jahre in Klimastudien führen zu Verzerrungen der Ergebnisse. Eine vorzeitige Harmonisierung der Szenariozeiträume könnte dies verhindern.

Anstatt wie in dieser Studie nur eine Klimakette zu simulieren, wird eine bessere Abdeckung der Unsicherheit durch die Simulation mehrerer Klimaketten, wie in den nationalen Ansätzen, auch in einem einzugsgebietsweiten Modell erreicht. Die Anrainerstaaten sollten darauf achten, Klimaketten, die für die Größenordnung des Rheineinzugsgebiets repräsentativ sind, in ihre nationalen Analysen einzubeziehen. Den Fokus nur auf die nationale Ebene zu legen, ist für die grenzüberschreitende Modellierung der Wassertemperatur (und der Hydrologie) nicht hilfreich. Bei der nationalen Analyse könnten die Länder die Leistung ihrer ausgewählten Klimaketten auch auf Einzugsgebietsebene betrachten.

Synthèse

Ce rapport est une mise à jour de l'évaluation des effets du changement climatique sur les températures futures de l'eau du Rhin (CIPR, 2014). L'étude est réalisée par le GE STEMP dans le cadre du plan de travail 2022-2027 de la CIPR (tâche III.2) et a été mandatée par le Groupe de travail Qualité de l'eau (GT S). L'évaluation précédente était basée sur le 4e rapport d'évaluation du GIEC (AR4, 2007). Une mise à jour est pertinente, étant donné que le GIEC a actualisé son évaluation du changement climatique dans le rapport AR5 (2014). Les changements survenus dans le réseau de centrales électriques font baisser les apports de chaleur dans le Rhin. En parallèle, la modélisation de la température de l'eau a désormais une résolution spatiale et temporelle plus élevée et de meilleures options existent pour inclure la variabilité climatique. En outre, la couverture géographique est élargie et inclut le tronçon rhénan suisse et les bras du Rhin néerlandais dans le delta.

Méthode

Les scénarios futurs présentés dans cette étude se rapportent à l'étude des scénarios climatiques du cinquième rapport d'évaluation (AR5) du GIEC (GIEC, 2014) avec pour horizons futurs 2050 et 2100. Toutes les chaînes climatiques de cette étude sont basées sur le scénario RCP8.5 d'émissions les plus élevées. Ce scénario est souvent appelé « business as usual ». Dans ce scénario, la trajectoire représentative de concentration présente des concentrations d'équivalent CO_2 de 1200 ppm en 2050 et en 2100. L'étude actuelle se base sur une période de 20 ans ; la période de référence retenue (1991-2010) est projetée dans un futur proche (2045-2065) et dans un futur lointain (2081-2100). Les apports de chaleur ne sont pas inclus dans les scénarios, car les futurs rejets thermiques ne sont pas connus et dépendent fortement de la situation socio-économique et énergétique des pays riverains du Rhin. Les impacts socio-économiques ne sont pas non plus pris en compte dans les simulations des scénarios.

Dans cette étude, deux approches ont été choisies pour présenter les résultats. Au niveau national, chaque État membre participant (CH, D, NL) utilise sa modélisation nationale, y compris différentes chaînes de modèles pour simuler le changement climatique. La première étape vers une approche à l'échelle du bassin a consisté à faire une sélection des résultats des simulations nationales et de les présenter sous forme de résultat commun. Pour ce faire, les modèles nationaux ont été forcés avec une combinaison commune d'un modèle de circulation générale (ECEARTH, run 1) et d'un modèle climatique régional (KNMI-RACMO).

Les projections des futures températures de l'eau sont basées sur les modèles hydrologiques nationaux disponibles (PREVAH, LARSIM, HYDRAX et SOBEK) pour la simulation du débit fluviaux, en combinaison avec les modèles nationaux de température de l'eau qui simulent la température de l'eau associée (air2water, QSim et SOBEK). Dans cette étude, les chaînes de modélisation nationales ont été validées à l'aide des mesures de la température de l'eau et des rejets thermiques réels pour la période 2018-2020. La comparaison des résultats de la validation des trois modèles de température de l'eau a montré une bonne concordance entre les températures de l'eau simulées et celles mesurées, ce qui prouve que toutes les formulations de modélisation sont valables pour les projections futures.

Pour la première fois à l'échelle du bassin, les chaînes de modélisation nationales ont été couplées hors ligne aux frontières nationales de Bâle et de Lobith.

Remarques

L'approche suivie a été harmonisée dans la plus grande mesure possible. En raison de contraintes pratiques, il n'y a eu que peu de recoupements entre les ensembles du changement climatique utilisés par les trois pays. Les méthodes et les concepts et formulations de modélisation étaient également différents.

Résultats attendus

Par rapport à l'évaluation réalisée en 2014 (basée sur AR4, 2007), l'évaluation actuelle de 2024 (basée sur AR5, 2014) prévoit que les températures de l'air seront (légèrement) plus élevées en 2100, que l'influence des apports thermiques sera plus faible, que les débits hivernaux augmenteront et les débits estivaux diminueront dans un avenir proche et un avenir lointain en raison du passage d'un régime hydrologique du Rhin alimenté par la fonte des neiges et des glaciers à un régime davantage alimenté par la pluie (CIPR, 2024).

Résultats

L'étude de validation pour 2018-2020 montre que l'influence des apports thermiques est encore significative dans certaines parties du Rhin allemand, ce qui se traduit par exemple par un réchauffement anthropique moyen de 1,33 ºC à Worms et de 0,47 ºC à Lobith à la frontière germano-néerlandaise. Cette contribution n'est pas incluse dans les runs des scénarios.

L'étude montre que des températures de l'eau (wT) plus élevées sont attendues dans un avenir proche et lointain dans tous les tronçons du Rhin. Dans un avenir proche, l'augmentation de la température moyenne de l'eau par an à l'échelle du bassin varie de +1,1 à +1,8 °C, tandis qu'elle varie de +2,9 à +4,2 °C dans un avenir lointain. Le réchauffement est plus rapide en été et à l'automne qu'en moyenne annuelle et est plus lent à l'hiver et au printemps. Le nombre de jours par an où le seuil de 25 °C est dépassé oscille entre 1 et 2 semaines dans un avenir proche. Dans un avenir lointain, la température de 28 °C est dépassée entre 1 ± 0,5 semaine par an. Le seuil de 30 °C n'est pas dépassé dans les scénarios.

Comparés à l'étude précédente, les résultats du réchauffement annuel moyen restent similaires pour l'avenir proche, mais légèrement plus froids pour l'avenir lointain. Dans un avenir proche, le nombre de jours < 3 °C augmente dans l'étude actuelle, tandis qu'il diminue dans un avenir lointain.

Il a par exemple été démontré que le membre de l'ensemble ECE-R1_RAC_RCP85 est moins « conventionnel » dans les runs de 20 ans lorsque l'on compare sa position à celle d'un run de 30 ans à Lobith. Les projections pour l'avenir proche sont donc plus froides (estimation de -0,1 à -0,6 °C, chapitre 6.3). La période de référence utilisée ici (1990-2010) est plus froide que celle de l'étude STEMP précédente (2000-2010), mais par exemple plus chaude que celle habituellement utilisée en Allemagne, où des années encore plus anciennes (et donc plus froides) sont incluses.

L'harmonisation des frontières nationales a constitué une amélioration méthodologique significative. Ce n'est qu'après le couplage des modèles nationaux qu'a pu être simulé un profil de température cohérent à l'échelle du bassin, avec des schémas saisonniers plausibles le long du Rhin. Certes, l'approche à l'échelle du bassin n'est pas encore idéale dans son application actuelle, mais elle est néanmoins préférable à la méthode consistant à combiner les trois approches nationales pour obtenir un profil des températures de l'eau du Rhin (comme il a été fait dans le chapitre 5).

Recommandations

Les conclusions actuelles sont basées sur les émissions de gaz à effet de serre du rapport AR5 (2014), publié il y a 10 ans. Le temps a manqué pour exploiter les dernières conclusions du rapport AR6 (2021). Il est suggéré de modifier la fréquence de mise à jour afin que la CIPR ait accès à des projections basées sur des modèles climatiques utilisant les dernières émissions de GES de l'AR (il devrait être possible de le faire dans les 2 à 3 prochaines années). En outre, l'objectif devrait être de mettre à jour simultanément les projections de débit et de température, ce qui amène à envisager une coopération plus étroite entre le GE HCLIM et le GE STEMP.

Les périodes couvertes par les scénarios utilisées dans l'évaluation précédente (10 ans) ainsi que dans l'évaluation actuelle (20 ans) étaient basées sur des choix pragmatiques qui ont dû être faits après que les études nationales aient été achevées. Les périodes plus courtes que la norme de 30 ans souhaitée dans les études climatiques introduisent des biais dans les résultats. L'harmonisation préalable des périodes couvertes par les scénarios peut empêcher ce biais.

Plutôt que de simuler une seule chaîne climatique comme dans cette étude, on obtient une meilleure couverture de l'incertitude en simulant plusieurs chaînes climatiques dans un modèle à l'échelle du bassin également, comme cela est fait dans les approches nationales. Les États riverains doivent veiller à inclure dans leur analyse nationale des chaînes climatiques représentatives à l'échelle du bassin versant du Rhin. Se concentrer uniquement sur une échelle nationale est contreproductif pour la modélisation transfrontalière de la température de l'eau (et de l'hydrologie). Dans le cadre de l'analyse nationale, les pays pourraient étudier les performances de leur sélection de chaîne climatique à l'échelle du bassin également.

Samenvatting

Dit rapport is een actualisering van de beoordeling van de effecten van de klimaatverandering op de toekomstige watertemperatuur van de Rijn (ICBR, 2014). De studie is uitgevoerd door de EG STEMP als onderdeel van het ICBR-werkprogramma 2022-2027 (taak III.2) en onder het mandaat van de werkgroep Waterkwaliteit (WG S). De vorige beoordeling was gebaseerd op het 4e evaluatierapport van het IPCC (Assessment Report AR4, 2007). Een update is relevant, omdat het IPCC zijn evaluatie van de klimaatverandering heeft bijgewerkt in AR5 (2014). Ook wordt er minder warmte geloosd op de Rijn door veranderingen in het netwerk van energiecentrales. Daarnaast heeft het modelleringskader voor watertemperatuur nu een hogere ruimtelijke en temporele resolutie en betere opties om klimaatvariabiliteit mee te nemen. Bovendien is het geografische gebied waarop de studie betrekking heeft uitgebreid met de Zwitserse Rijn en de Nederlandse Rijntakken.

Methode

De toekomstscenario's in deze studie zijn gerelateerd aan de studie naar klimaatscenario's van het IPCC ''AR5'' (IPCC, 2014) met zichtjaren rond 2050 en 2100. Alle klimaatketens in deze studie zijn gebaseerd op het hoogste emissiescenario RCP8.5. Dit scenario wordt vaak ''business as usual'' genoemd. In dit representatieve concentratiescenario is er sprake van equivalente CO_2-concentraties van 1200 ppm in 2050 en 2100. De huidige studie is gebaseerd op een periode van 20 jaar, waarbij de geselecteerde referentieperiode (1991-2010) wordt geprojecteerd naar de nabije toekomst (2045-2065) en de verre toekomst (2081-2100). Warmte-emissies zijn niet opgenomen in de scenario's, omdat toekomstige warmtelozingen onbekend zijn en sterk afhangen van de sociaal-economische en energiesituatie in de Rijnoeverstaten. Sociaal-economische invloeden zijn ook niet opgenomen in de scenariosimulaties.

In dit onderzoek zijn er twee benaderingen gekozen om de resultaten te presenteren. Op nationaal niveau gebruikt elke deelnemende lidstaat (CH, DE, NL) zijn nationale modelaanpak, inclusief verschillende modelketen(s) om klimaatverandering te simuleren. Als eerste stap in de richting van een stroomgebiedbrede aanpak is een selectie gemaakt van de nationale simulatieresultaten en deze werden als gemeenschappelijk resultaat gepresenteerd. Hiervoor werd in de nationale modellen een gemeenschappelijke combinatie van een mondiaal circulatiemodel (ECEARTH, run 1) en een regionaal klimaatmodel (KNMI-RACMO) als input gebruikt.

De projecties van toekomstige watertemperaturen zijn gebaseerd op beschikbare nationale hydrologische modellen voor de simulatie van rivierafvoer (PREVAH, LARSIM, HYDRAX en SOBEK), in combinatie met nationale watertemperatuurmodellen die de bijbehorende watertemperatuur simuleren (air2water, QSim en SOBEK). In deze studie werden de nationale modelketens gevalideerd met behulp van watertemperatuurmetingen en reële warmtelozingen voor de periode 2018-2020. De vergelijking van de validatieresultaten van de drie watertemperatuurmodellen toonde een goede overeenkomst tussen de gesimuleerde en gemeten watertemperaturen, wat bevestigt dat alle modelformuleringen kunnen worden gebruikt voor toekomstige projecties.

Voor het eerst werden op weg naar een stroomgebiedbrede benadering de nationale modelketens aan de nationale grenzen bij Bazel en Lobith offline aan elkaar gekoppeld.

Opmerkingen

De gevolgde aanpak is zoveel mogelijk geharmoniseerd. Vanwege praktische beperkingen was de overlap tussen de ensembles voor klimaatverandering die door de drie landen worden gebruikt beperkt. Ook de methodes en modelopbouw en -formulering verschilden.

Verwachte resultaten

Vergeleken met de beoordeling in 2014 (gebaseerd op AR4, 2007), wordt in de huidige beoordeling in 2024 (gebaseerd op AR5, 2014) verwacht dat de luchttemperaturen in 2100 (iets) hoger zullen zijn, dat de invloed van warmtelozingen zal afnemen, dat de

winterafvoeren zullen toenemen en de zomerafvoeren zullen afnemen in de nabije en de verre toekomst als gevolg van een verschuiving van een door sneeuw en gletsjers gevoed afvoerregime naar een meer door regen gevoed afvoerregime in de Rijn (ICBR, 2024).

Bevindingen

De validatiestudie voor 2018-2020 laat zien dat de invloed van warmtelozingen nog steeds aanzienlijk is in delen van de Duitse Rijn, wat bijvoorbeeld resulteert in een gemiddelde antropogene opwarming van 1,33 ºC bij Worms en 0,47 ºC bij Lobith aan de Duits-Nederlandse grens. Deze bijdrage is niet meegenomen in de scenarioruns.

Uit het onderzoek blijkt dat er op alle Rijntrajecten voor de nabije en de verre toekomst warmere watertemperaturen (wT) worden verwacht. In de nabije toekomst varieert de jaargemiddelde wT-stijging in het hele stroomgebied tussen +1,1 en +1,8 °C, in de verre toekomst varieert de jaargemiddelde wT-stijging in het hele stroomgebied tussen +2,9 en +4,2 °C. In de zomer en de herfst gaat de opwarming sneller dan het jaargemiddelde en in de winter en de lente trager. Het aantal dagen per jaar dat de drempel van 25 °C wordt overschreden, varieert tussen 1-2 weken in de nabije toekomst. In de verre toekomst schommelt het aantal dagen met overschrijding van 28 °C tussen 1 ± 0,5 week per jaar. De drempel van 30 °C wordt in de scenario's niet overschreden.

Vergeleken met de vorige studie zijn de resultaten voor de jaargemiddelde opwarming vergelijkbaar voor de nabije toekomst en iets koeler voor de verre toekomst. In de huidige studie is het aantal dagen < 3 °C in de nabije toekomst toegenomen en in de verre toekomst afgenomen.

Er is bijvoorbeeld aangetoond dat ensemblelid ECE-R1_RAC_RCP85 in de 20-jaarsrun minder ''mainstream'' is dan wanneer zijn positie wordt vergeleken met die in de 30-jaarsrun bij Lobith. De projecties voor de nabije toekomst zijn daarom kouder (naar schatting -0,1 tot -0,6 °C, zie hoofdstuk 6.3). De referentieperiode die hier wordt gebruikt (1990-2010) is kouder dan in de vorige STEMP-studie (2000-2010), maar bijvoorbeeld warmer dan wat normaal wordt toegepast in Duitsland, waar zelfs oudere (en dus koudere) jaren worden opgenomen.

De harmonisatie van de nationale grenzen was een belangrijke verbetering in de methode. Pas na koppeling van de nationale modellen werd een consistent stroomgebiedbreed temperatuurprofiel met plausibele seizoenspatronen over de Rijn gesimuleerd. De stroomgebiedbrede aanpak is in zijn huidige uitvoering dus nog niet ideaal, maar verdient desondanks de voorkeur boven de methode waarbij de drie nationale benaderingen worden gecombineerd tot een wT-profiel voor de Rijn (zoals gedaan in hoofdstuk 5).

Aanbevelingen

De huidige bevindingen zijn gebaseerd op broeikasgasemissies in AR5 (2014), dat tien jaar geleden werd gepubliceerd. De tijd was te kort om de nieuwste AR6-bevindingen (2021) te gebruiken. Er wordt voorgesteld om de actualiseringsfrequentie zodanig aan te passen dat de ICBR toegang heeft tot projecties met klimaatmodellen die zijn gebaseerd op de meest recente AR-broeikasgasemissies (binnen 2-3 jaar zou mogelijk moeten zijn). Bovendien moet worden gestreefd naar een gelijktijdige actualisering van de afvoer- en temperatuurprojecties, waarvoor een nauwere samenwerking tussen de expertgroepen HCLIM en STEMP kan worden overwogen.

De scenarioperiodes die in de vorige beoordeling (10 jaar) en in de huidige beoordeling (20 jaar) zijn gebruikt, waren gebaseerd op pragmatische keuzes die moesten worden gemaakt, nadat de nationale studies al waren afgerond. Periodes die korter zijn dan de gewenste standaard van 30 jaar in klimaatstudies vertekenen de resultaten. Voorafgaande harmonisatie van scenarioperiodes kan dit voorkomen.

In plaats van één klimaatketen te simuleren zoals in deze studie, wordt een betere dekking van de onzekerheid verkregen door ook in een model voor het hele stroomgebied meerdere klimaatketens te simuleren, zoals in de nationale benaderingen wordt gedaan. De oeverstaten moeten ervoor zorgen dat zij in hun nationale analyse klimaatketens opnemen die representatief zijn voor de schaal van het Rijnstroomgebied. Focus op alleen de nationale schaal is niet nuttig voor grensoverschrijdende modellering van de watertemperatuur (en hydrologie). In het kader van de nationale analyse kunnen landen ook kijken naar de prestaties van hun selectie van klimaatketens op stroomgebiedniveau.

2 Introduction

2.1 Background, earlier study (ICPR technical reports no. 214 and no. 188)

In 2014, the expert group "water temperature" (EG STEMP) assessed the effects of climate change on future Rhine water temperature on the basin preparation for the 15th Rhine ministers conference. The study was based on the 4th assessment of the IPCC (AR4, 2007), selected simulation models were used for the prognosis.

Important input was given by EG HCLIM (former EG KLIMA). They provided so called "change vectors" for two future periods (2021-2050 and 2071-2100) for seasonally averaged meteorological variables (air temperature etc.) and for summer and winter Rhine discharge. The changes were based on the model chain depicted in (ICPR, 2011). The synthesis was also based on the results of the International Commission for the Hydrology of the Rhine basin (CHR) project RheinBlick2050 using a reduced number of climate projections. The simulated fields for air temperature, precipitation and global radiation were checked for plausibility and were bias corrected before the input to gauging stations in the Rhine catchment. For EG STEMP, the mean discharge (MQ) and the minimum discharge averaged over 7 days (NM_7Q) per half year were used. This resulted in a future scenario matrix which used medians for the near and far future combined with high and low discharge members.

The change vectors were used to model the future water temperature by applying them to a reference simulation (reference period: 2001-2010). For the reference period, the simulation models were forced with measured data (meteorology, discharge, water temperature). For practical reasons, thermal heat input in the reference period was based on (50 % of) permitted heat input.

Three partly overlapping models were used to cover the Rhine from Basel to the Netherlands (Rhine-km 150-950) allowing inter model comparison which was deemed necessary at that time. There were six model runs: reference, reference without anthropogenic heat input and four future scenarios. Results were presented as longitudinal profiles (with Rhine kilometres on the horizontal axis) of average summer temperatures for the various scenarios and statistically presenting the change in the number of days per year when water temperature exceeded 25 °C and 28 °C and underrun 3 °C.

Some conclusions were:

- The extreme conditions experienced in August 2003 may serve as a model for the average summer situation in the far future (2071–2100).
- The number of days exceeding 25 °C is predicted to double on average in the near future.
- The number of days exceeding 28 °C is predicted to double on average in the far future.
- The number of days with water temperatures below 3 °C in the reference situation is small already and does not decrease much further in the future.
- Although the reference period (2001-2010) is characterized by strong variations in water temperature and river discharge, it is a relatively short period compared to the 30 years usually used to define climate.

2.2 Assignment of EG STEMP

As part of the ICPR working plan 2022-2027, the EG STEMP has the task to update the projections for water temperature in the Rhine based on climate change scenarios by 2024 (cf. mandate of WG S, task III.2). This is a follow up of the ICPR technical report no. 214 (ICPR, 2014). The update is relevant for several reasons. First, the IPCC has updated its assessment of climate change in AR5 (2014). In AR5, the global climate models include e. g. a coupled carbon cycle and new greenhouse gas (GHG) emission scenarios. Second, due to changes in the powerplant network, less heat is discharged into the Rhine nowadays.

What can be expected comparing the current assessment in 2024 (based on AR5, 2014) to the assessment made in 2014 (based on AR4, 2007):

- (slightly) higher air temperature in 2100
- less influence of heat inputs (Deltares, 2022)
- discharge projections point to increasing winter discharge and decreasing summer discharge in the near and far future as a result of a shift from snow- and glacier-fed to a more rain-fed flow regime of the Rhine (ICPR, 2024)

In addition, an advanced methodology to reflect climate change is expected to improve results in this report:

- a longer 20-year instead of 10-year reference period that includes a higher variability
- long-time 20-year periods including daily resolved, simulated time series (D and CH) instead of applying of constant climate change vectors (NL and former ICPR report no. 214) to reflect climate change
- inclusion of the Dutch part of the Rhine delta
- extended cooperation: inclusion of the Swiss part of the Rhine

2.3 Approach to the assignment

The countries involved in the modelling (CH, D, NL) have finished their modelling work with AR5 data in the past (2019-2023) and in parts started working with the 6th IPCC assessment report (AR 6) results now (NL, D). Since the time frame for EG STEMP was relatively short, the current effort made use of existing models and, as much as possible, of existing model results and data. Germany carried out further modelling work during this study to cover a longer stretch of the Rhine.

On a national level, each modelling member state used its national model chains for the simulation of river discharge and water temperature. In this national approach, each country was responsible for the conditions at the national boundary like the discharge and water temperature in future scenarios. These may e. g. be based on empirical relationships between air and water temperature. The number of different climate chains (Global Circulation Models and Regional Climate Models) used to evaluate the future water temperature differed per country, and therefore the amount of uncertainty included. Details of the approach and results are reported in chapter 5.

For consistent basin-wide climate impact projections, the contributing national models must be based on the same climate signal. For the highest emission scenario RCP8.5 there is only one common climate model chain used in the three national approaches (namely ECEarth-RACMO_1). Using a single model chain limits the assessment of variability. Nevertheless, as a first step towards a basin-wide approach the results of applying a common climate chain are described in chapter 6.

The national models (for Germany and the Netherlands) using the common climate chain are also applied in an offline "coupled" approach. In the coupled approach, the conditions at the national boundaries follow from the result of the model applied to the upstream part of the Rhine, performed by the neighbouring country. The table 2-1 summarises this. For Switzerland, there is only one approach as the source of the Rhine lies in Switzerland.

The common coupled approach is followed to see if model results and conclusions change when countries harmonize their modelling efforts and whether further harmonization would be favourable. The findings of this first attempt to a basin-wide approach are reported in chapter 6.

Table 2-1 Boundary conditions at the national borders in the different simulation approaches.

Boundary condition	**D**	**NL**
National approach	national estimate* Germany Weil am Rhein (D)	national estimate* Netherlands Lobith (NL)
Coupled approach	model result Switzerland Weil am Rhein (CH)	model result Germany Bimmen (D)
* estimates can be national models or relationships, details in chapter 3.3		

3 Study area and models used

This chapter starts with a description of the study area, the Rhine basin in chapter 3.1, followed by two chapters describing the models. Chapter 3.2 starts with the modelled area followed by chapter 3.3 in which the national models covering the model area are briefly introduced. For details of the models see the appendix in chapter 10.

3.1 The Rhine basin

The mainstream Rhine and its tributaries are divided into six sections (Alpine Rhine / Lake Constance, High Rhine, Upper Rhine, Middle Rhine, Lower Rhine, Delta Rhine) connecting the Alps to the North Sea (Figure 3-1). *Figure 3-1*The description below is composed from the ICPR-website.

This model study does not include the 'Alpine Rhine' as the modelling starts downstream of Lake Constance. The 'High Rhine' begins at Stein am Rhein, at the outlet of Lake Constance (Untersee) and is governed by eleven barrages. After the confluence with the River Aare, the mean discharge almost doubles near Rhine-km 103.

The 'Upper Rhine' is the river section between Basel and Bingen and has high discharge in early summer, which is due to snow melt in the Alps. The River Ill is an about 220 km long left bank tributary to the French Upper Rhine, the largest Rhine tributary in Alsace entering the Rhine downstream the Gambsheim barrage, near Strasbourg, at Rhine-km 311.3.

In the 'Middle Rhine' between Bingen and Bonn, the Rhine flows in a steep and narrow valley draining the Rhenish Massif (Rheinisches Schiefergebirge). The Lahn and Moselle (at Koblenz) join the Rhine in this section (UNESCO cultural heritage).

The Rhine widens its course entering the 'Lower Rhine' (Bonn to Dutch border), passing Cologne. Before there were dikes, the Rhine used to meander here. It now enters a densely populated and industrialised area. Near the German-Dutch border, the Rhine is more than 700 m wide before entering the Delta Rhine.

The 'Delta Rhine' in the Netherlands (Lobith to North Sea) has two west-facing Rhine branches. The various often interconnected river arms are linked in their lower reaches to the River Meuse in many places with which they form the Rhine-Meuse estuary. This network is partly natural, partly artificial.

The southern branch ('Waal', 'Merwede', 'Noord' and 'Nieuwe Maas' and finally 'Nieuwe Waterweg') is the largest and most important river course in the delta area and carries two-thirds of the Rhine water. This is the mainstream that also follows the Rhine kilometre line. The branch further north ('Nederrijn') eventually returns to the 'Nieuwe Maas'. From the Nederrijn splits off the northern branch, the 'IJssel'.

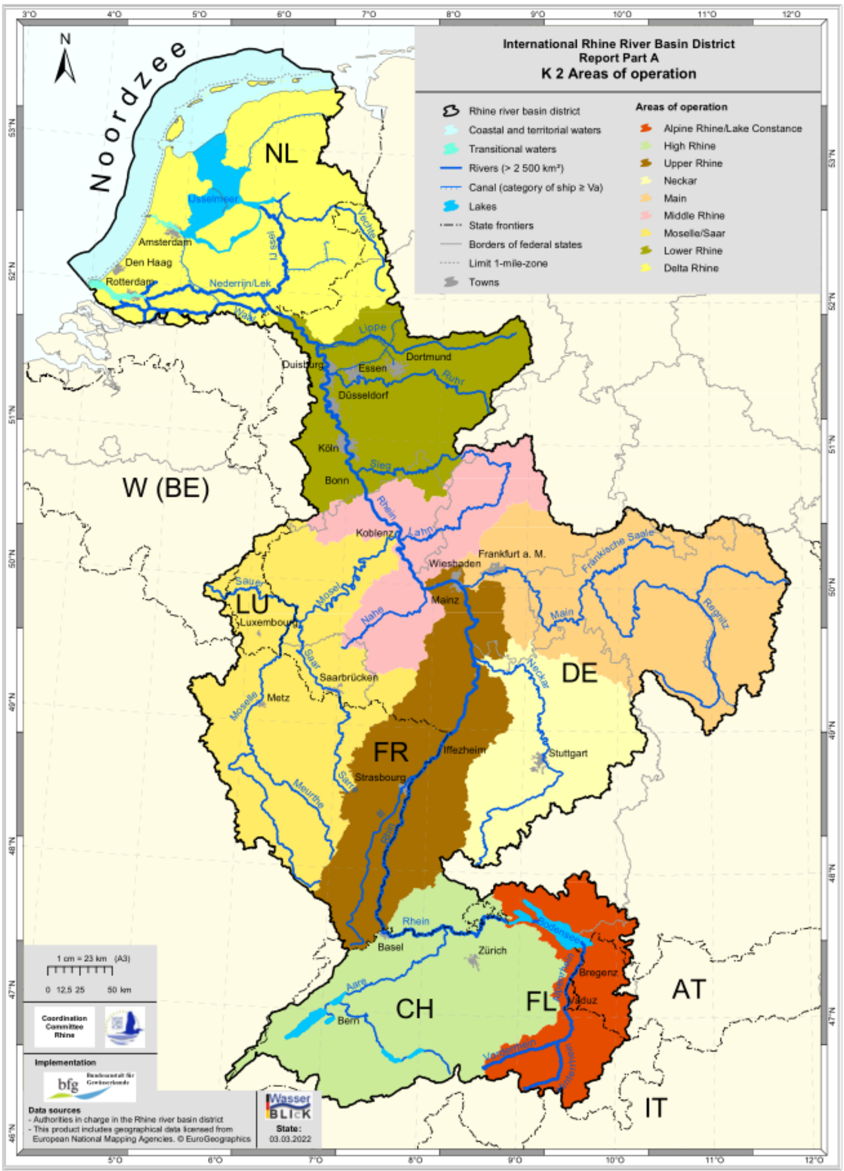


Figure 3-1 Rhine basin showing the River Rhine and its larger tributaries.

3.2 Model area

The models cover parts of the full Rhine basin (chapter 3.1) focussing on the main branch of the River Rhine. In Switzerland, the alpine region is excluded, in Germany tributaries are not simulated, but are represented by data from a gauging or monitoring station placed near to the mainstream of the Rhine and in the Netherlands the North Sea is excluded.

Figure 3-2 shows the model domain viz. the main stem of the Rhine (purple) and its major tributaries (blue). Boundaries of the Rhine model domain are located at all confluences of tributaries with the main stem (not explicitly marked in this figure). Tributaries are not modelled but fed with discharge data collected from monitoring stations as close to the confluence with the Rhine as possible. Tables Table 4-2 to Table 4-4 list these monitoring and gauging stations including station name and average discharge for 2018-2020 (MQ) and data sources used. Water temperature of tributaries are either based on measurements or on empirical relationships with air temperature or air temperature and discharge.

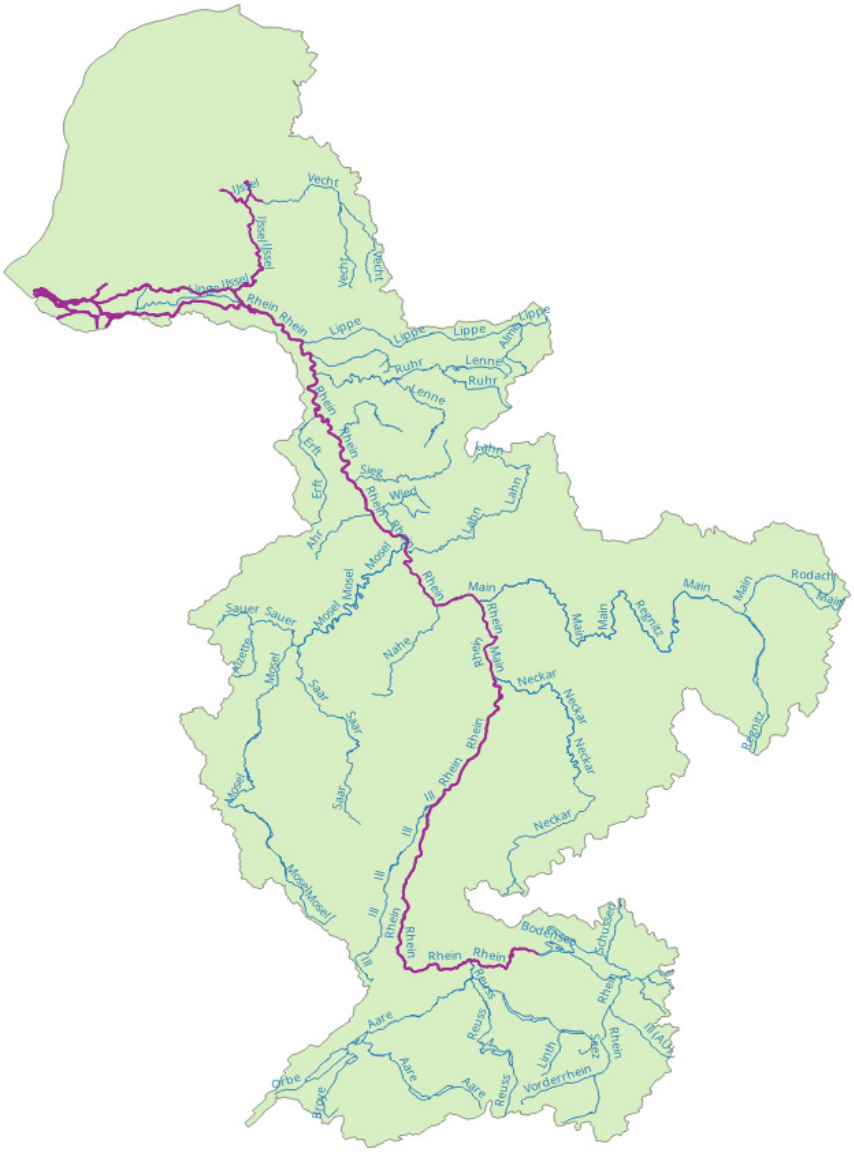


Figure 3-2 Model domain used (purple) to simulate the water temperature in the Rhine basin from Switzerland (Rheinau, Rhine-km 56) to the Netherlands (Hoek van Holland, Rhine-km 1030). The tributaries (blue) are outside the model domain and referred to as model boundaries.

Figure 3-3 shows heat inputs and locations with measurements for model validation.

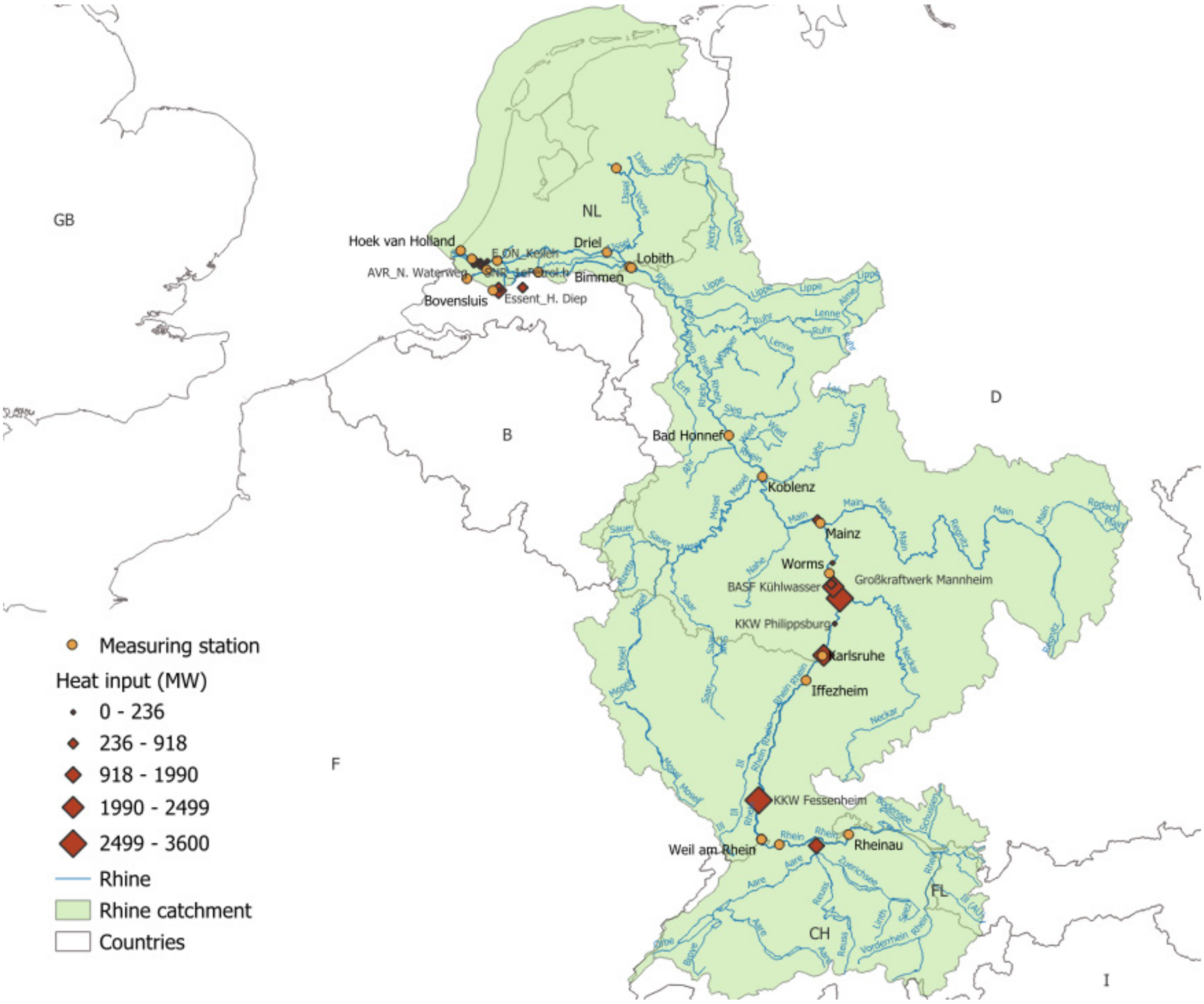


Figure 3-3 Permitted heat input locations (red) along the River Rhine model area (green) and measuring stations for validation of the models (orange).

3.3 Models

3.3.1 air2water

In Switzerland, the *air2water* (Piccolroaz et al., 2013)[1] surface water temperature model is used. The lake model is classified as a lumped model as it lumps complex physics like stratification and meteorological forcing. The *air2water* model can be classified as a hybrid model which combines a physically based equation with a stochastic calibration of model parameters to estimate water temperatures. The model code is available at https://github.com/spic-colroaz/air2water.

The model identifies parameters (a_1 to a_8) for weighing physically dependent processes through a Monte-Carlo calibration process. In the application for this study on the Rhine a six-parameter version of the model fits best to the available data without over-parameterisation. The parameters of the *air2water* model are calibrated for different air station and water station pairs.

[1] https://github.com/marcotoffolon/air2water

The model formula for the six-parameter version (parameters a_1 to a_6) is shown below where t is the time in days, t_y is the duration of the year expressed in days, T_a the air temperature, T_w the water temperature and T_r the reference temperature for deeper layers of the lake (hypolimnion). δ is the dimensionless volume (or depth) defined as the ratio between the reactive volume (influenced by atmospheric conditions) and the reference volume being the entire volume of the lake. For unstratified lakes $\delta = 1$, decreasing when the water temperatures (T_w) exceed the reference temperature (T_r) during periods of thermal stratification. The six-parameter version assumes that the lake does not become inversely stratified.

The equations are solved together numerically resulting in a daily (Δt) water temperature change (ΔT_w).

$$\frac{\Delta T_w}{\Delta t} = \frac{1}{\delta}\left\{a_1 + a_2 T_a - a_3 T_w + a_5 \cos\left[2\pi\left(\frac{t}{t_y} - a_6\right)\right]\right\} \quad (1)$$

$$\delta = exp\left(-\frac{T_w - T_r}{a_4}\right) \quad \text{for} \quad (T_w \geq T_r)$$

$$\delta = 1 \quad \text{for} \quad (T_w < T_r)$$

The model links water temperature and discharge measured at BAFU stations along the Rhine to air temperature measured at meteorological stations (Figure 3-4) as follows.

Table 3-1 List of weather stations assigned along the River Rhine.

Meteorological station	**Measurement station Rhine**	**Coordinates meteorological station (latitude, longitude)**
Zurich Fluntern (SHA)	Neuhausen Flurlingerbrücke (2288) Rheinau (2392)	47.380942, 8.567358
Zurich airport (KLO)	Rekingen (2143)	47.478383, 8.530164
Ruenenberg (RUE)	Laufenburg (2130)	47.434572, 7.879414
Basel (BAS)	Rheinfelden (2091) Weil am Rhein (2613)	47.541142, 7.583525

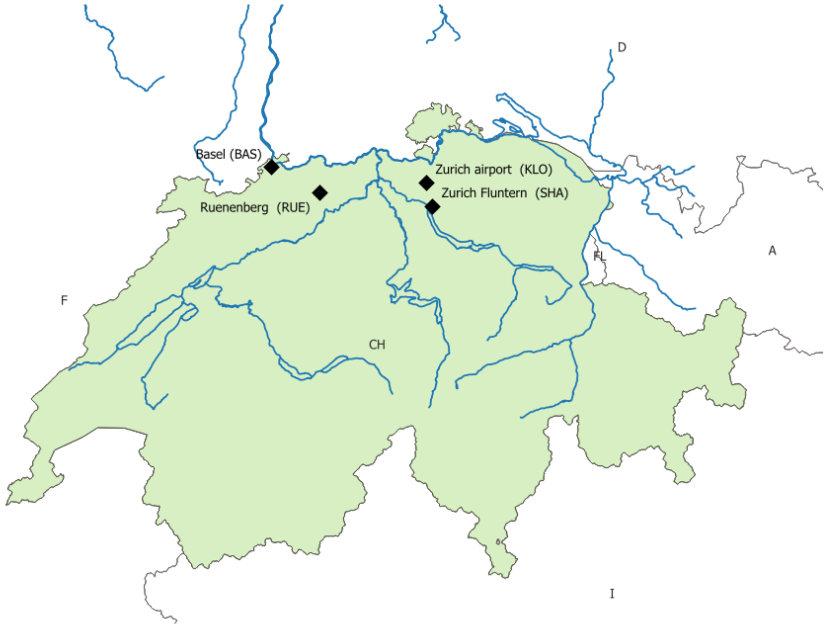


Figure 3-4 Location of meteorological stations used (see Table 4-1).

3.3.2 QSim & HYDRAX

To model the temperature regime of the German part of the Rhine, the water quality model QSim (Schöl et al., 2014) of the BfG is used. QSim is coupled with the one-dimensional hydrodynamic model HYDRAX (BfG-2088, 2021) integrated together in a common graphical user interface called GERRIS. QSim is a deterministic model, meaning that the processes relevant for the temperature regime of a river are described functionally in the form of differential and algebraic equations without any stochastic effect. The identification and parameterisation of the mathematical functions are based on published scientific knowledge or on one's own experimental results.

The driving forces of the water temperature module of QSim are the discharge at the upper model boundary (the starting point of the model section) and of the main tributaries, as well as meteorological conditions (global radiation, air temperature, evaporation, cloudiness, wind velocity) and heat input. All variables in QSim depending on solar radiation (including the temperature module) are modelled dynamically at an interval of one hour. The module used to simulate the water temperature in QSim is described in detail in the related ICPR technical report no. 214 in appendix D (ICPR, 2014).

For this report, the QSim version "1d_14.08", the HYDRAX version "5.0.27.0" and the GERRIS version "2.1.14.873" were used.

The QSim model covers the Rhine stretch from Basel (Rhine-km 164) to Lobith (Rhine-km 865) (Figure 3-5). The morphological conditions of this 700 km Rhine stretch are derived from gauged cross sections. The same Rhine model from the last ICPR report is used for the stretch from Karlsruhe to Bimmen from 2004 from gauged cross sections at every 500 m (digital terrain model (DGM) WSD West P-2004, Rhine-km 862-336.5). The Upper Rhine model from Basel to Karlsruhe was newly constructed using cross sections between 100-500 m distance (DGM W Oberrhein 2010 Rhine-km 164.1-336.3).

Data from ten weather stations are used in QSim (Figure 3-5). A total of 22 major tributaries and eight heat input sites as shown in Figure 3-5 are considered. Discharge and water temperature data for the tributaries were taken from the gauging or monitoring station nearest to the confluence of the tributary and the Rhine.

HYDRAX-QSim uses input from the hydrological model LARSIM for the climate simulations.

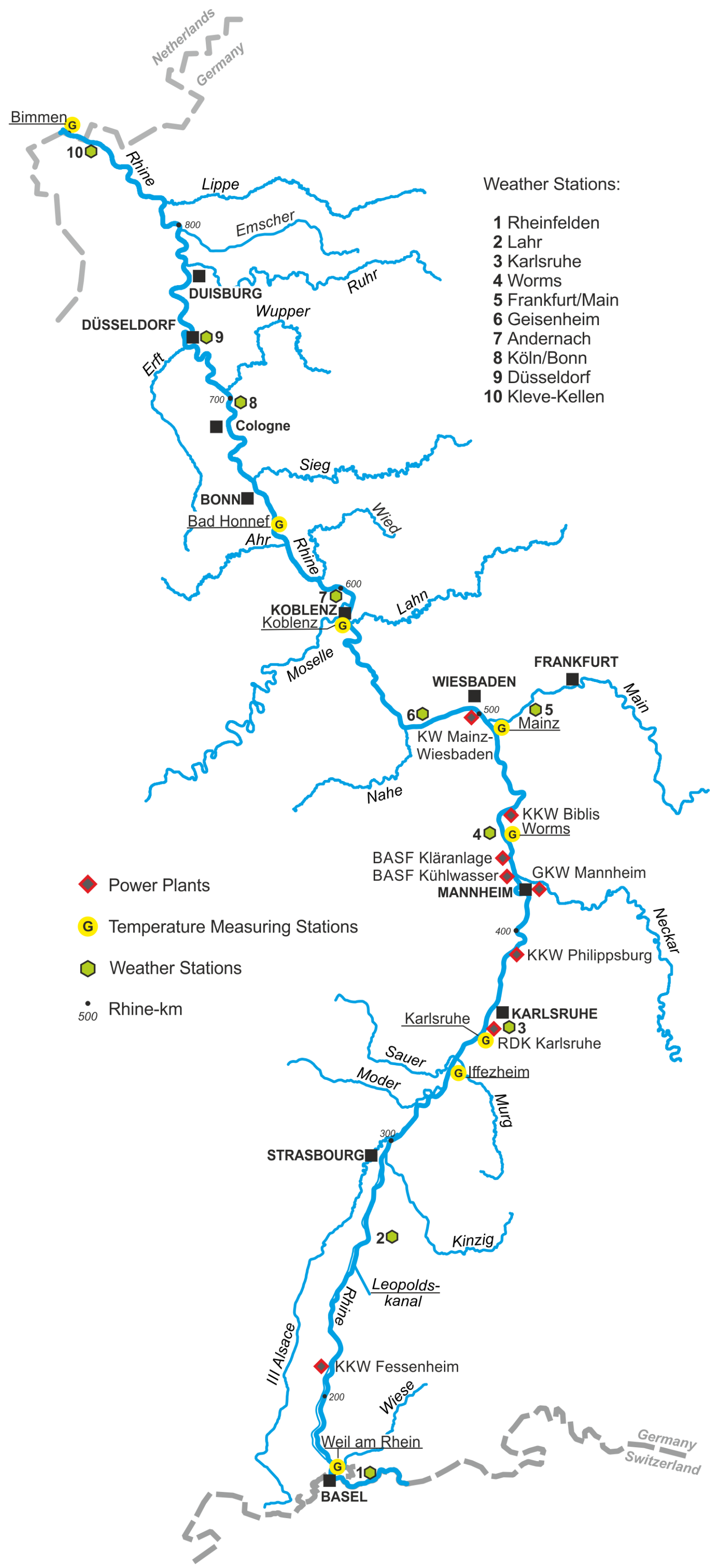


Figure 3-5 QSim schematisation of the Rhine from Basel (Rhine-km 164) to Bimmen (Rhine-km 865). The implemented heat input sites, tributaries, water temperature and weather measuring stations are shown.

3.3.3 SOBEK

The water temperature model is part of the water quality model D-WAQ (Delft Water quality model) and has a set of deterministic formulations describing the water atmosphere heat exchange similar to QSim. Formulations are described in Delft3D-FLOW User Manual (chapter 9.8). D-WAQ is part of and coupled with the one-dimensional hydrodynamic model SOBEK described in ICPR technical report no. 214 (ICPR, 2014).

Boundary conditions for SOBEK are simulated by a set of models referred to as National Hydrological Model (LHM, https://publicwiki.deltares.nl/display/LHM), which is a national coverage ground and surface water model (on a daily basis with a spatial resolution of 250x250 m) integrated with water balance and distribution of regional surface waters including canals. It may be considered the delta (not free flowing) equivalent of a rainfall runoff model like HBV. Distribution of water is, notably in summer, influenced by water demand for agriculture, the latter is also simulated in LHM. Next to climate change effects this national model framework is also used to simulate socio-economic scenarios with changes in land use and subsequent on water demands[2].

In the western part of the Netherlands there is salt intrusion into the rivers which causes density stratification. The 1D model cannot represent this physical phenomenon. Salt intrusion is therefore modelled by using velocity dependent dispersion which is calibrated using salt measurement. The 1D temperature model in this area has not been calibrated for water temperature and therefore is expected to perform less accurate compared to regions without density stratification.

The focus in this study lies on the Rhine branches but the Dutch Meuse is included as well because part of the mixing with Meuse water influences the simulated temperature of measuring stations in the delta areas (Rotterdam area and the coast).

The three boundaries for the Rhine model shown in chapter 3.2 are thus connected to the Meuse model (which is an integral part of the LHM framework). The boundaries may be considered as internal boundaries for which no measurements are required. The boundary for the Meuse model is located at station Eijsden and the Meuse model uses atmospheric data from two KNMI stations Maastricht and Eindhoven.

Note that the river branch HollandsDiep - Haringvliet is not part of the Rhine catchment (see chapter 3.1). As the main discharge in this branch originates from the Rhine it is considered here, nevertheless.

In this report the LHM-SOBEK-DWAQ model framework is referred to as SOBEK.

[2] Deltascenarios_actualisering2017_hoofdrapport.pdf (deltares.nl)

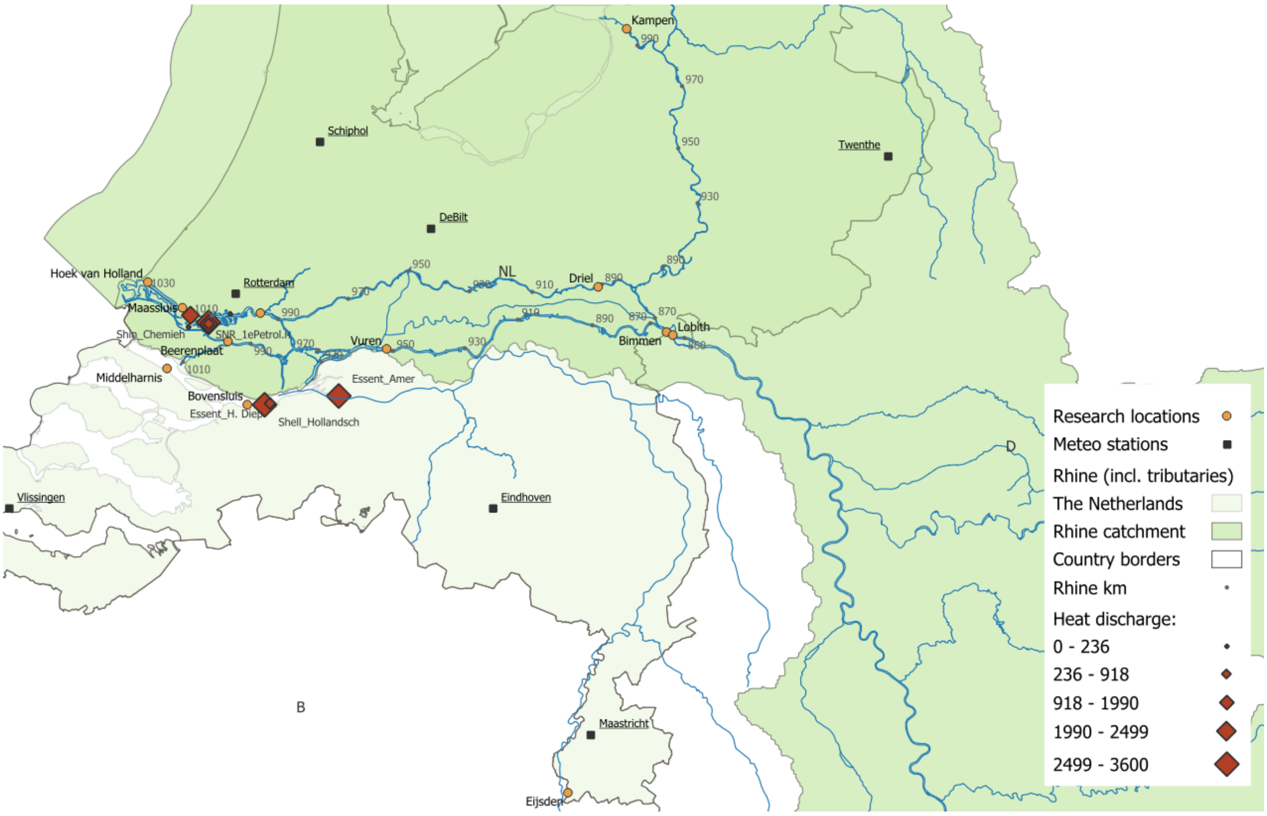


Figure 3-6 Model schematisation for SOBEK from Lobith (Rhine-km 862.3) and Hoek van Holland (Rhine-km 1030) including heat input sites, tributaries, water temperature and meteorological measuring stations. Note the interaction between Rhine and Meuse catchment.

4 Model validation

A three-year validation period (2018-2020) is a part of this study to demonstrate that the applied model setups can describe adequately the measured water temperatures along the Rhine. These measurements include the influence of the associated heat input from thermal, industrial or nuclear power plants within this time frame, thus the heat input is part of the model input for the validation period.

4.1 Model data

In the following chapters, the forcing for the models at the respective boundaries is described starting with the atmospheric boundary (chapter 4.1.1), the discharge and temperature at tributaries (chapter 4.1.2) and the direct heat inputs (chapter 4.1.3) followed by the Rhine measuring stations used for validation of the model simulations (chapter 4.1.4).

4.1.1 Meteorology

The actual weather data used in the validation period were taken from nearby weather stations provided by the national weather institutes (Table 4-1). The locations of the stations are indicated in Figure 3-4 to Figure 3-6.

Table 4-1 List of weather stations assigned along the Rhine River sections.

Rhine-km	Weather station (acronym)	Altitude (m)	Location	Source[1]
47.0-56.0	Zurich Fluntern (SHA)	438	Figure 3-4	Meteo Swiss
90.7	Zurich airport (KLO)	434	Figure 3-4	Meteo Swiss
123.0	Ruenenberg (RUE)	611	Figure 3-4	Meteo Swiss
149.0-171.4	Basel (BAS)	316	Figure 3-4	Meteo Swiss
164.1-249.0	Rheinfelden	283	Figure 3-5, no. 1	DWD
249.0-291.3	Lahr	157	Figure 3-5, no. 2	DWD
291.3-385.0	Karlsruhe	112	Figure 3-5, no. 3	DWD
385.0-476.0	Worms	88	Figure 3-5, no. 4	DWD
476.0-510.0	Frankfurt/Main	104	Figure 3-5, no. 5	DWD
510.0-565.0	Geisenheim	111	Figure 3-5, no. 6	DWD
565.0-601.5	Andernach	76	Figure 3-5, no. 7	DWD
601.5-702.0	Köln/Bonn	92	Figure 3-5, no. 8	DWD
702.0-800.5	Düsseldorf	37	Figure 3-5, no. 9	DWD
800.5-862.0	Kleve-Kellen	14	Figure 3-5, no. 10	DWD
862.0-960.0	De Bilt	1.9	Figure 3-6	KMMI
960.0-1030.0	Rotterdam	-5.1	Figure 3-6	KNMI

[1] *Source Meteo Swiss: https://www.meteoswiss.admin.ch/services-and-publications/applications/measurement-values-and-measuring-networks.html*

[1] *Source DWD: Wetter und Klima - Deutscher Wetterdienst - Leistungen - Stationsliste der 83 Messstationen (nach Stationsname sortiert) (dwd.de)*

[1] *Source KNMI: KNMI - Daggegevens van het weer in Nederland*

4.1.2 Hydrological and water temperature input data

This chapter reports the stations where data were obtained for the boundaries of the hydrodynamic models, viz. discharge and water levels, and for the water temperature models, viz. water temperatures.

Switzerland uses (only) data from the hydrometeorological stations provided by BAFU (chapter 4.1.1). Water temperature is measured at the stations reported, discharge is measured at two of them. As the temperature model air2water is basically a stochastic model without a grid, the stations are strictly speaking not boundary conditions but nevertheless presented here as such.

In the Netherlands, the main inflow location for the Rhine branch is Lobith. Because of the interconnection with the Meuse reaches (Rhine-Meuse estuary) also the inflow of the Meuse at Eijsden is relevant. At the North Sea, a time variable (10 min) water level is applied. In between, numerous spatially distributed lateral inflows occur, the inflows are not measured but modelled using rainfall-runoff modelling (chapter 3.3.3).

Table 4-2 List of stations with output from the model air2water (CH).

Rhine-km	Measuring station	MQ (m3/s)	Source
56	Rheinau (2392)	< 440	BAFU
90.7[Q]	Rekingen (2143)	-	BAFU
123[Q]	Laufenburg (2130)	-	BAFU
149[Q]	Rheinfelden (2091)	1030	BAFU
174	Weil am Rhein (2613)	-	BAFU
[Q] **station measures discharge. All stations measure water temperature.**			

Table 4-3 List of model upper boundary and tributaries, their gauge station, average discharge for 2018–2020 (MQ) and data sources for QSim (D).

Rhine-km	Tributaries	Gauge station	MQ (m^3/s)	Source
164.1	Inflow	Basel Rheinhalle	970.5	WSV
169.0	Wiese	Zell Wiese	6.7	LUBW
175.5	Kander	Märkt Kander	0.7	LUBW
225.5	Möhlin	Oberambringen	0.3	LUBW
253.6	Leopoldskanal	Riegel Leopoldskanal	10.3	LUBW
298.0	Kinzig	Schwaibach	18.2	LUBW
311.0	Ill Alsace	Kalter Jäger	61.1	LUBW
334.4	Moder	Drusenheim	8.2	LUBW
343.5	Sauer	Beinheim	2.8	LUBW
344.5	Murg	Bad Rotenfels	12.7	LUBW
428.0	Neckar	Rockenau	109.3	WSV
496.5	Main	Raunheim	177.8	WSV
529.0	Nahe	Dietersheim	28.1	WSV
585.5	Lahn	Kalkofen	39.1	WSV
592.5	Mosel	Cochem	288.8	WSV

610.0	Wied	Friedrichsthal	6.2	WSV
629.0	Ahr	Bad Bodendorf	5.4	WSV
659.0	Sieg	Menden	40.1	WSV
702.0	Wupper	Opladen	11.6	WSV
740.0	Erft	Neubrück	8.7	WSV
780.0	Ruhr	Hattingen	52.5	WSV
798.0	Emscher	Oberhausen	13.6	WSV
815.0	Lippe	Schermbeck	32.2	WSV

Table 4-4 List of model boundaries, their gauge station, average discharge or water level for 2018-2020 (MQ) and data sources for SOBEK (NL).

Rhine-km	Model boundary	Measuring station	MQ (m^3/s)	Source
863	Inflow	Lobith	2153.1	Waterinfo
1032	Sea boundary	NDB_Maasmond	0 m + NAP	Waterinfo
(Meuse)	Inflow	Eijsden	261.9	Waterinfo

4.1.3 Data used for heat input

A heat input inventory for the time frame 2010-2020 was made by the EG STEMP. The heat inputs for 2018-2020 are part of the water temperature simulation of the validation study (this chapter). For validation purposes, actual heat inputs are most useful but not always available. In that case, the models fall back on estimates of the actual heat input based on permitted heat inputs. Validation results then show how valid this approach is.

For practical reasons, the inventory is limited to the larger heat inputs (exceeding 200 MW). The heat inventory does include Switzerland, though the Swiss model (chapter 3.3.1) does not use heat loads as input.

The current status of the heat input inventory reads as follows: Switzerland made data available for one power plant from 2013-2020 (permitted and actual heat inputs). In general, Germany has permitted as well as actual heat input for the period 2010-2020. For North Rhine-Westphalia only permitted heat inputs were made available. The Netherlands delivered four actual, yearly averaged, heat inputs for 2010-2020, only one of them exceeds 200 MW. Permitted heat inputs for Switzerland and Germany are listed in Table 4-5. Actual heat inputs for the Netherlands are listed in Table 4-6.

The German model uses a total of seven thermal heat inputs from power plants located between Rhine-km 212.5 and Rhine-km 502.0. Thermal discharge from power plants present in North Rhine-Westphalia (NRW) are neglected due to their negligible influence on the Rhine water temperatures (*personal communication LANUV*). When no measured and only permitted heat inputs were available, a seasonally varying percentage of permitted heat inputs was used for thermal and industrial power plants (Table 4-7). The seasonal pattern of thermal discharge was derived from actual measurements of BASF's cooling water ("BASF Kühlwasser") heat input (

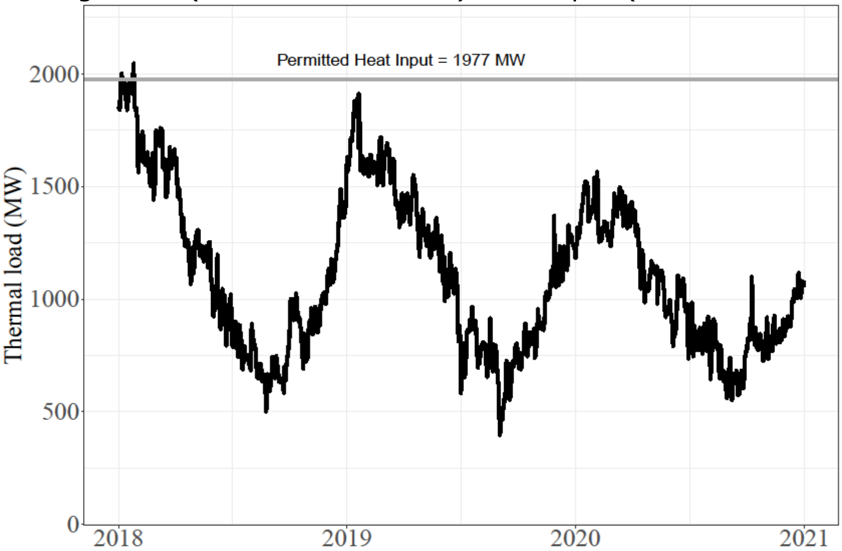


Figure 4-1). In general, heat input is significantly higher in winter than in summer season. A seasonally varying heat input leads to a better model performance for the Rhine water temperature simulation 2018-2020.

It should be noted that no threshold value, like a maximum water temperature of the Rhine, was used to limit heat input by power plants. Since France has provided the temperature difference between the water entering and leaving the Grand Canal d'Alsace (between Rhine-km 174 and 224), these measurements were used to correct the estimated seasonal thermal inputs from the nuclear power plant Fessenheim.

The Swiss heat input was not explicitly part of the model input for the validation period. The heat input from nuclear power plant ("Kernkraftwerk" = KKW) Beznau was implicitly included in the model as water temperature measurement downstream of the Aare confluence include the effect of this heat input.

Dutch heat inputs (total 2.5 GW) were used as yearly averaged values in the validation modelling. The largest part of this heat (2.0 GW) is discharging into the Hollands Diep branch (combined Rhine-Meuse branch). The Dutch heat input data reflect the result of moving power generation towards the western part of the country (e. g. to the location Maasvlakte) discharging into the North Sea. Furthermore, there are many small heat inputs (over 30 known individual discharges summing up to 1 GW in the model domain). This sum is twice the amount discharged in the model domain excluding Hollands Diep (0.5 GW).

Table 4-5 Thermal, industrial or nuclear power plants and their permitted heat inputs into the Rhine in Switzerland and Germany (downstream Rhine-km 212).

Rhine-km	**Thermal/industrial/nuclear power plants**	**Permitted heat inputs (MW)**	
		2018-2019	**2020**
±103*	KKW Beznau (on tributary Aare)	1400-1450	1400-1450
212.5	KKW Fessenheim	3600	3600 (Jan-June) 0 (July-Dec)
359.5	Rhein-Dampfkraftwerk Karlsruhe	2125	1151-2125
389.5	KKW Philippsburg	2810	20

416.5	Großkraftwerk Mannheim	1536.5 (June-Sep) 2947 (Oct-May)	1536.5-2947
428.0	BASF Kühlwasser	1977	1977/2200
433.0	BASF Kläranlage	280/380	280/380
502.0	Kraftwerke Mainz-Wiesbaden	785	785
* Heat input in River Aare close to the confluence with the Rhine at Rhine-km 103.			

Table 4-6 Thermal heat inputs in MW (for heat inputs > 100 MW) of different companies per year into the Rhine and Rhine branches in the Netherlands.

Rhine-km	2010[4]	2018	2019	2020
960	586	0	0	0
998	461	369	331	307
1008	193	157	119	95
(975[2])	636	636	636	636
(995[2])	0	115	121	124
(995[2])	970	970	970	970
(995[2])	180	180	180	180
(1005[3])	160	100	96.5	101
Sum in Rhine branches:	3186	2527	2454	2413

[1] at Rhine branch "Hartelkanaal"

[2] at Rhine branch "Hollands Diep"

[3] discharge at sea

[4] for reference

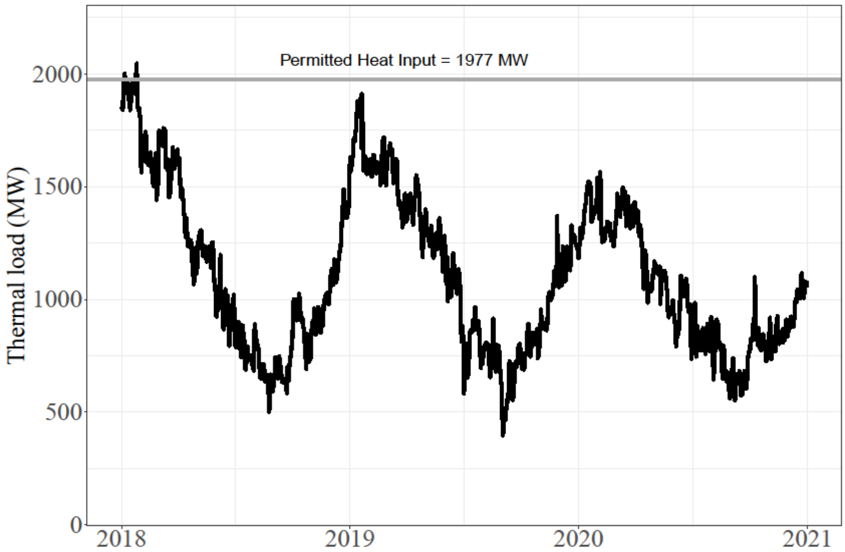


Figure 4-1 Measured thermal loads into the Rhine River from BASF cooling water.

Table 4-7 From Figure 4-1 derived seasonal pattern of thermal discharge of power plants in Germany for which only permitted heat input data were available.

Months	**Heat input (%)**
January–February	80
March–April	70
May	55
June–September	40
October–November	45
December	65

4.1.4 Measured temperature data used for model validation

Several water temperature measuring stations along the Rhine were considered for the validation of the modelled water temperatures (Table 4-8).

Table 4-8 Water temperature measuring stations along the Rhine for Switzerland (up to Rhine-km 171.4), Germany (up to Rhine-km 865) and the Netherlands (up to Rhine-km 1030).

Rhine-km	Water temperature measuring stations	Data source[1]
47	Neuhausen-Flurlingerbrücke (2288)	BAFU
56	Rheinau (2392)	BAFU
90.7	Rekingen (2143)	BAFU
123	Laufenburg (2130)	BAFU
149	Rheinfelden (2091)	BAFU
171.4	Weil am Rhein(2613)	BAFU/LUBW
334.0	Iffezheim	LUBW
359.2	Karlsruhe	LUBW
443.3	Worms	HLNUM
498.5	Mainz	HLNUM
590.3	Koblenz	BfG
640.0	Bad Honnef	LANUV-NRW
865.0	Bimmen	LANUV-NRW
863.2[2]	Rhine-NWW_1_Lobith	RWS
891.1	Nederrijn-Lek_1_Driel	RWS
922	Nederrijn-Lek_2_Amerongen	RWS
945.3	Rhine-NWW_2_Brakel	RWS
946.7	Nederrijn-Lek_3_Hagestein	RWS
951.7	Rhine-NWW_3_Vuren	RWS
984.4	OudeMaas_1_Puttershoek	RWS
985.5	HD-HV_1_DortseKill	RWS
993.7	HD-HV_2_Bovensluis	RWS
995.2	Rhine-NWW_4_Brienenoord-RO	RWS
995.5	IJssel_Kampen	RWS
996.1	OudeMaas_2_Beerenplaat	RWS
1017	HD-HV_3_Middelharnis	RWS
1018.5	Rhine-NWW_6_Maasluis	RWS
1030.1	Rhine-NWW_7_HoekvanHolland	RWS

[1] BAFU: https://www.bafu.admin.ch/bafu/en/home/topics/water/info-specialists/state-of-waterbodies/state-of-watercourses/watercourse-temperatures.html/

[1] LUBW: https://udo.lubw.baden-wuerttemberg.de/public/

[1] HLNUM: https://www.hlnug.de/messwerte/datenportal/gewaesserguete

[1] BfG: http://tvil-u2db.bafg.de/pydb/

[1] LANUV-NRW: https://www.elwasweb.nrw.de/elwas-web/index.xhtml

[1] RWS: https://waterinfo.rws.nl/#/nav/bulkdownload

[2] *At the German-Dutch border the Rhine is the national boundary for about 5 km. As stations Lobith and Bimmen are on opposite shores of the river, Bimmen (D) is indeed further downstream than Lobith (NL).*

4.2 Model results

4.2.1 Time-series for selected stations

Model results of discharge were evaluated for HYDRAX and are presented in the appendix in chapter 10. Air2water and SOBEK were not specifically validated for discharge in the validation period 2018-2020. SOBEK discharge validation for the year 2018 is available in (Prinsen, 2018). SOBEK discharge validations for a particular dry (2003) and wet (1989) hydrological year are available in (Prinsen, 2015). Validation for water temperature was performed for all three models and is summarised in this chapter.

The water temperature measurement frequency in the Rhine varies depending on the station. It reaches from approximately once a month to 10 minutes. All measurement frequencies higher than one day have been aggregated to daily data, in line with the time resolution of the water temperature models. The data can show gaps and periods with less frequent measurement. However, enough data was available to allow for a validation of the model results.

Figure 4-2 shows time series (2018-2020) for selected stations along the Rhine showing the simulated water temperature (light blue line) and measurements (green dots).

Model simulations without heat inputs (dark blue line) were further used to evaluate the effect of heat inputs on Rhine water temperatures (chapter 4.2.3).

The model simulations (light blue, including heat inputs) showed close agreement to measured water temperatures at different water temperature measuring stations along the Rhine (Figure 4-2) indicating a good performance of the model for most of the displayed stations. Further, statistical analysis (under the graphs and summarised in

Table 4-8) manifested good model performance with high R^2 values (> 0.99) and NSE values (> 0.99) fostered with smaller water temperature deviations ranging between 0.50 °C and 0.81 °C. Additionally, percentage of bias (PBIAS) scores indicated high model accuracy for the water temperature simulations.

Especially for Worms and Mainz (2018-2020), the performance of the model decreases when heat inputs are left out. This demonstrates how strongly thermal emissions influence those stations. Also, the water temperature differences at Bimmen can be partly attributed to the influence of smaller thermal emissions which are left out from NRW in our study. For the last station close to the sea (Hoek van Holland), the model shows an overestimation in summer and an underestimation in winter indicating that the present 1D model underestimates the dampening effect of seawater temperature.

In general, stations in the Netherlands underestimate water (winter) temperatures stronger than it is the case in Germany. Most likely this is caused by missing heat inputs.

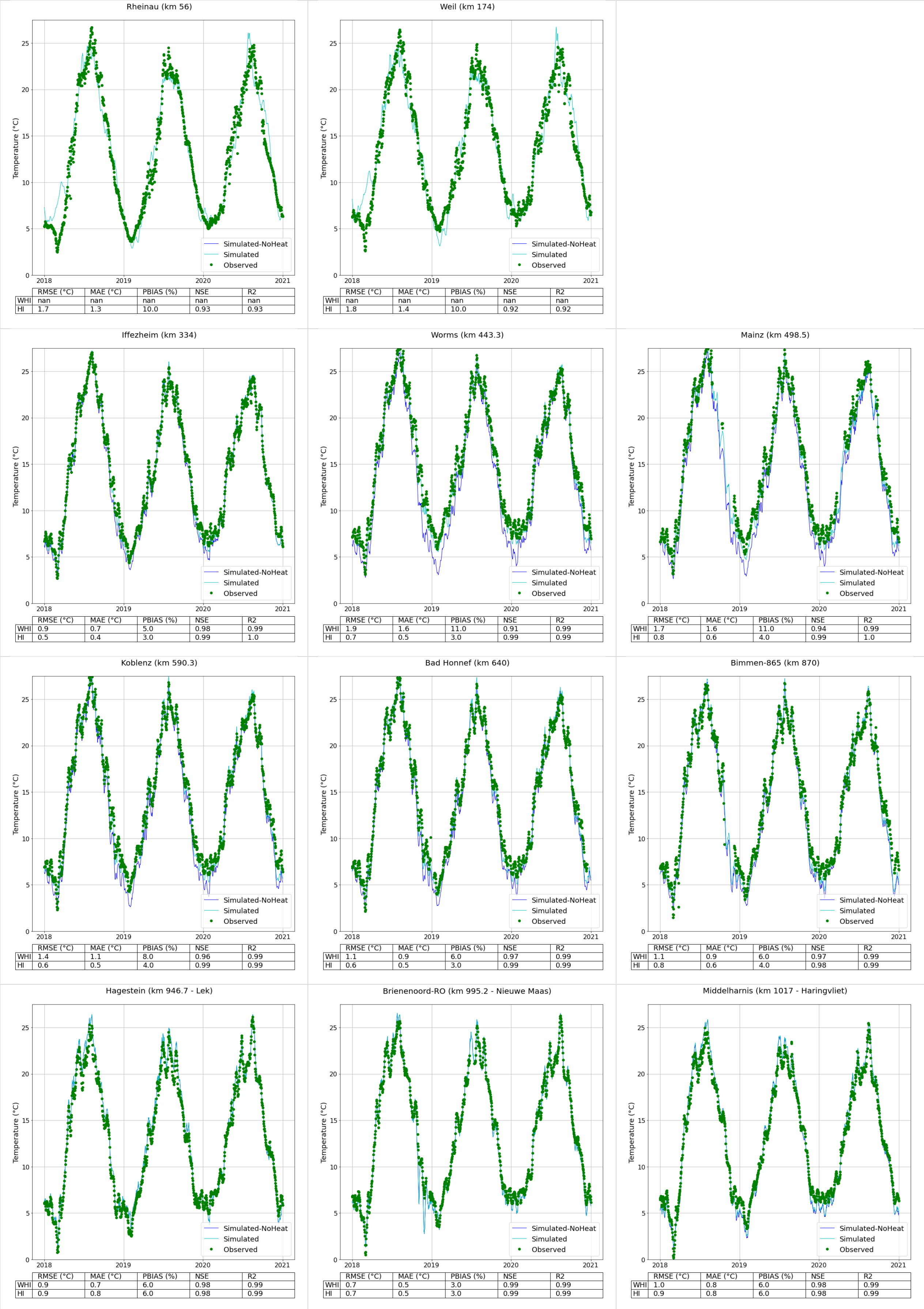


Figure 4-2 Comparison between measurements (green dots) and simulations without (WHI) and with heat input (HI) (blue lines) of water temperatures (2018-2020) at different stations along the Rhine including model statistics based on measurements and simulation.

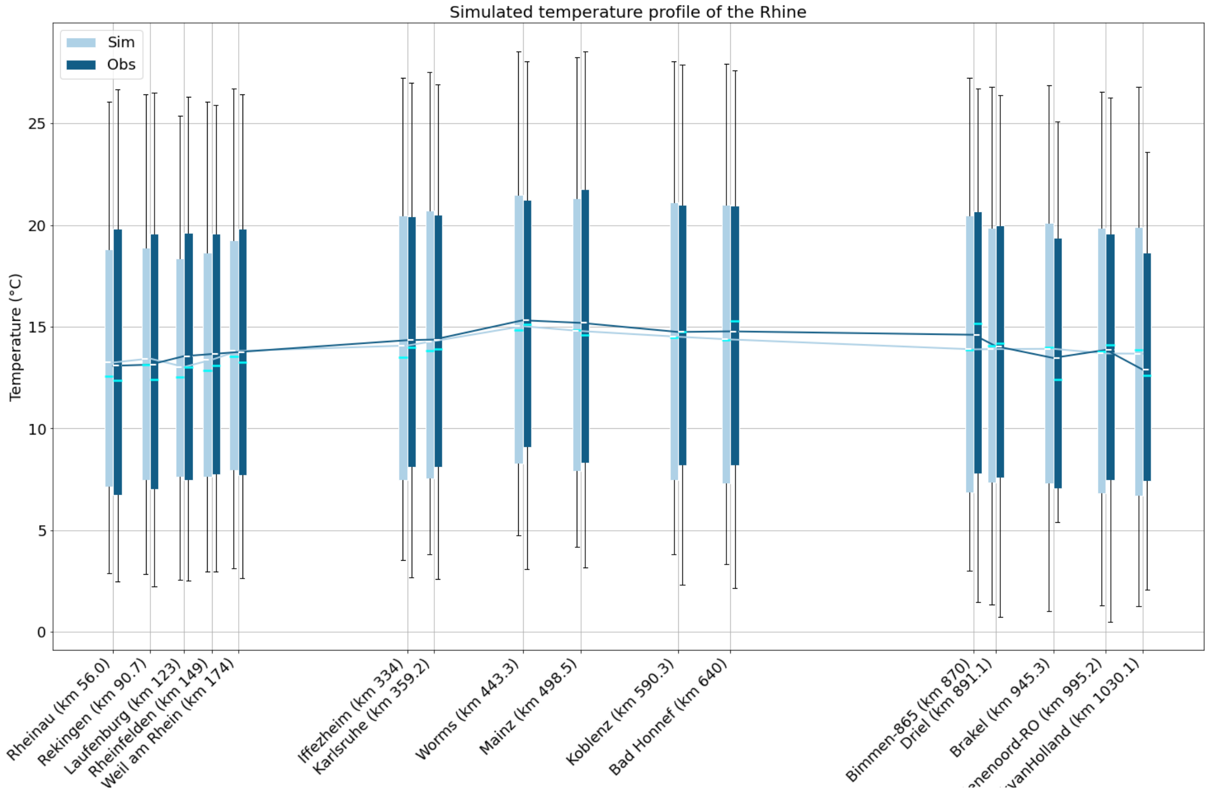
Table 4-8 Statistical coefficients for simulation results of water temperature (2018-2020) without heat input (WHI) and with heat input (HI) for selected stations along the Rhine.

Rhine-km / Station	**RMSE (°C)**		**MAE (°C)**		**PBIAS (%)**		**NSE**		**R^2**	
	WHI	**HI**	**WHI**	**HI**	**WHI**	**HI**	**WHI**	**HI**	**WHI**	**HI**
56_Rheinau	1.7		1.3		10		0.93		0.93	
90.7_Rekingen	1.9		1.4		11		0.92		0.92	
123_Laufenburg	1.8		1.4		11		0.91		0.92	
149_Rheinfelden	1.7		1.4		10		0.92		0.92	
171.4_Weil am Rhein	1.8		1.4		10		0.92		0.92	
334_Iffezheim	0.9	0.5	0.7	0.4	5	3	0.98	0.99	0.99	0.99
359.2_Karlsruhe	1.0	0.5	0.8	0.4	5	3	0.98	0.99	0.99	0.99
443.3_Worms	1.9	0.7	1.6	0.5	11	3	0.91	0.99	0.99	0.99
498.5_Mainz	1.7	0.8	1.6	0.6	11	4	0.94	0.99	0.99	0.99
590.3_Koblenz	1.4	0.6	1.1	0.5	8	4	0.96	0.99	0.99	0.99
640_Bad Honnef	1.1	0.6	0.9	0.5	6	3	0.97	0.99	0.99	0.99
870_Bimmen-865	1.1	0.8	0.9	0.6	6	4	0.97	0.98	0.99	0.99
891.1_Driel	0.9	0.9	0.5	0.5	3	3	0.98	0.98	0.98	0.98
922.0_Amerongen	2.8	2.7	1.1	1.2	9	9	0.84	0.84	0.85	0.85
945.3_Brakel	1.1	1.1	0.9	0.9	7	7	0.97	0.97	0.98	0.98
946.7_Hagestein	0.9	0.9	0.8	0.7	6	6	0.98	0.98	0.99	0.99
951.7_Vuren	0.9	0.9	0.6	0.6	4	4	0.98	0.98	0.99	0.99
984.4_Puttershoek	0.6	0.7	0.5	0.5	4	4	0.99	0.99	1.00	1.00
985.5_Monding DortseKill	0.7	0.8	0.6	0.6	4	4	0.99	0.99	0.99	0.99
993.7_Bovensluis	0.8	1.1	0.7	0.9	5	6	0.98	0.97	1.00	0.99
995.2_Brienenoord-RO	0.7	0.7	0.5	0.5	3	3	0.99	0.99	0.99	0.99
995.5_Kampen	1.0	1.0	0.7	0.7	5	5	0.98	0.98	0.99	0.99
996.1_Beerenplaat	0.8	0.8	0.6	0.6	5	5	0.99	0.98	0.99	0.99
1017_Middelharnis	0.9	1.0	0.8	0.8	6	6	0.98	0.98	0.99	0.99
1018.5_Maasluis	2.0	2.0	1.0	1.0	7	7	0.89	0.89	0.93	0.93
1030.1_HoekvanHolland	1.8	1.8	1.5	1.5	12	11	0.89	0.90	0.96	0.96

4.2.2 Longitudinal Rhine profile

Analysing the longitudinal temperature development of the Rhine puts model results into a spatial context. The temperature profile varies depending on the location within the Rhine. Close to the source, the measured water temperature is generally colder due to the alpine influences, whereas in regions with decreasing flow velocity, higher air temperature and diverse heat inputs, water temperature increases. In the delta, cooling effects from the North Sea become visible (Figure 4-3, dark blue).

Later in this study, the models were used to analyse scenario results for the longitudinal temperature profile of the Rhine. To check that this profile is covered correctly by the models, the simulated profile of the validation period was compared with the measured profile.



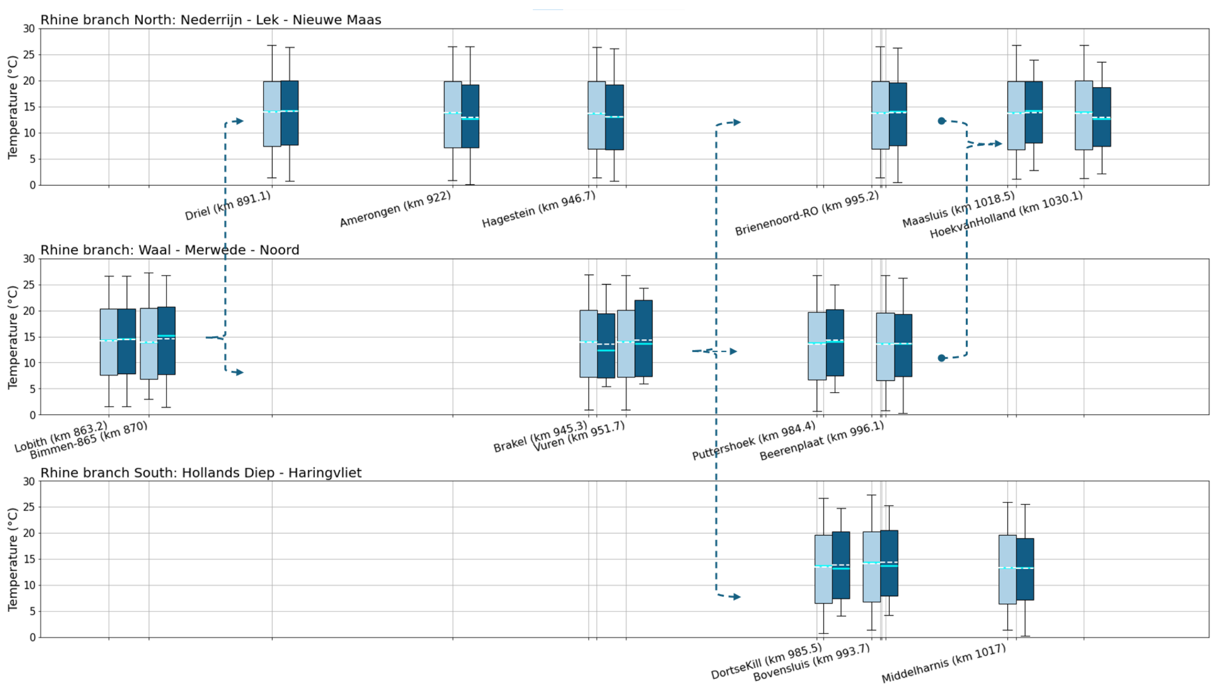


Figure 4-3 Longitudinal temperature profile of the Rhine (2018-2020) based on simulation results (light blue) with heat input compared to measurements (dark blue). The boxplots show the median (cyan line, solid) and the mean (white line, dashed), the first and the third

quartile (upper and lower borders) as well as 1.5 times the inter quartile relation (whiskers). The lower panel shows details in the Dutch part of the Rhine delta.

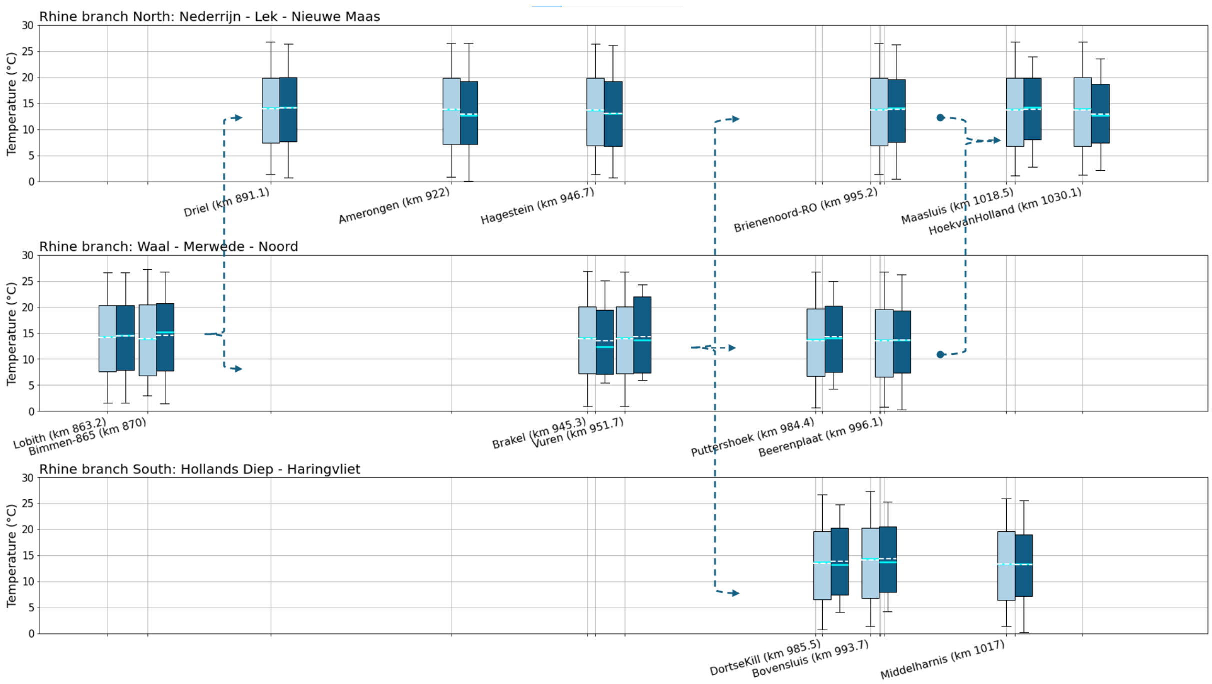


Figure 4-3 shows the longitudinal water temperature profile (2018-2020) of the Rhine from Rheinau in Switzerland to the North Sea based on the modelled temperatures at specific locations. The median temperature over the three years along the river does not show a large variation. It ranges between 13 °C and 15 °C. The highest water temperatures were observed at Mainz and Worms. Downstream of Mainz, the longitudinal profile slightly indicates a decreasing temperature profile.

4.2.3 Evaluation of effects of heat input

This chapter focuses on evaluating the effect of thermal emission in Rhine water temperatures in Germany. The evaluation was carried out by comparing two simulation runs that only differed in heat inputs. One of the simulations was performed with estimated or measured heat input values from industries and power plants. The other simulation included no thermal emissions. The simulation run with heat input performed superior with better fitting of the simulation results to water temperature measurements than the simulation run without heat input (chapter 4.1.3). The addition of thermal emission into the simulation produced improved R^2 and NSE values with reduced deviations between simulation results and measurements (

Table 4-8).

The Upper Rhine is largely influenced by higher heat input from power plants between Karlsruhe and Mainz as compared to the Lower Rhine (Table 4-6). It is evident that the difference in water temperatures is larger at stations which are in proximity and thus have high influence of thermal emissions than at stations which are far from the sources of those emission and have minor or no influence. For example, in 2018-2020, Worms recorded an average water temperature difference with and without heat input of 1.33 °C due to elevated thermal loads into the Upper Rhine. Whereas the water temperature deviation was reduced to 0.47 °C at Bimmen located in the Lower Rhine. This deviation is also in agreement with the previous results from LANUV-modelling of the Rhine water temperatures for the periods between June to October 2008. Likewise, the discrepancies in water temperatures were larger at lower water temperatures when emissions were comparatively higher than in summer and spring periods (chapter 4.1.3,

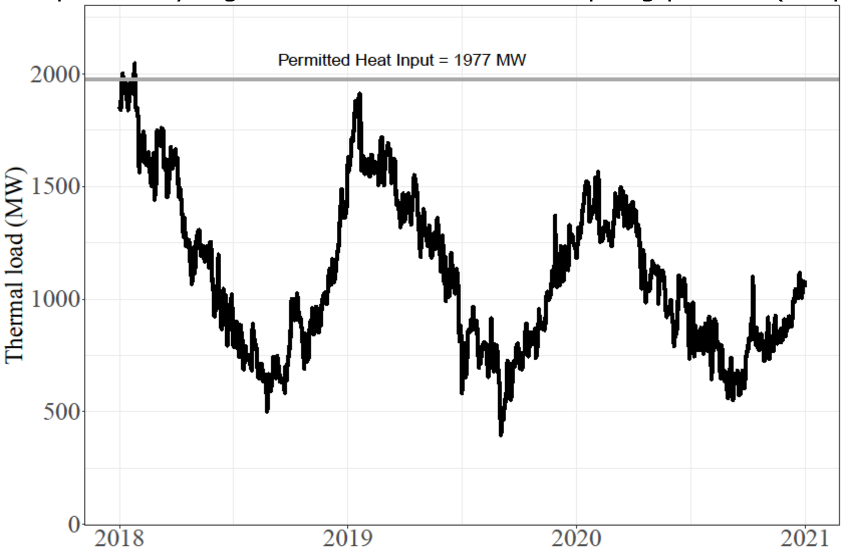
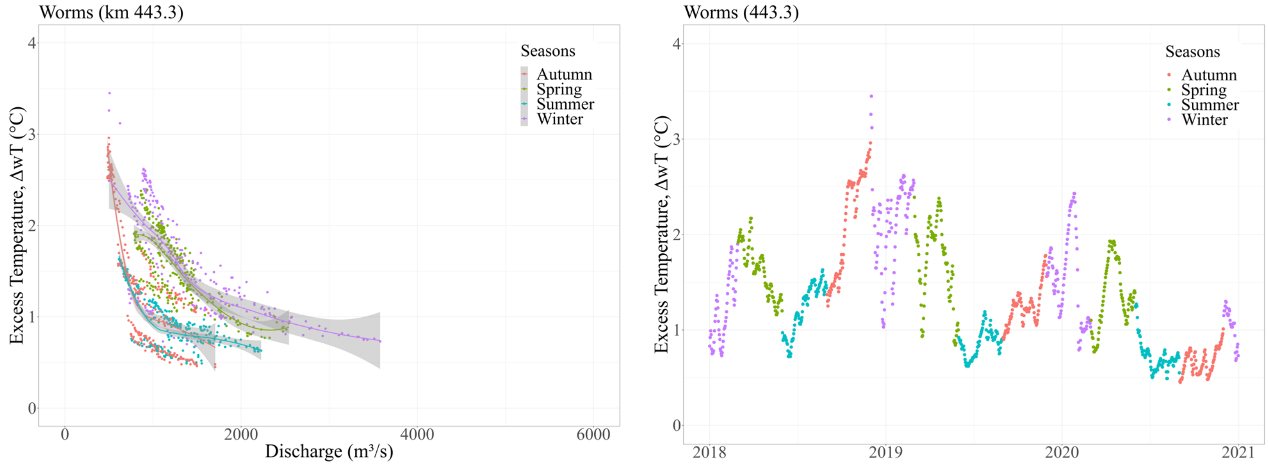


Figure 4-1).

Also, with the increase in discharge in the Rhine either seasonally or downstream, the effect of thermal loads is diluted, resulting in a smaller impact on water temperatures (Figure 4-4).



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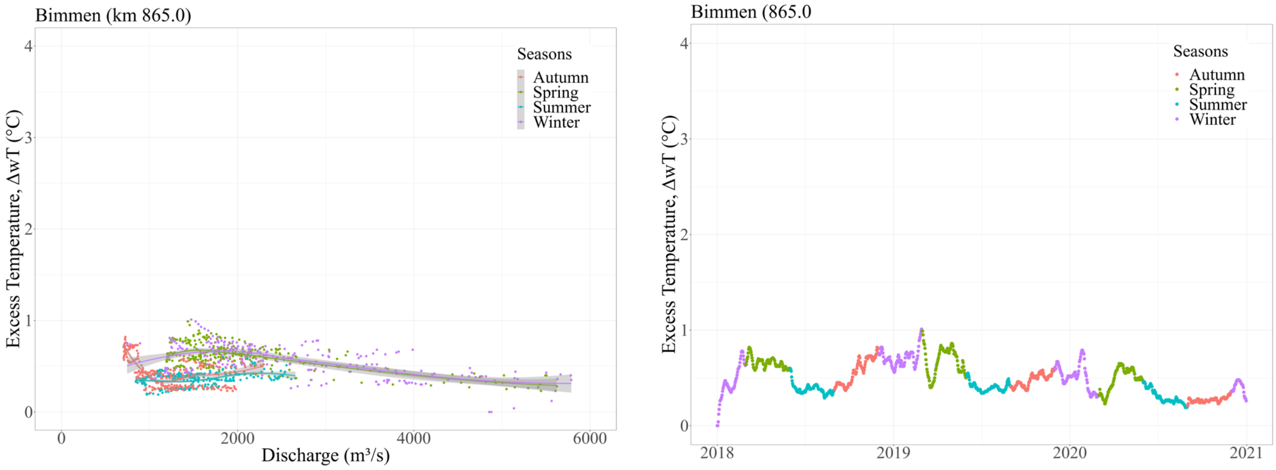


Figure 4-4 Temperature excess (QSim simulation) from thermal emissions from power plants at Worms and Bimmen (2018-2020) differentiated by season.

With respect to the influence of heat inputs (2018-2020) by power plants in Germany the following conclusions hold:

- In the Rhine stretch represented by the station Worms (Rhine-km 443.3), the average daily water temperature increase attributed to heat inputs varies between 0.5 °C and 3.0 °C depending on the Rhine's discharge conditions and season (where RMSE difference with and without heat 3-year validation period (2018-2020) is 1.48 °C).
- In the Rhine entering the Netherlands at Bimmen (Rhine-km 865.0), the influence of heat inputs varies between 0.3 °C and 1.0 °C depending on discharge conditions and season (where RMSE difference with and without heat in the 3-year validation period (2018-2020) is 0.52 °C).
- The heat input is smallest in summer and highest in winter/autumn.
- The contribution of heat input to water temperature is most significant in winter, when heat input is highest and water temperatures are lowest, resulting in the highest excess temperature contribution in absolute degree Celsius.

For the Netherlands, the remaining excess heat is small. Only in one location in Hollands Diep (not shown) there is a noticeable influence (RMSE difference with and without heat is 0.2 °C). The limited influence is caused by moving larger heat inputs to waterbodies with a large water volume and thus high capacity (Hollands Diep, North Sea).

Because many small heat inputs are not included, the simulation is an underestimation of the actual heat input. The contribution of the significant heat input to the Swiss Rhine from Bernau (estimated effect: 0.8 °C at 1.000 m^3/s) is not included in air2water.

4.3 Conclusions of model validation

The validated water temperature models perform well to predict water temperatures along the Rhine and therefore, can be further used for modelling climate change scenarios.

Performance of statistical models used in Switzerland is less than the deterministic models used in Germany and in the Netherlands (

Table 4-8) for several reasons. Firstly, the relation between water temperature and the atmosphere is described more accurately when next to air temperature other meteorological variables like solar radiation, wind and anthropogenic heat inputs are explicitly considered. Second, the deterministic models QSim and SOBEK rely on measured water temperatures for their boundaries, which makes predictions more accurate.

Performance near the North Sea is less than in other stations as salt intrusion causes temperature stratification which is not included in the model. In one Dutch station, the measurements are obviously wrong and uncorrected (station Amerongen) causing poorer model performance indicators.

Effects of heat inputs along the Rhine depend on the location of the emitting industries and power plants. For the period 2018 to 2020, average cumulative water temperature impact of thermal discharges along the German Rhine ranged between 0.35 °C and 1.36 °C. The influence of thermal heat inputs modelled in the Dutch part of the Rhine main branch is neglectable. Note that in this study smaller (< 200 MW) thermal inputs are not included.

5 Water temperature projections

On a national level, each participating member state (CH, D, NL) used its national model chain for simulating the impact of climate change on Rhine discharge and water temperature. A selection of the national simulation results is made and analysed in this chapter. Chapter 5.1 describes what the selected national simulations have in common (such as the emission scenario and simulation periods). Chapter 5.2 lists the ensemble members of the climate projections used in the national studies and identifies overlaps. Chapter 0 explains the method used, and results for future water temperature are presented in chapters 5.4 (ensemble variation) and chapter 5.5 (threshold exceeding frequency).

This chapter focuses on the variability of the temperature projections in the national studies. Beside the differences in the models used, variability is caused by the different climate projections that countries chose to force their models with. Results are presented per country as the number and the choice of climate model ensemble members varies. In chapter 6 as a first step towards a future basin-wide approach, the result of one common GCM-RCM model chain along the whole investigated Rhine stretch is presented.

5.1 Selection of national results

The water temperature models applied (chapter 3.3) were forced with air temperature and precipitation projections simulated by regional climate models (RCMs) which get their boundary conditions from global climate models (GCMs). Both types of climate models are designated atmospheric models in the following. Most (European) countries produce national climate projections based on the same data (RCM projections) from European projects (e. g. ENSEMBLES, EURO-CORDEX). Due to the tight schedule and following EG HCLIM (ICPR, 2024), it was decided to run the atmospheric models associated with the 5th IPCC assessment report only, although some countries have started working with the 6th IPCC assessment report results (NL, D).

Global Climate models GCMs

The results in this chapter are all based on climate projections on a global scale from multi-model ensembles of CMIP5 (Coupled Model Intercomparison Project phase 5 of the World Climate Research Programme (WCRP)). These model outputs contribute to the physical science basis of the Intergovernmental Panel on Climate Change (IPCC) reports. More details are given in (Taylor et al., 2012) and by EG HCLIM (ICPR, 2024) (chapter 2.2, table 1).

Greenhouse Gas (GHG) level scenario (RCPs)

In the 5th assessment report (AR5, 2014), the IPCC introduced the Representative Concentration Pathways (RCPs) (IPCC, 2014). RCPs are future concentrations of greenhouse gases in the atmosphere (and other factors) changing the amount of the sun’s energy trapped by earth (the ‘radiative forcings’ in W m^{-2}). The IPCC adopted four pathways spanning a broad range of emission scenarios (2.6, 4.5, 6.0, and 8.5 W m^{-2}) to explore a broad range of possible futures and to evaluate the corresponding range of warming and climate changes.

Although the participating countries in this study (CH, D, NL) used more than one scenario, it was decided in line with EG HCLIM (ICPR, 2024), for pragmatic and precautionary reasons, to limit the evaluation to the high emission scenario RCP8.5.

RCP8.5 assumes no-mitigation policy. The continually rising GHG emissions throughout the 21st century leads to CO_2 concentrations of 650 ppm and around 1200 ppm in 2050 and 2100 (“business as usual” scenario (IPCC, 2014)). Depending on the sensitivity of the GCM applied, this leads to a global air temperature increase of 1.4 °C to 2.6 °C (average 2.0 °C) in 2050 and to 2.6 °C to 4.8 °C (average 3.7 °C) in 2100.

In the most recent assessment report (AR6) (IPCC, 2023), the IPCC introduced so called “Shared Socio-economic Pathways” (SSPs) as a separate modelling effort looking at how factors such as population, economic growth, education, urbanization and the rate of technological development determine the level of greenhouse gas emissions. The SSPs allow researchers to assess the impacts of different socio-economic pathways on climate change and to evaluate the effectiveness of various mitigation and adaptation strategies The two modelling exercises (RCPs and SSPs) were designed as complementary. The RCPs still set pathways for greenhouse gas concentrations and are used as input to climate simulations (additional RCPs have been made available since then, viz. RCP1.9, RCP3.4 and RCP7).

Reference period (1991-2010)

The reference period for the model projections is 1991-2010. This period of 20 years is the largest overlapping period in the model results of the participating countries. It overlaps with the reference period 2001-2010 in the previous study (ICPR, 2014) but is significantly longer. A full 30-year reference period (e. g. 1985-2015) was not feasible for the Netherlands (only up to 2011) and Switzerland (only after 1990).

This reference period does not add recent years to the climate projections compared to the previous study with the reference period 2001-2010 (ICPR, 2014). More recent years will likely become available in national studies using IPCC AR6.

Future projection periods

The study makes projections for two future periods, in short reference to as:

- Near Future (NF)
- Far Future (FF)

The definition of the 30 years near future in the Netherlands (KNMI) is 2036-2065 (median year is 2050). Germany uses 2031-2060, which was extended to 2065 for the basin-wide approach. The Swiss simulations range from 1990-2099, so that any period in the future could be picked. As the reference period was only 20 years, a maximum period of 20 years for the future projection periods was possible, too. The overlapping period for the near future therefore is 2045[3]-2064 (20 years).

For the far future, the available results for the three countries have a similar overlap, the far future period used is therefore 2080-2099.

Heat inputs to the climate projections

For the climate projections, the heat inputs were excluded. The motivation for this was manifold: the future amount of heat input is unknown and strongly dependent on the socio-economic situation in the riparian countries. Moreover, it is proven difficult to get a complete overview of all heat inputs (including the sum of many smaller ones). Further, with the energy transition underway in Germany, heat inputs may change to heat removal, due to the construction of river heat pumps. There is a high uncertainty in the energy situation in the near and far future. From a methodological point of view, it is therefore clearer to study the effect of climate change only, without direct anthropogenic heat inputs and to base future prognoses of absolute water temperature (required to evaluate the number of days exceeding for example 28 °C) on projections without heat inputs in the reference period and future periods.

A priori, it was assumed that heat inputs at present play a less important role than before and in future heat inputs will be further reduced as a result of further nuclear power phase-out in Germany and a tendency to move power plants towards the North Sea in the Netherlands. In combination with increased cooling water efficiency and reuse of heat it is likely that in the near future influence of direct heat inputs becomes insignificant.

The validation study for 2018-2020 in this report (chapter 4.2.3) shows that the influence of heat input is still significant in parts of the German Rhine resulting in an average

[3] The common reference period starts 10 years after the Dutch reference period used in KNMI14 in the Netherlands (1981-2010), the Dutch NF therefore starts 2045.

anthropogenic heating of 1.33 °C at Worms and 0.47 °C at Lobith near the German-Dutch border. This contribution is not included in the climate simulations.

Socio-economics

Socio-economic influences on river discharge and water temperature (other than heat inputs, see previous section) are not reported for Germany and Switzerland.

In the Netherlands (Deltares, 2018), climate scenarios are combined with two socio-economic developments, one under a high and one under a limited economic growth scenario. The socio-economic scenarios consider population dynamics and changes in land use and consequent changes in water use. The influence on river discharge and water temperature in the Rhine branches is negligible as changes in land use and population mainly affect the smaller regional waterways, not the River Rhine branches.

Socio-economic influences are thus not included in the scenario simulations in this study.

5.2 Climate chains in national projections

The national hydrological and water temperature models are described in chapter 3.3 and their data requirement in chapter 4.1. Here, the meteorological forcing that is used in the future climate projection is described.

IPCC "climate projection" refers to a simulated response of the climate system to an imposed forcing derived from scenarios of future concentrations of greenhouse gases and aerosols. Switzerland, Germany and the Netherlands use different climate data as forcing to their hydrological models (precipitation, evaporation) and water temperature models (air temperature, radiation etc.).

Uncertainty, inherent to the climate system, is usually captured by using an ensemble of climate simulations (projections) instead of a single simulation. As in this study, ensemble members from the highest emission scenario were selected, the approach classifies as a multi-model ensemble approach (as opposed to a multi scenario ensemble). Each member of an ensemble is the simulation result of a single model run with a climate chain (viz. a global-regional climate model chain developed by different research groups) with a certain parameter setting and initial condition.

Switzerland and Germany use outputs of the coordinated regional climate modelling activities (CORDEX[4]). CORDEX uses the output from CMIP5[5] GCMs to drive regional climate models (downscaling). The Netherlands uses one global climate model from the CMIP5 ensemble followed by downscaling using RACMO[6]. In summary, CMIP5 provides the global-scale climate data, CORDEX refines this data to offer more detailed regional climate projections, and RACMO is one of the regional models used within CORDEX to achieve this downscaling. There are six RCMs used in the national ensembles: RCA4 (Rossby Centre Regional Atmospheric Model), REMO (Max Planck Institute for Meteorology), CLM (Climate Limited-area Modelling Community with roots in the DWD) and RACMO (KNMI and DMI). The regional models have a horizontal resolution of ~12.5 km. These data can be further

[4] Coordinated Regional Climate Downscaling Experiment. It is an international initiative that aimed at improving regional climate predictions and understanding climate change impacts at a local level by taking the coarse-resolution data from GCMs and refining it to higher-resolution climate information for specific regions.
[5] Coupled Model Intercomparison Project Phase 5. CMIP5 ran from 2010 to 2014, provided data for the IPCC's 5th AR, compared different climate models and provided a set of standardized global climate model (GCM) simulations.
[6] RACMO stands for Regional Atmospheric Climate Model. It was developed in the 1990s by the Royal Netherlands Meteorological Institute (KNMI) in collaboration with the Danish Meteorological Institute. RACMO2 is one of the models used in CORDEX. RACMO2 integrates the dynamical core of HIRLAM (3-16 km resolution) with the European Centre for Medium-range Weather Forecasts (ECMWF) Integrated Forecast System (IFS) physics.

downscaled to a higher temporal resolution. In Germany, data were downscaled and interpolated to 5x5 km resolution (Brienen et al., 2020).

Table 5-1 gives an overview of the climate chains (global circulations models (GCM) and regional climate models (RCM)) selected per country. The table is reworked from EG HCLIM (ICPR, 2024) (appendix A). The ensemble numbers refer to the figures in chapter 5.5.

Note that the number of ensemble members in each country's ensemble differs, and the individual chains selected differ as well. Switzerland and Germany rely on the CORDEX output but selected different chains, so that there are five overlapping chains between Switzerland and Germany.

The Dutch ensemble is reported as two "chains", viz W_H and W_L, each representing four climate chains [16, 18]. The number of overlapping chains for Germany and the Netherlands is limited to two (W_H and W_L) but water temperature simulations were not made available for W_L. A third climate chain (WHdry (KNMI, 2015)) was later added and used for the Dutch boundaries with Germany and Belgium (for the Meuse).

There is only one overlapping climate chain for all countries. The latter was a-priori selected to be used in the basin-wide approach presented in chapter 6.

In the national approach (this chapter), wT is simulated for each individual climate chain in the national ensembles and the results are presented for a selection of measurement stations (in each country) evaluating the ensemble mean and the spread of results as an indication for possible future scenarios, helping to understand uncertainty resulting from the climate forcing used.

Table 5-1 Available model chains for this study. CH used 14, D 16 and NL 2 climate chains for RCP8.5. There are two overlapping chains for D and NL (green) and there are four overlapping chains for D and CH (blue) and one for all countries (light orange).

Global Circulation Model (GCM)	Run	Regional Climate Model (RCM)	air2water (n=13)	QSim (n=16)	SOBEK (n=2)
NORESM	1	RCA4	13		
CanESM	1	RCA4	8		
CanESM	1	REMO2015		1	
ECEARTH	12	CLM4		2	
ECEARTH	12	CLM5	1		
ECEARTH	1	KNMI-RACMO	6[1]	6[2]	W_H[3]
ECEARTH	12	KNMI-RACMO		4	(W_L)[5]
ECEARTH	12	RCA4	9	4	
ECEARTH	12	REMO2015		5	
ECEARTH	3	HIRLAM5	5		
HADGEM2	1	CLM5	2		
HADGEM2	1	KNMI-RACMO	7	7	(W_{HDry}[4])
HADGEM2	1	RCA4	10	8	
HADGEM2	1	REMO2015		9	
IPSL	1	RCA4		10	
MIROC	1	CLM5	3		

MIROC	1	CLM4		11	
MIROC	1	RCA4	11		
MIROC	1	REMO2015		12	
MPI-ESM	1	CLM4		13	
MPI-ESM	1	CLM5	4		
MPI-ESM	1	RCA4	12	14	
MPI-ESM	1	REMO2009		15	
MPI-ESM	2	REMO2009		16	

MIP-ESM = MPI-M-MPI-ESM-LR	RCA4 = SMHI-RCA4
MIROC = MIROC-MIROC5	REMO2009 = MPI-CSC-REMO2009
IPSL = IPLS-IPSL-CMA5-MR	CLM4 = CLMcom-CCLM8-8-17
HADGEM2 = MOHC-Hadgem2-ES	CLM5 = CLMcom-CCLM5-0-7
ECARTH = ICHEC-EC-EARTH	RACMO = KNMI-RACMO022E

1 common chain, CH naming is 'KNMI-RACMO_ECEARTH_EUR44'

2 common chain, D naming is 'ECE_r1_RAC_RCP85'

3 common chain, NL naming is 'W_H'

4 W_{HDry} is an additional unofficial KNMI scenario. W_{HDry} (KNMI, 2015) is used to derive boundary conditions for Meuse and Rhine only (Deltares, 2018). Climate inside NL is W_H which has a strong response to air circulation patterns (wetter and warmer winters, dryer and warmer summers). Placed in brackets as W_{HDRY} is not applied inside NL.

5 W_L is an official KNMI scenario with a low response to air circulation. For this climate chain no hydrological model runs were (made) available.

5.3 Method used to present the national ensembles

Before presenting the national ensembles in the next chapters, the (post)processing applied is explained.

Post-processing the simulation results of the water temperature models involves: (1) calculate for each ensemble member the average wT per day of the year (DOY) across the years included in the simulation period (the harmonized period of 20 years in this case), then (2) calculate the difference between future(s) and the reference (dT in °C). The result for Germany, for example, is 16 mean water temperature differences (see Figure 5-1).

Reducing the evaluation period from 30 years, which is the regular definition of climate, to the harmonised 20-year period used here may cause different results (see Figure 5-1). The overall picture, viz. the enclosure of the ensemble members, is similar, whereas results of individual runs may differ significantly (see black line in Figure 5-1). This is due to the calculation of the average per DOY. Every DOY wT value is an average of 20 or 30 years. Within shorter periods, single cold or hot years will have a larger impact on the average than within longer periods. This is especially visible, when looking at the margin of the ensemble. By chance, around day 150 here, the simulated value for the reference period is higher than the simulated value for the near, or even the far future. Root cause is the climate variability included in the period used. Within a longer period, more extreme years have less impact, that is the relative number and severity of large temperature signals is reduced.

Note that the evaluation periods used in this study (20-year period, lower row) are later in time compared to the 30-year period (upper row) normally used in the German approach. Compared to the 30-year period, the STEMP harmonised 20-year period excludes from its reference the years 1971-1990 and includes years 2000-2010. The excluded years 1971-1990 are colder compared to the included years 2000-2010 which leads to a warmer reference period in the 20-year runs and thus reduces the temperature difference between reference and future(s).

Note that ensemble member ECE-R1_RAC_RCP85 in the 20-year runs is less "mainstream" when comparing its position to the one in the 30-year runs (for this location).

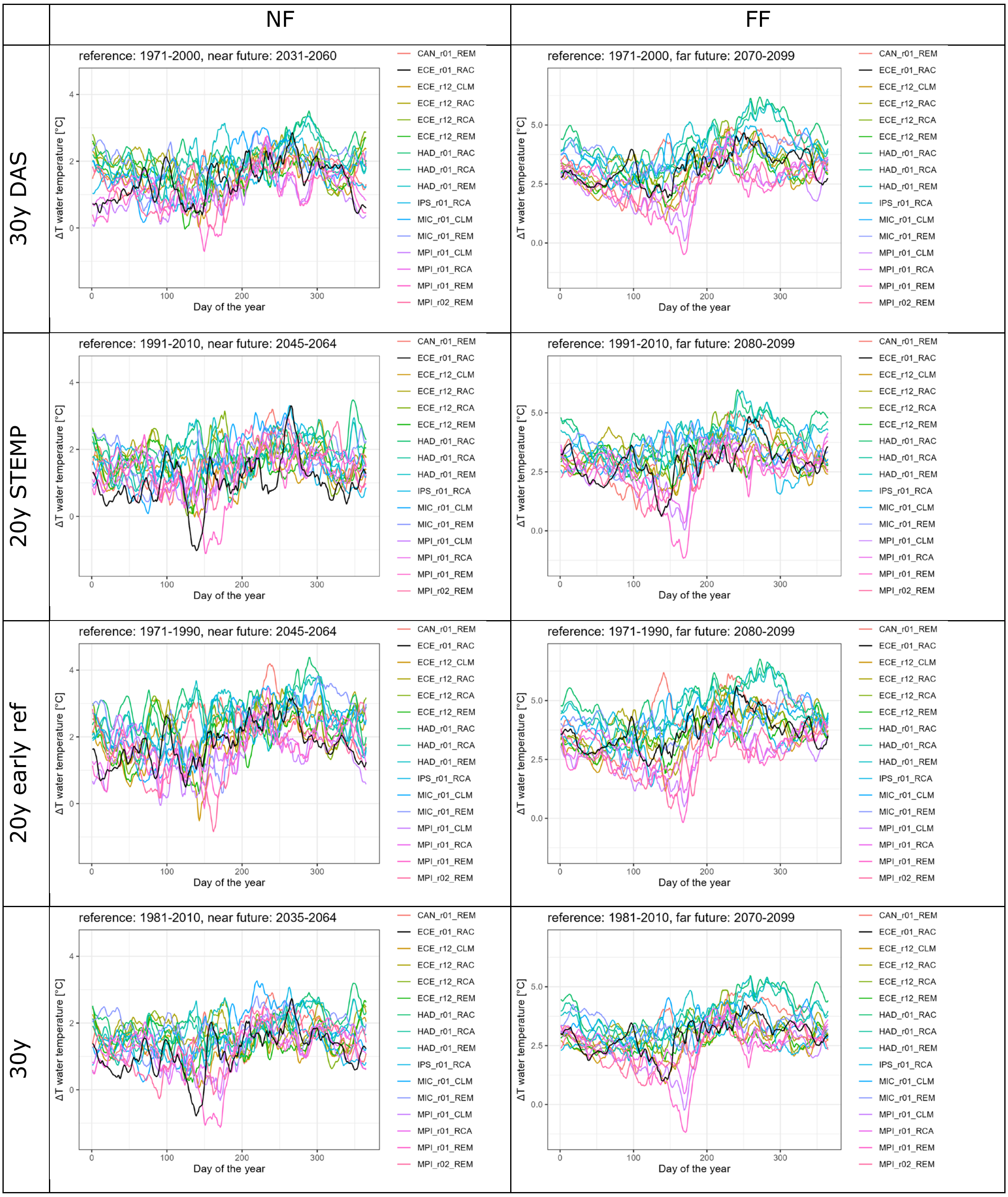


Figure 5-1 Simulated water temperature change at Bimmen in the near (left) and far (right) future using a 30-year period normally applied in Germany ("30 y DAS") and the harmonised 20-year period used in this study ("20 y STEMP").The two bottom rows show the effect when the harmonised 20-year period of the near future is compared to a 20 y earlier reference period ("20 y earlier ref") or when the harmonised 20-year periods are extended to 30 years ("30y"). Shown is the German model ensemble, which consists of 16 model chains.

As all ensemble members are possible futures, in the remainder of this chapter, the ensemble variation is represented by the ensemble range (minimum to maximum, Figure *5-2*, red shaded area) and the median value of this ensemble range (red line). The red shaded area is the enclosure (envelope) of the individual model results presented inFigure 5-1 Figure 5-1. This ensemble range provides a range of possible futures, helping to understand the uncertainty in climate projections.

Not all ensemble members should be assigned the same weight since more ensemble members may stem from the same model family compared to others. For this reason, no ensemble mean has been calculated. The ensemble median though may help to understand and interpret the results. The median value of the ensembles indicates, for that day in the year, where the centre of gravity of the ensembles lies, relative to the minimum and maximum values. For example, only two out of 16 ensemble members predict dT values < 0 °C in the near future (Figure 5-1, DOY 120 to 150 lower panel) this is recognisable in Figure 5-2, because the median value is further away from the minimum value (red shaded area) in that period of the year. The position of the median in between the minimum and maximum value is thus an indication on the skewness of the ensemble members.

Note that Figure 5-2 also shows the range in water temperatures resulting from the within-20-year (year to year) temperature variation. The grey area shows the 20- and 80-percentile range (instead of the mean) for the DOY of the 20-year period of each model chain.

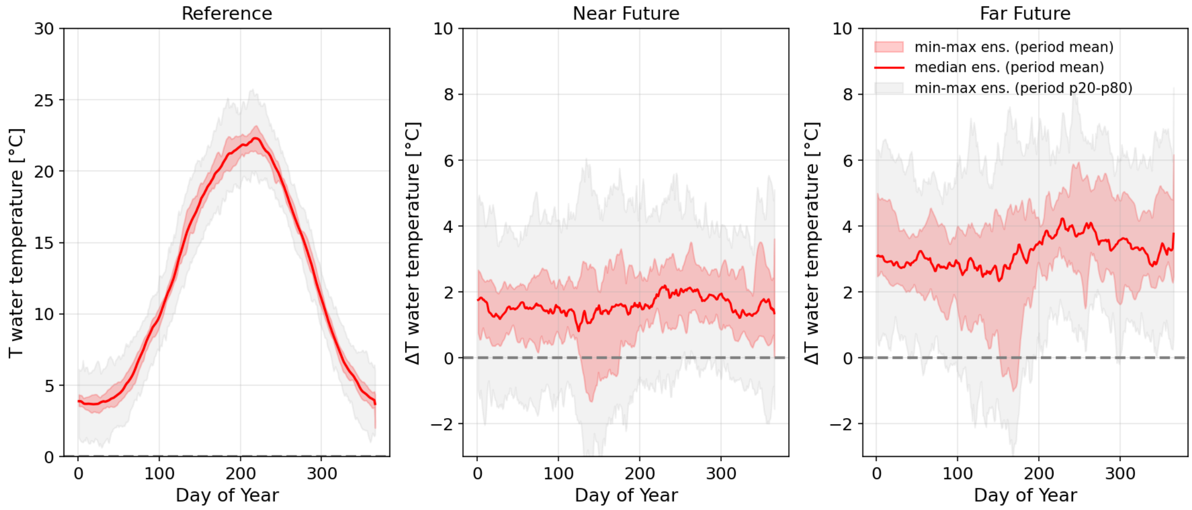
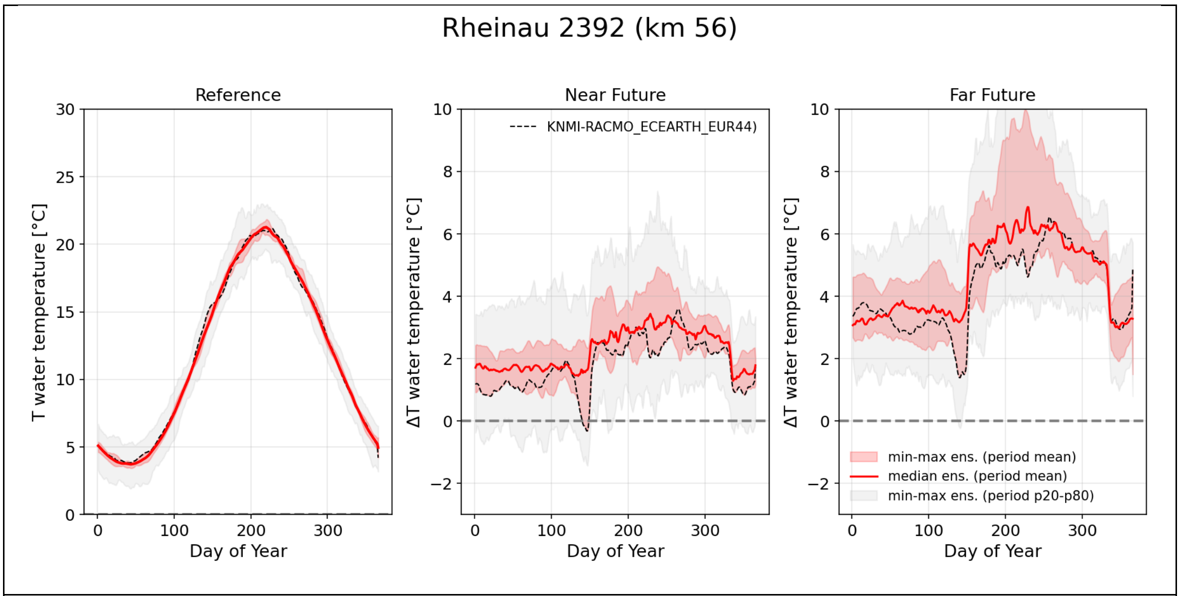


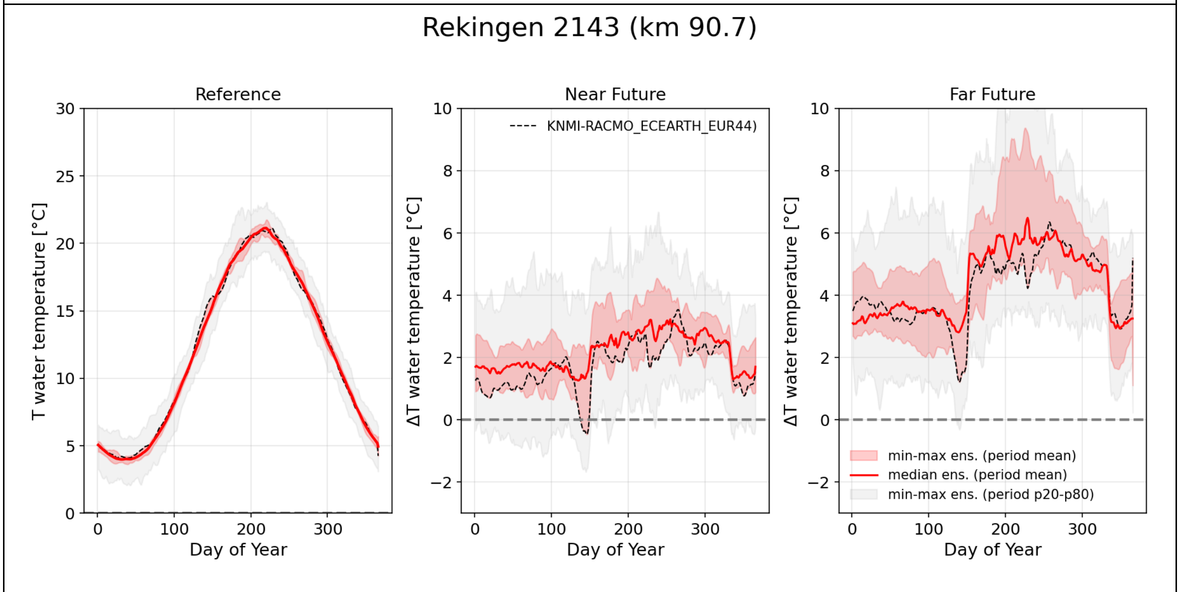
Figure 5-2 Water temperature (left panel: reference period, T in ºC) response to climate change (middle and right panels: near and far future dT in ºC). Location Bimmen as in Figure 5-1. Graphs show ensemble variation over the year: solid red line: ensemble median (n = 16), red shaded: range of ensemble means (min-max) and grey shaded area: range of weather variation (20-80 p of 20 y) of ensembles period (20 y).

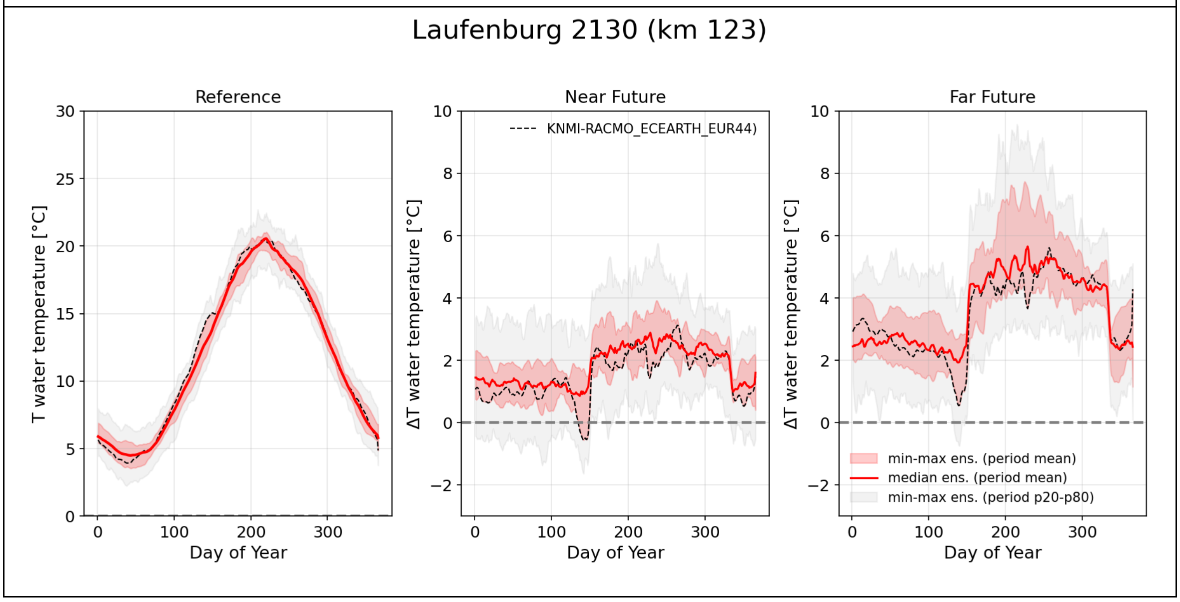
5.4 Results national ensembles: water temperature

This chapter shows the impact of a future climate on water temperature. Results are shown as the difference of water temperature in the future relative to the reference period (dT) per day of the year. The calculation method is explained in chapter 5.3. The red line and red area present the ensemble variation using a period median, the grey area gives an indication of the annual variation.

5.4.1 Switzerland







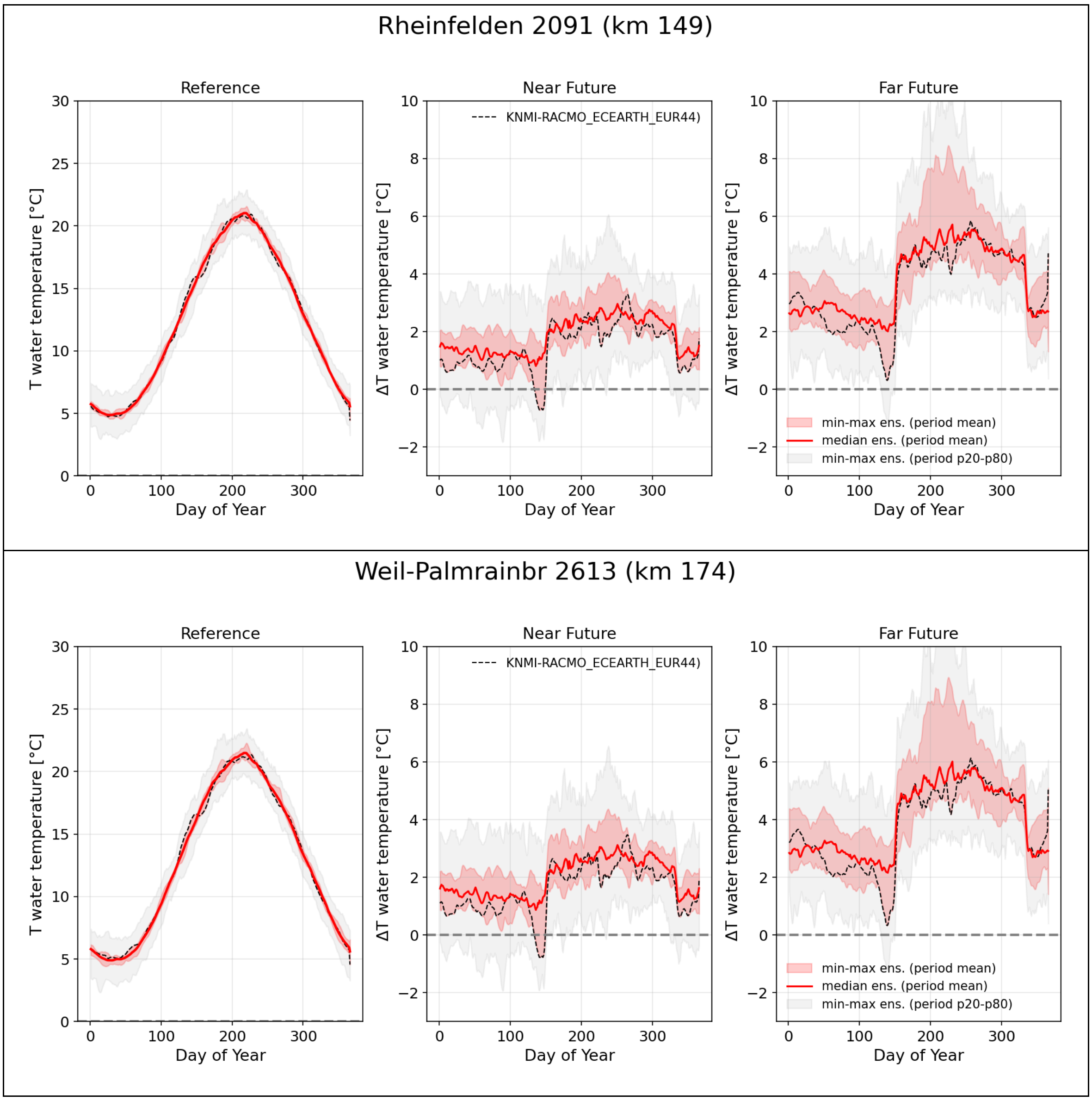
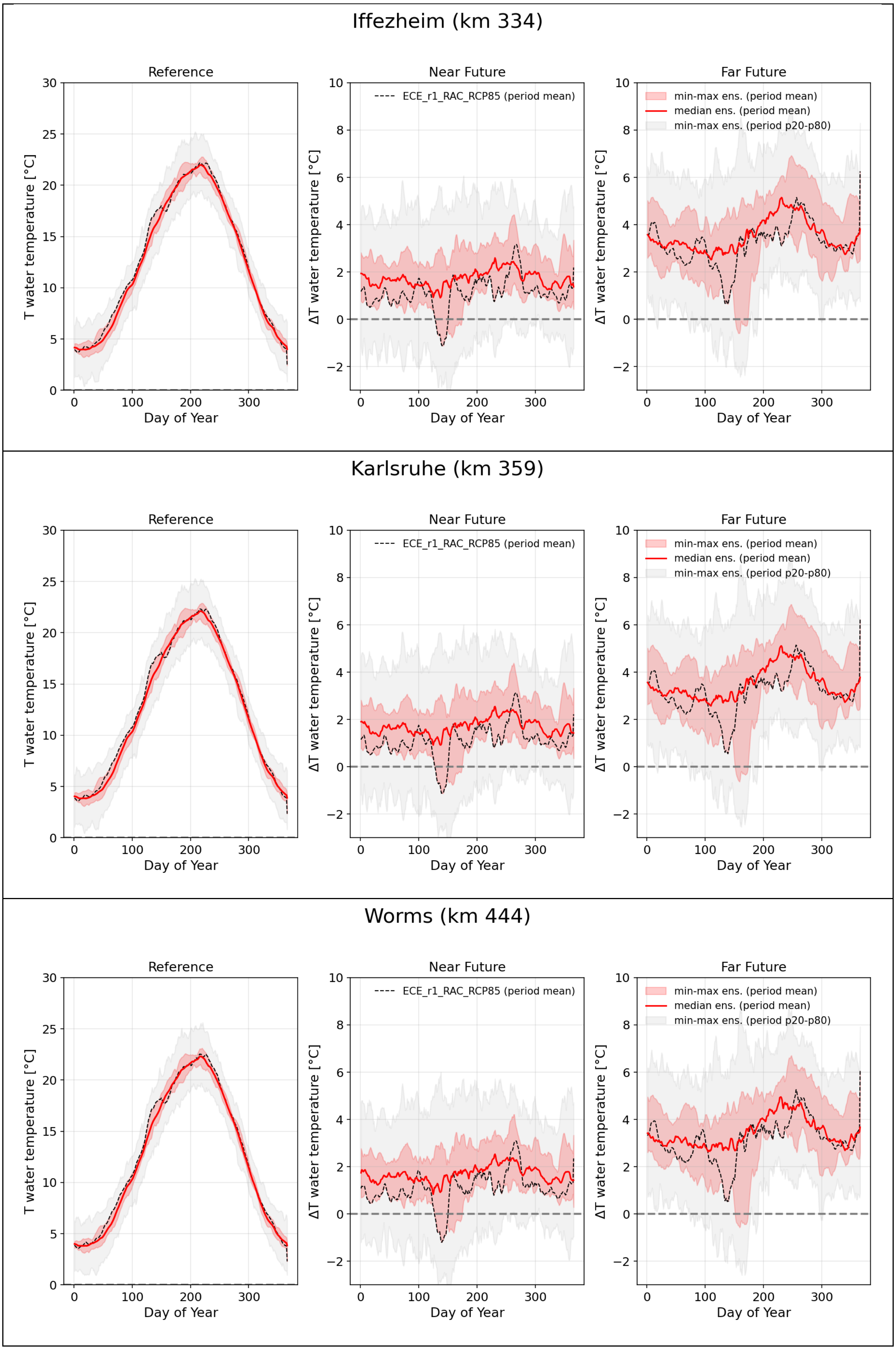


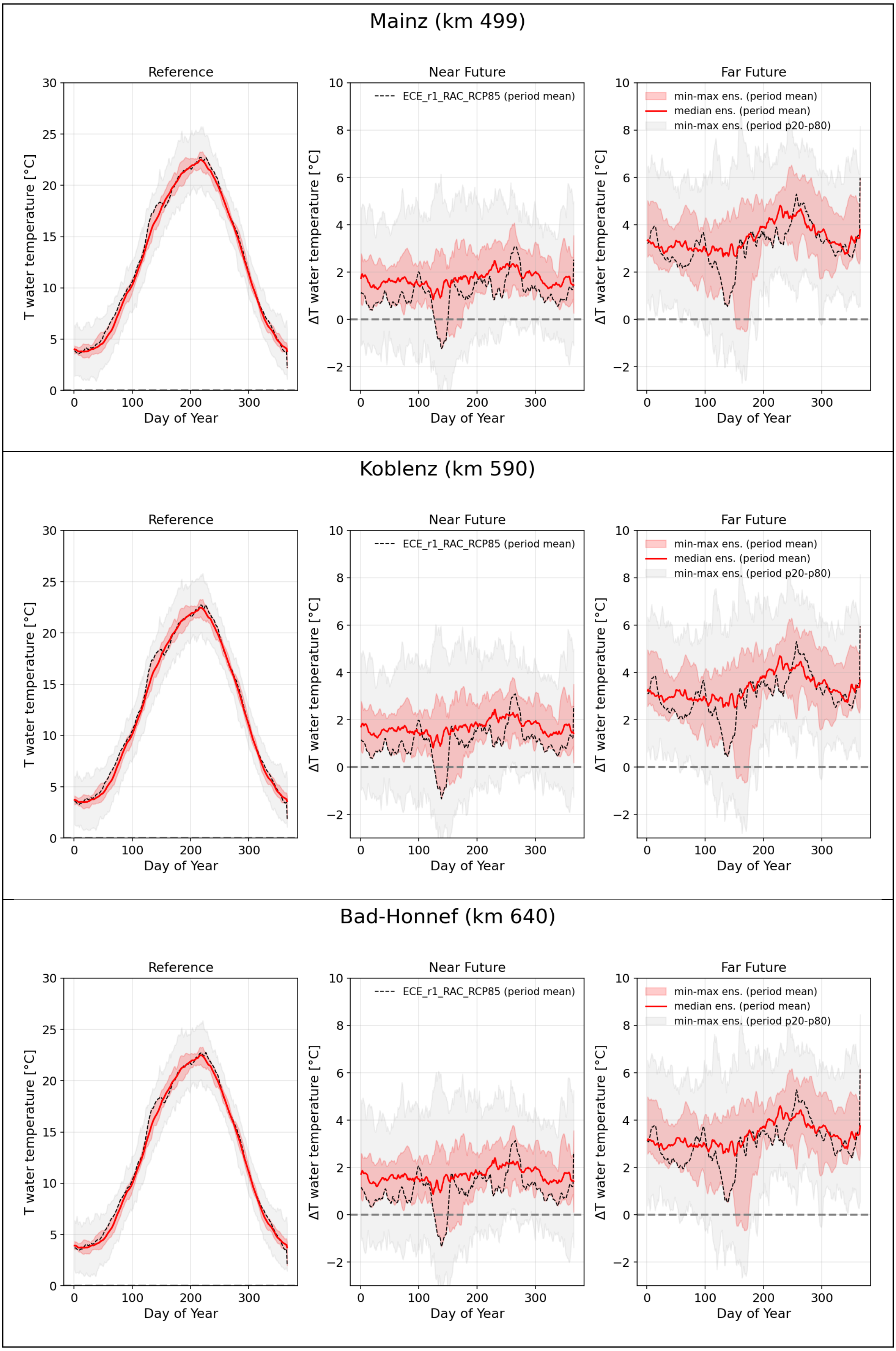
Figure 5-3 Water temperature (left panel: reference period, T in ºC) response to climate change (middle and right panels: near and far future dT in ºC) for selected Swiss stations. Graphs show ensemble variation over the year: solid red line: ensemble median (n = 14), red shaded area: range of ensemble means (min-max) and grey shaded area: range of weather variation (20-80 p of 20 y) of ensembles period (20 y). Note: temperature variation for the common climate chain (ECEARTH_01_KNMI-RACMO) is shown as black dashed line.

In Figure 5-3, note that the temperature increase in summer (DOY 150-320) is significantly higher than the increase in the remaining part of the year, the changeover is abrupt, and the effect is more pronounced for the far future. The median value shows this step trend as well. This increase is stronger than the river heterogeneity reported (-0.05 °C to 4.32 °C). River water temperatures are sensitive to complex upstream lake thermal regime, including ice coverage and stratification phenomena (BAFU, 2023). The semi-deterministic model implementation chosen (chapter 3.3.1 eq. 1 excluding ice formation) using sinusoidal forcing may not always capture the timing and "memory" of the water system perfectly.

Summer water temperatures (Basel) increase from 3.0±1.0 °C in near future to 5.5±2.0 °C in the far future. Winter water temperatures (Basel) increase from 1.0±1.0 °C in the near future to 2.5±1.0 °C in the far future. In the near future, the common climate chain results in a negative dT (cooling) around day 120. In the far future, all ensemble members show positive values for dT (warming).

5.4.2 Germany


Iffezheim (km 334)
Reference
Near Future
Far Future
T water temperature [°C]
ΔT water temperature [°C]
Day of Year
ECE_r1_RAC_RCP85 (period mean)
min-max ens. (period mean)
median ens. (period mean)
min-max ens. (period p20-p80)
Karlsruhe (km 359)
Reference
Near Future
Far Future
T water temperature [°C]
ΔT water temperature [°C]
Day of Year
ECE_r1_RAC_RCP85 (period mean)
min-max ens. (period mean)
median ens. (period mean)
min-max ens. (period p20-p80)
Worms (km 444)
Reference
Near Future
Far Future
T water temperature [°C]
ΔT water temperature [°C]
Day of Year
ECE_r1_RAC_RCP85 (period mean)
min-max ens. (period mean)
median ens. (period mean)
min-max ens. (period p20-p80)



Mainz (km 499)
Reference
Near Future
Far Future
T water temperature [°C]
ΔT water temperature [°C]
Day of Year
ECE_r1_RAC_RCP85 (period mean)
min-max ens. (period mean)
median ens. (period mean)
min-max ens. (period p20-p80)
Koblenz (km 590)
Reference
Near Future
Far Future
T water temperature [°C]
ΔT water temperature [°C]
Day of Year
ECE_r1_RAC_RCP85 (period mean)
min-max ens. (period mean)
median ens. (period mean)
min-max ens. (period p20-p80)
Bad-Honnef (km 640)
Reference
Near Future
Far Future
T water temperature [°C]
ΔT water temperature [°C]
Day of Year
ECE_r1_RAC_RCP85 (period mean)
min-max ens. (period mean)
median ens. (period mean)
min-max ens. (period p20-p80)

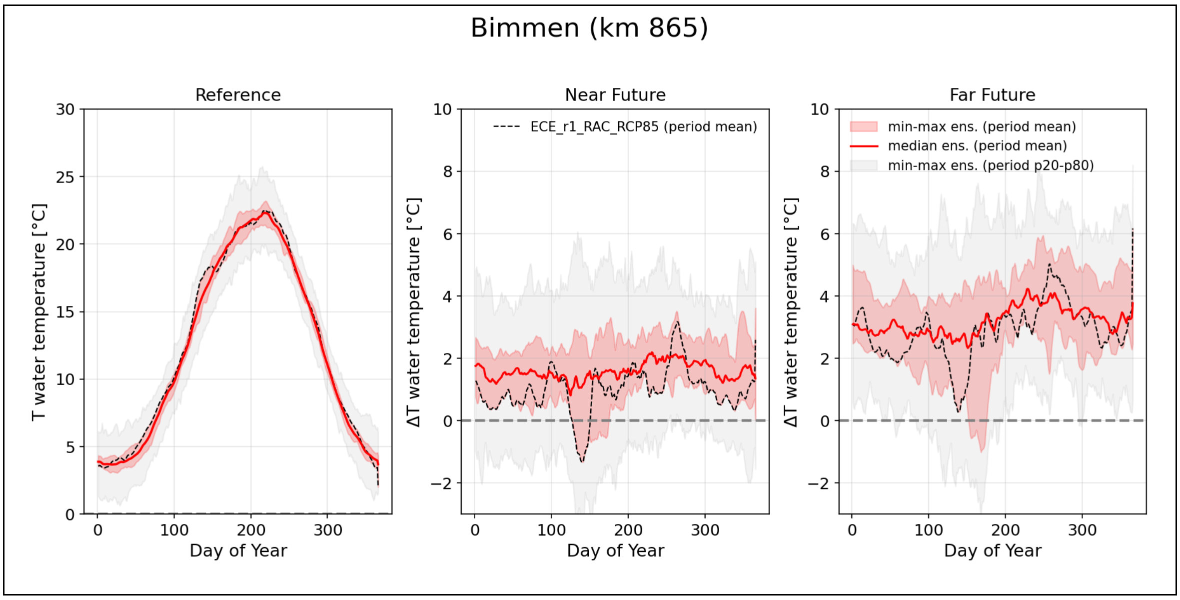


Figure 5-4 Water temperature (left panel: reference period, T in ºC) response to climate change (middle and right panels: near and far future dT in ºC) for selected German stations. Graphs show within ensemble variation over the year: solid red line: ensemble median (n = 16), red shaded area: range of ensemble means (min-max) and grey shaded area: range of weather variation (20-80 p of 20 y) of ensembles period. Note: temperature variation for the common climate chain (ECEARTH_01_KNMI-RACMO) is shown as black dashed line.

In Figure 5-4, note that German ensembles (5 out of 16 overlapping with Switzerland) show lower dT and lower minimum-maximum range compared to Switzerland, the transition from summer to winter is also more gradually.

The upstream German stations show, similar to the Swiss stations, higher temperature increase (dT) in summer compared to the remaining part of the year. Ensemble range in Switzerland (Basel) reaches +8 °C, in Germany (Iffezheim) +6.5 °C, the median of the ensembles in Germany is 1 °C lower compared to Switzerland. The difference diminishes going downstream.

Average water temperature in far future summers ranges from +5 °C in upstream stations to +4 °C near the Dutch border. Note that absolute temperatures (not shown) increase going downstream.

5.4.3 The Netherlands

KNMI'14 uses only one GCM and an ensemble of eight RACMO members. In essence, the model projections with EC-Earth/RACMO are then divided into two different subsets. The subset representing a strong response to air circulation (labelled with subscript "H") with wetter winters and drier summers is used for hydrological modelling [19]. For the subset with a relatively weak response (labelled with subscript "L"), with smaller changes in precipitation, no hydrological model runs were (made) available.

So, emission scenario RCP8.5 within the Netherlands relies on one hydrological simulation based on the KNMI climate "chain" W_H. The KNMI scenarios were optimized to represent the spread in seasonal mean temperature and precipitation changes in CMIP5 (when interpolated) for the Netherlands (Lenderink et al., 2014) covering at least the 25 to 75 percentile range of the CMIP5 model outcomes for seasonal mean changes and preferably about the 10 to 90 percentile range. The Dutch scenarios are not specifically designed for the Rhine catchment area.

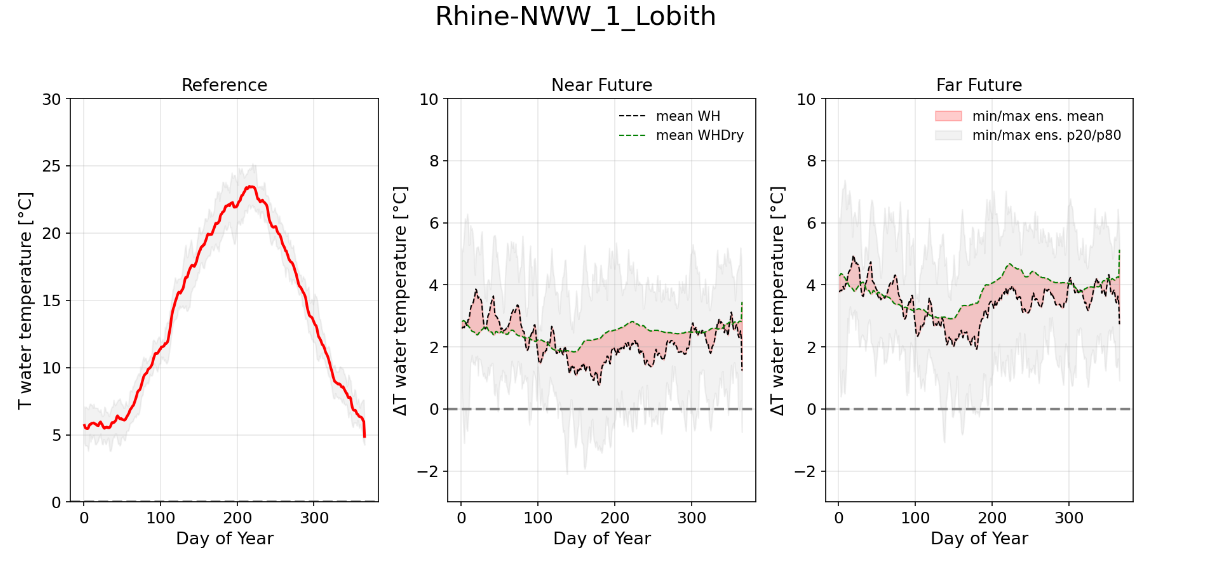
The W_H scenario is the most extreme KNMI'14 scenario in terms of summer drying. The mean change over the Netherlands is -23 % in precipitation (between the 25th and 75th

percentile) out of CMIP5. For the Rhine catchment (upstream of Lobith), the projected CMIP5 change is a decrease of about 30 % in summer, while the set of four RACMO2/EC-Earth simulations (the above-mentioned H-pool) used for the W_H scenario (for the Netherlands) projects a decrease of only −10 %. So, optimal results for the Rhine area could not be obtained with the chosen method (construction of W_H) while simultaneously retaining the required results for the Netherlands. In essence, this is a consequence of downscaling only one global climate model (that is, EC-Earth), which has a persistent east-west precipitation gradient and only one realization of the strength of large-scale soil moisture feedback (required to reduce precipitation further in the German part of the Rhine basin).

With the release of the KNMI'14 scenarios, it was thus realized that the potential decrease in summer precipitation was underestimated in particular for the Rhine catchment area. An additional scenario (denoted as $W_{H,dry}$) was prepared based on the downscaling of a different GCM, HadGEM2-ES, again with RACMO2 for downscaling.

For EG STEMP, one additional hydrological simulation was prepared next to the national approach, to summarize:

- The national approach uses W_H (ECEARTH_01_KNMI-RACMO) for climate inside the Netherlands and derives its national boundaries for Rhine and Meuse from the unofficial KNMI scenario W_{HDRy} (ensemble HADGEM2_01_KNMI-RACMO) (Deltares, 2018).
- The common run (prepared for EG STEMP) uses W_H (ECEARTH_01_KNMI-RACMO) for climate inside the Netherlands as well as driver for the national boundaries for Rhine and Meuse.



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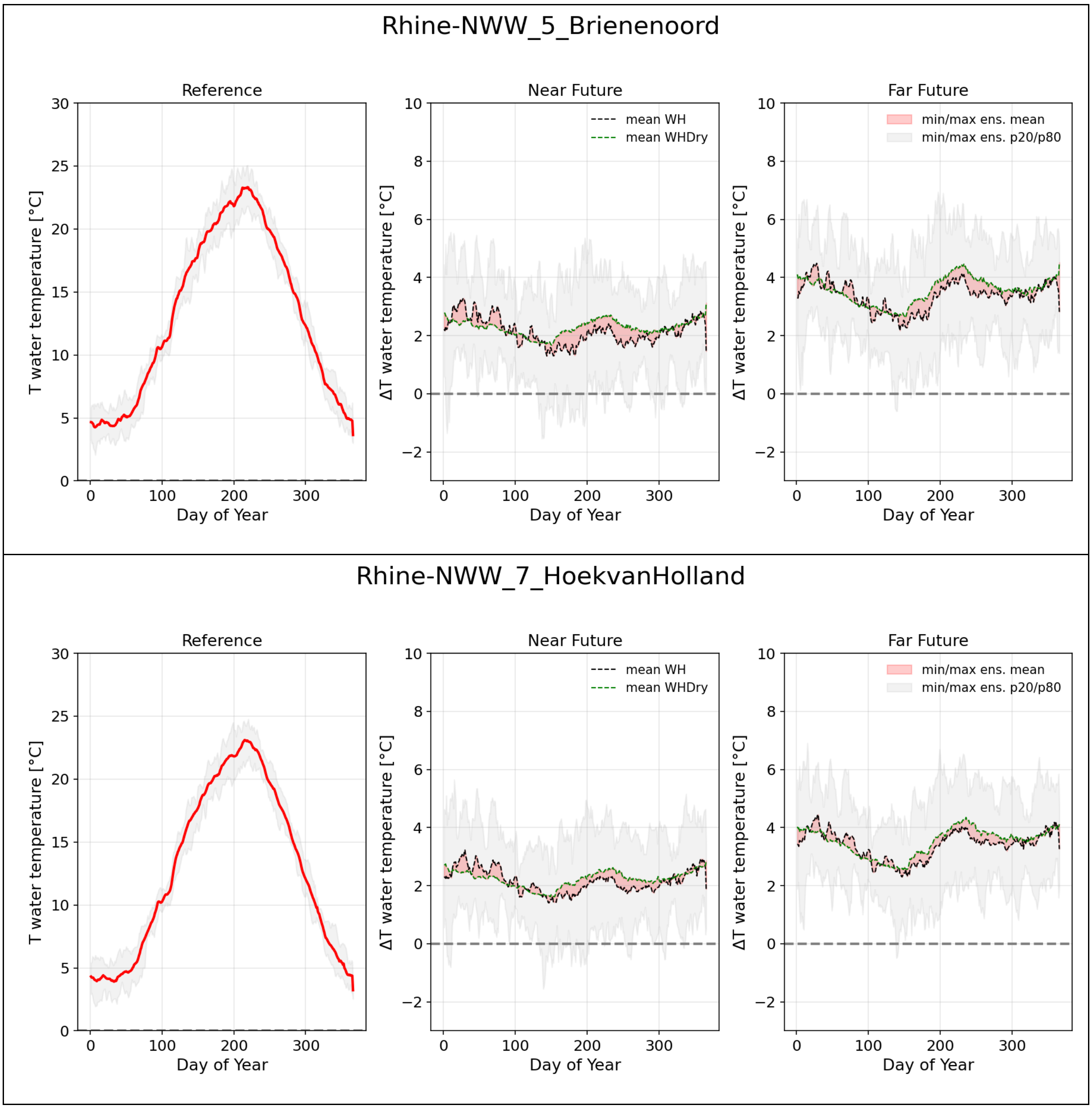

Figure 5-5 Water temperature (left panel: reference period, T in ºC) response to climate change (middle and right panels: near and far future dT in ºC) for selected Dutch stations. Graphs show within ensemble variation over the year: solid red line: ensemble mean (n = 2), red shaded area: range of ensemble means and grey shaded area: range of weather variation (20-80 p of 20 y) of ensembles period. Note: temperature variation for the common climate chain (ECEARTH_01_KNMI-RACMO) is shown as black dashed line.

In Figure 5-5, note that only two ensembles are presented, the Dutch variation is therefore small compared to the German and Swiss stations and stronger dominated by interannual variation. Average water temperature in far future summer (+4 °C) is in line with the upstream Lower Rhine stations in Germany. Towards the North Sea, the variation in water temperature increase is reduced.

5.4.4 Rhine profile for national ensemble temperatures

The interannual temperature variation is large and mostly exceeds the ensemble variation. The overall variation (interannual and ensemble) is combined in the longitudinal box plot (Figure 5-6) below. Figure 5-6 presents the national water temperature projections (chapters 5.4.1, 5.4.2 and 5.4.3) as boxplots along the longitudinal axis of the Rhine. Note that the wT from statistical relationships at the national boundaries (Basel and Lobith) are shown, too.

The following observations can made from this graph:

- There is no consistent trend in water temperature along the Rhine, looking at the "boxes" (25 and 75 p) and the whiskers (95 p).
- Variation across the stations in Germany is small.
- The transition from Switzerland (Weil am Rhein) to Germany (Basel) is fairly smooth where the German upper boundary is cooler (5 p values, 75 p values notably for the future scenarios).
- The transition from Germany (Bimmen) to the Netherlands (Lobith) is classified as a 'jump' where the Dutch national boundary is warmer, including the reference scenario.

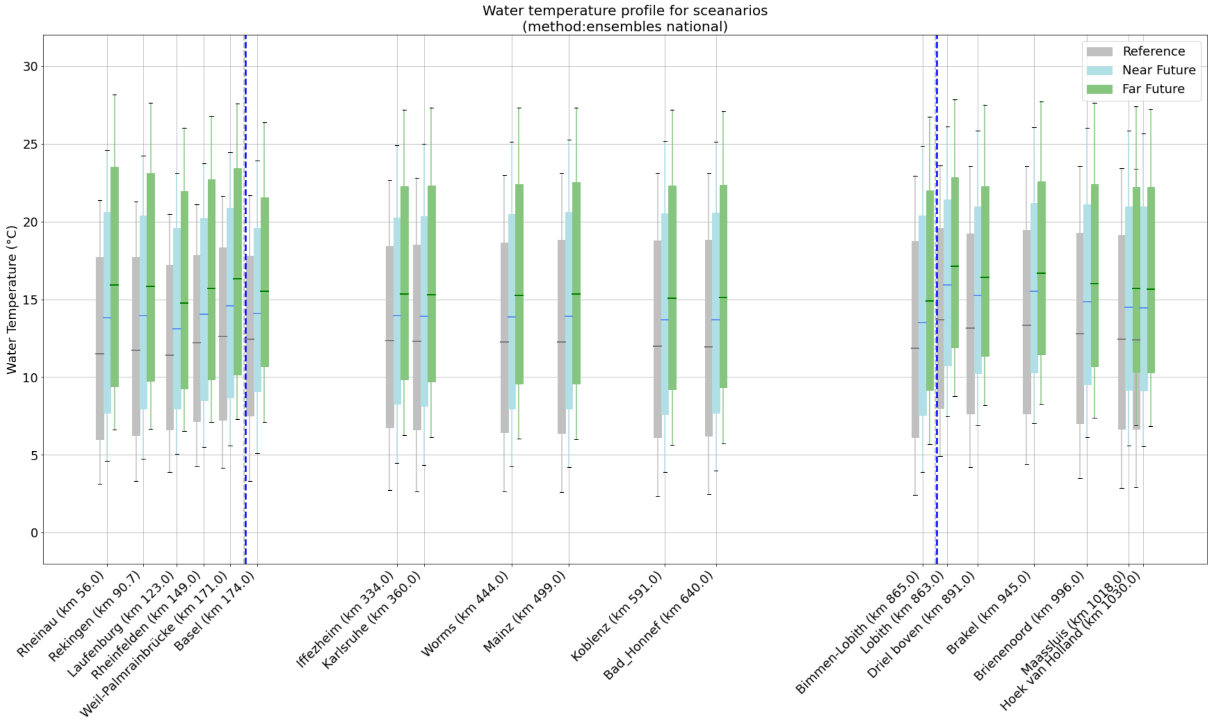

Figure 5-3 Longitudinal water temperature profile of the Rhine from simulation without heat input using the national ensembles, shown as temperature for the three scenarios (reference period (1990-2010), near future (2045-2065) and far future (2080-2100). The boxplots show the period median (horizontal solid line), the first and the third quartile (borders) and the 5 and 95 percentile data (whiskers). wT at the national boundaries (Basel and Lobith) are shown (next to the vertical blue line).

5.4.5 Data summary

Table *5-3 Summary statistics showing the range in quarterly averaged Rhine water temperature (°C) for the three scenario and temperature increase (dT, (°C) for near and far future scenarios in national runs (ensemble mean). Quarters per column: winter-DJF, spring-MAM, summer-JJA and autumn-SON. Colours are relative per column indicating longitudinal temperature gradient (per scenario and per season). Relevant differences at national boundaries are indicated by yellow boxes.*

variabele	T(°C)			T(°C)			T(°C)			T(°C)		
season	WINTER			SPRING			SUMMER			AUTUMN		
scenario	REF	NF	FF	REF	NF	FF	REF	NF	FF	REF	NF	FF
Rheinau_2392_km-56	5.0	6.5	8.3	8.7	10.4	12.4	19.4	22.4	25.6	14.3	17.2	19.9
Rekingen_2143_km-90.7	5.0	6.6	8.4	9.3	10.9	12.8	19.4	22.2	25.2	14.1	16.9	19.4
Laufenburg_2130_km-123	5.7	7.0	8.4	8.7	9.9	11.2	18.5	20.9	23.5	14.4	16.8	19.0
Rheinfelden_2091_km-149	5.8	7.1	8.6	10.2	11.4	12.8	19.5	21.9	24.6	14.3	16.8	19.2
Weil-Palmrainbr_2613_km-174	5.9	7.3	8.9	10.5	11.7	13.2	20.0	22.6	25.4	14.7	17.4	19.8
Basel (km 171)	5.5	7.1	9.0	11.6	13.1	14.7	19.7	21.6	23.7	13.3	15.2	17.0
Iffezheim (km 334)	4.7	6.3	8.0	11.5	12.9	14.4	20.5	22.5	24.5	13.4	15.3	17.2
Karlsruhe (km 359)	4.6	6.2	7.9	11.5	12.9	14.4	20.6	22.6	24.6	13.3	15.2	17.0
Worms (km 444)	4.5	6.1	7.7	11.5	12.9	14.4	20.8	22.7	24.7	13.2	15.1	16.9
Mainz (km 499)	4.5	6.0	7.7	11.5	13.0	14.5	21.0	22.9	24.8	13.3	15.2	17.0
Koblenz (km 590)	4.2	5.7	7.4	11.4	12.8	14.3	21.0	22.8	24.7	13.0	14.8	16.6
Bad-Honnef (km 640)	4.3	5.8	7.5	11.3	12.8	14.3	21.0	22.8	24.6	13.0	14.9	16.7
Bimmen (km 865)	4.3	5.7	7.4	11.2	12.5	14.0	20.9	22.6	24.3	13.0	14.8	16.5
Rhine-NWW_1_Lobith (km 863)	6.4	9.1	10.4	12.6	14.8	15.7	21.7	23.7	25.2	14.9	17.1	18.7
Rhine-NWW_2_Brakel (km 945)	5.9	8.6	9.9	12.4	14.5	15.4	21.6	23.6	25.1	14.5	16.7	18.2
Rhine-NWW_3_Vuren (km 951)	5.9	8.6	9.8	12.3	14.5	15.4	21.6	23.6	25.1	14.5	16.7	18.2
Rhine-NWW_4_Brienenoord_RO (km 995)	5.1	7.7	8.9	12.0	14.0	15.0	21.5	23.6	25.0	14.0	16.1	17.6
Rhine-NWW_5_Brienenoord (km 996)	5.1	7.7	8.9	12.0	14.0	15.0	21.5	23.6	25.0	14.0	16.1	17.6
Rhine-NWW_6_Maasluis (km 1018)	4.7	7.3	8.5	11.6	13.6	14.5	21.3	23.4	24.8	13.9	16.0	17.4
Rhine-NWW_7_HoekvanHolland (km 1030)	4.7	7.2	8.5	11.5	13.5	14.4	21.2	23.3	24.7	13.9	16.0	17.5

summarises the results of the national water temperature simulations. The summary statistics show quarterly Rhine water temperatures (T in °C) for the three scenario and temperature increase (dT in °C) for near and far future scenarios per season.

The following observations are made fromTable 5-4

Table 5-3 Summary statistics showing the range in quarterly averaged Rhine water temperature (°C) for the three scenario and temperature increase (dT, (°C) for near and far future scenarios in national runs (ensemble mean). Quarters per column: winter-DJF, spring-MAM, summer-JJA and autumn-SON. Colours are relative per column indicating longitudinal temperature gradient (per scenario and per season). Relevant differences at national boundaries are indicated by yellow boxes.

variabele	T(°C)			T(°C)			T(°C)			T(°C)		
season	WINTER			SPRING			SUMMER			AUTUMN		
scenario	REF	NF	FF	REF	NF	FF	REF	NF	FF	REF	NF	FF
Rheinau_2392_km-56	5.0	6.5	8.3	8.7	10.4	12.4	19.4	22.4	25.6	14.3	17.2	19.9
Rekingen_2143_km-90.7	5.0	6.6	8.4	9.3	10.9	12.8	19.4	22.2	25.2	14.1	16.9	19.4
Laufenburg_2130_km-123	5.7	7.0	8.4	8.7	9.9	11.2	18.5	20.9	23.5	14.4	16.8	19.0
Rheinfelden_2091_km-149	5.8	7.1	8.6	10.2	11.4	12.8	19.5	21.9	24.6	14.3	16.8	19.2
Weil-Palmrainbr_2613_km-174	5.9	7.3	8.9	10.5	11.7	13.2	20.0	22.6	25.4	14.7	17.4	19.8
Basel (km 171)	5.5	7.1	9.0	11.6	13.1	14.7	19.7	21.6	23.7	13.3	15.2	17.0
Iffezheim (km 334)	4.7	6.3	8.0	11.5	12.9	14.4	20.5	22.5	24.5	13.4	15.3	17.2
Karlsruhe (km 359)	4.6	6.2	7.9	11.5	12.9	14.4	20.6	22.6	24.6	13.3	15.2	17.0
Worms (km 444)	4.5	6.1	7.7	11.5	12.9	14.4	20.8	22.7	24.7	13.2	15.1	16.9
Mainz (km 499)	4.5	6.0	7.7	11.5	13.0	14.5	21.0	22.9	24.8	13.3	15.2	17.0
Koblenz (km 590)	4.2	5.7	7.4	11.4	12.8	14.3	21.0	22.8	24.7	13.0	14.8	16.6
Bad-Honnef (km 640)	4.3	5.8	7.5	11.3	12.8	14.3	21.0	22.8	24.6	13.0	14.9	16.7
Bimmen (km 865)	4.3	5.7	7.4	11.2	12.5	14.0	20.9	22.6	24.3	13.0	14.8	16.5
Rhine-NWW_1_Lobith (km 863)	6.4	9.1	10.4	12.6	14.8	15.7	21.7	23.7	25.2	14.9	17.1	18.7
Rhine-NWW_2_Brakel (km 945)	5.9	8.6	9.9	12.4	14.5	15.4	21.6	23.6	25.1	14.5	16.7	18.2
Rhine-NWW_3_Vuren (km 951)	5.9	8.6	9.8	12.3	14.5	15.4	21.6	23.6	25.1	14.5	16.7	18.2
Rhine-NWW_4_Brienenoord_RO (km 995)	5.1	7.7	8.9	12.0	14.0	15.0	21.5	23.6	25.0	14.0	16.1	17.6
Rhine-NWW_5_Brienenoord (km 996)	5.1	7.7	8.9	12.0	14.0	15.0	21.5	23.6	25.0	14.0	16.1	17.6
Rhine-NWW_6_Maasluis (km 1018)	4.7	7.3	8.5	11.6	13.6	14.5	21.3	23.4	24.8	13.9	16.0	17.4
Rhine-NWW_7_HoekvanHolland (km 1030)	4.7	7.2	8.5	11.5	13.5	14.4	21.2	23.3	24.7	13.9	16.0	17.5

Table 5-3 focussing on the differences between the three national stretches and the transition at the national boundaries.

- Switzerland shows warming up to Weil am Rhein (144 km) in all seasons (+0.1-1.4 °C).
- Germany, over the stretch Basel-Bimmen (almost 700 km), shows cooling in all seasons (DJF: -1.5 °C, MAM: -0.9 °C and SON: -0.4 °C) except for summer (JJA: +1.0 °C.
- The Netherlands (177 km) show cooling in all seasons (-0.5 °C in summer, other seasons -1.1 °C to -1.7 °C).

- In the winter half year (DJF, SON), water temperature in Germany is significantly colder compared to Switzerland as well as compared to the Netherlands (visible from the two blue cells in the table). The difference between D and CH is smaller (-1 °C to -1.5 °C) compared to the difference between D and NL (-1.5 °C to -2 °C).
- The order in which temperature changes along the Rhine in winter is therefore: cooling from CH to D and warming from D to NL. In the summer half year, the Rhine profile shows continuous gradual warming from CH to D to NL.
- There are strong temperature gradients at national boundaries (Table 5-2). It shows that wT at the German national border is notably warmer in spring and notably colder in autumn and it shows that wT at the Dutch national border is warmer through the year with highest warming in winter.

Table 5-2 Water temperature differences at national boundaries (from Table 5-3).

	REF	NF	FF	REF	NF	FF	REF	NF	FF	REF	NF	FF
		WINTER			SPRING			SUMMER			FALL	
border CH->D	-0.4	-0.2	0.1	1.2	1.4	1.5	-0.3	-0.9	-1.7	-1.5	-2.2	-2.8
border D->NL	2.1	3.4	3.0	1.5	2.2	1.7	0.8	1.1	0.9	1.9	2.3	2.2

Notably, the sudden changes at the national boundaries need to be explained:

The explanation has two aspects, both relate to the empirical relations used to derive water temperature at the upper boundaries of the national models.

Starting with the Germany (Bimmen) to the Netherlands (Lobith) boundary has the biggest discrepancy. It is observed that the reference scenario is already very different (the difference in the reference is included in the future scenario's too as NL uses a dT vector). The most plausible explanation for the reference scenario is the fact that the contribution of direct heat inputs is excluded from the national models (by intention). This means that at location Bimmen (the most downstream station of the German model) there is no excess heat in the simulation result. In the Dutch model starting at Lobith however, heat input remains are implicitly included as the water temperature is based on measured water temperatures. The difference between the model without heat inputs at Bimmen and the empirical relation at Lobith is ostensibly large (+1.9 °C to 2.1 °C in winter, +0.8 °C to 1.5 °C in summer in the reference scenario) to be explained by excess heat. Afterall, the heat simulated in chapter 4.2.3 in the QSim validation for the validation period (2018-2020) shows only contribution of 1.0 °C (winter) to 0.5 °C (summer), roughly half. However, one has to realise that the boundary at Lobith is based on water temperature recordings originating from the reference period (1991-2010). It is very likely that heat inputs have reduced by factor two in the 20 to 30 years that have passed since for the following reasons:

- Direct heat input downstream of Fessenheim in the validation for QSim is 5800 MW (summer) to 8100 MW (winter); permitted discharges in 2010 (ICPR, 2014) in the same river stretch was 18600 MW (more than twice the highest (winter) value).
- Although actual heat inputs are not known and probably lower than the permitted discharges the smaller heat loads (< 200 MW) are excluded from the inventory.

The above explanation cannot explain all of the observed differences between the two approaches for the future scenarios. This will be further discussed in chapter 6.2.1.

The discrepancy in wT from Switzerland (Basel) to Germany (Weil am Rhein) has a different explanation. Both Weil am Rhein (upper wT boundary Germany) and all Swiss model stations are empirical models somehow trained on measured water temperature data. So, at both sides of the CH-D boundary remains of heat inputs (e. g. from KKW Beznau) are implicitly included. Heat inputs can therefore not be the cause of the difference and are not further discussed here, apart from the remark that the models applied in CH (ICPR, 2014) cannot distinguish anthropogenic heat which hampers, at least theoretically, the prediction of a future without heat inputs.

The likely explanation for the difference at the CH-D boundary is the nature of the empirical relationships used. The relation used for Weil am Rhein (D) is a simple linear relationship between wT and air temperature. The Swiss semi-deterministic model (chapter 3.3.1) is more advanced and includes memory effects by including the reference temperature for deeper layers of lakes in the equation. This explains that Weil am Rhein is colder in spring compared to Basel: wT predicted from air temperature is (too) high if not corrected for inflow from colder lakes. The opposite holds for the fall season, when wT is based on air temperature only, it is underestimated because water in autumn is warmer as influenced by relatively warm lakes acting as heat storage over summer.

Table 5-3 Summary statistics showing the range in quarterly averaged Rhine water temperature (°C) for the three scenario and temperature increase (dT, (°C) for near and far future scenarios in national runs (ensemble mean). Quarters per column: winter-DJF, spring-MAM, summer-JJA and autumn-SON. Colours are relative per column indicating longitudinal temperature gradient (per scenario and per season). Relevant differences at national boundaries are indicated by yellow boxes.

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scenario	REF	NF	FF	REF	NF	FF	REF	NF	FF	REF	NF	FF
Rheinau_2392_km-56	5.0	6.5	8.3	8.7	10.4	12.4	19.4	22.4	25.6	14.3	17.2	19.9
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Basel (km 171)	5.5	7.1	9.0	11.6	13.1	14.7	19.7	21.6	23.7	13.3	15.2	17.0
Iffezheim (km 334)	4.7	6.3	8.0	11.5	12.9	14.4	20.5	22.5	24.5	13.4	15.3	17.2
Karlsruhe (km 359)	4.6	6.2	7.9	11.5	12.9	14.4	20.6	22.6	24.6	13.3	15.2	17.0
Worms (km 444)	4.5	6.1	7.7	11.5	12.9	14.4	20.8	22.7	24.7	13.2	15.1	16.9
Mainz (km 499)	4.5	6.0	7.7	11.5	13.0	14.5	21.0	22.9	24.8	13.3	15.2	17.0
Koblenz (km 590)	4.2	5.7	7.4	11.4	12.8	14.3	21.0	22.8	24.7	13.0	14.8	16.6
Bad-Honnef (km 640)	4.3	5.8	7.5	11.3	12.8	14.3	21.0	22.8	24.6	13.0	14.9	16.7
Bimmen (km 865)	4.3	5.7	7.4	11.2	12.5	14.0	20.9	22.6	24.3	13.0	14.8	16.5
Rhine-NWW_1_Lobith (km 863)	6.4	9.1	10.4	12.6	14.8	15.7	21.7	23.7	25.2	14.9	17.1	18.7
Rhine-NWW_2_Brakel (km 945)	5.9	8.6	9.9	12.4	14.5	15.4	21.6	23.6	25.1	14.5	16.7	18.2
Rhine-NWW_3_Vuren (km 951)	5.9	8.6	9.8	12.3	14.5	15.4	21.6	23.6	25.1	14.5	16.7	18.2
Rhine-NWW_4_Brienenoord_RO (km 995)	5.1	7.7	8.9	12.0	14.0	15.0	21.5	23.6	25.0	14.0	16.1	17.6
Rhine-NWW_5_Brienenoord (km 996)	5.1	7.7	8.9	12.0	14.0	15.0	21.5	23.6	25.0	14.0	16.1	17.6
Rhine-NWW_6_Maasluis (km 1018)	4.7	7.3	8.5	11.6	13.6	14.5	21.3	23.4	24.8	13.9	16.0	17.4
Rhine-NWW_7_HoekvanHolland (km 1030)	4.7	7.2	8.5	11.5	13.5	14.4	21.2	23.3	24.7	13.9	16.0	17.5

5.5 Results national ensembles: temperature thresholds

In this chapter, the effect of climate change on water temperature is shown with respect to the number of days certain water temperature thresholds are passed. It evaluates against ‘absolute’ temperature rather than evaluating temperature increase as in the previous chapter. Such evaluation is relevant for living organisms functioning only within a certain temperature range or requiring cooler periods for reproduction and the development of eggs or larvae. In this chapter, several water temperature thresholds are evaluated, viz. 21.5 °C, 23 °C, 25 °C, 28 °C and 30 °C (number of days above) and 3 °C and 10 °C (number of days below). The reason for this relatively large number of thresholds is that countries along the Rhine use different limits. Different countries have different allowable water temperatures for surface water because of local climate conditions (natural water temperatures vary significantly so what is considered e. g. high in one country might be normal in another) and different water bodies have unique ecological characteristics and fish species with specific temperature requirements in different regions.

The simulated threshold violations strongly vary from year to year, this interannual variation is demonstrated for one location in the Netherlands (Figure 5-4).

*Figure 5-4 Number of days per year the water temperature is above 21.5 °C or 23 °C (upper panel), above 25 °C or 28 °C (middle panel) or below 10 °C or 3 °C (lower panel) for **Brienenoord_RO (Rhine-km 995)**. Each panel shows the years for three periods (reference, near and far future) on the x-axis. The number of days shown on the y-axis is the average number of days for the coupled common run (Table 5-1).*

The interannual variation is obviously large (Figure 5-8). For temperature thresholds that are not, or not yet, exceeded every year (in the Netherlands this is the case for temperatures below 3 °C and for temperatures above 25 °C and 28 °C) the relative error in the reported average number of days is large. For example, the number of days above 28 °C in the far future in the figure shows some years that have no threshold violations, others have 20 or more days per year.

The ensemble variation is presented in chapter 5.5.1, this is done for a selection of a few stations characterising the basin and six thresholds. In Table 5-4, a representative range of threshold violations is summarized for more stations and all threshold values.

5.5.1 Ensemble variation

Figure 5-5 shows the variation in days violating water temperature thresholds for the 13 climate ensembles used in the air2water model at station Rekingen (CH). Each ensemble on the x-axis is presented by the average number of days per year when a threshold is violated (the line connects the points). As each ensemble covers a 20-year period, there is a strong variation in the number of days a threshold is exceeded. This interannual variation is shown through the shaded area around the line, indicating the range covered by the 20th and 80th percentile (basically leaving out 4 out of 20 years, viz. the two lowest and two highest).

The ensemble variation is greatest for threshold temperatures furthest away from the mean temperature value at the location, for Rekingen these are < 3 °C (reference) and > 28 °C and > 25 °C (far future).

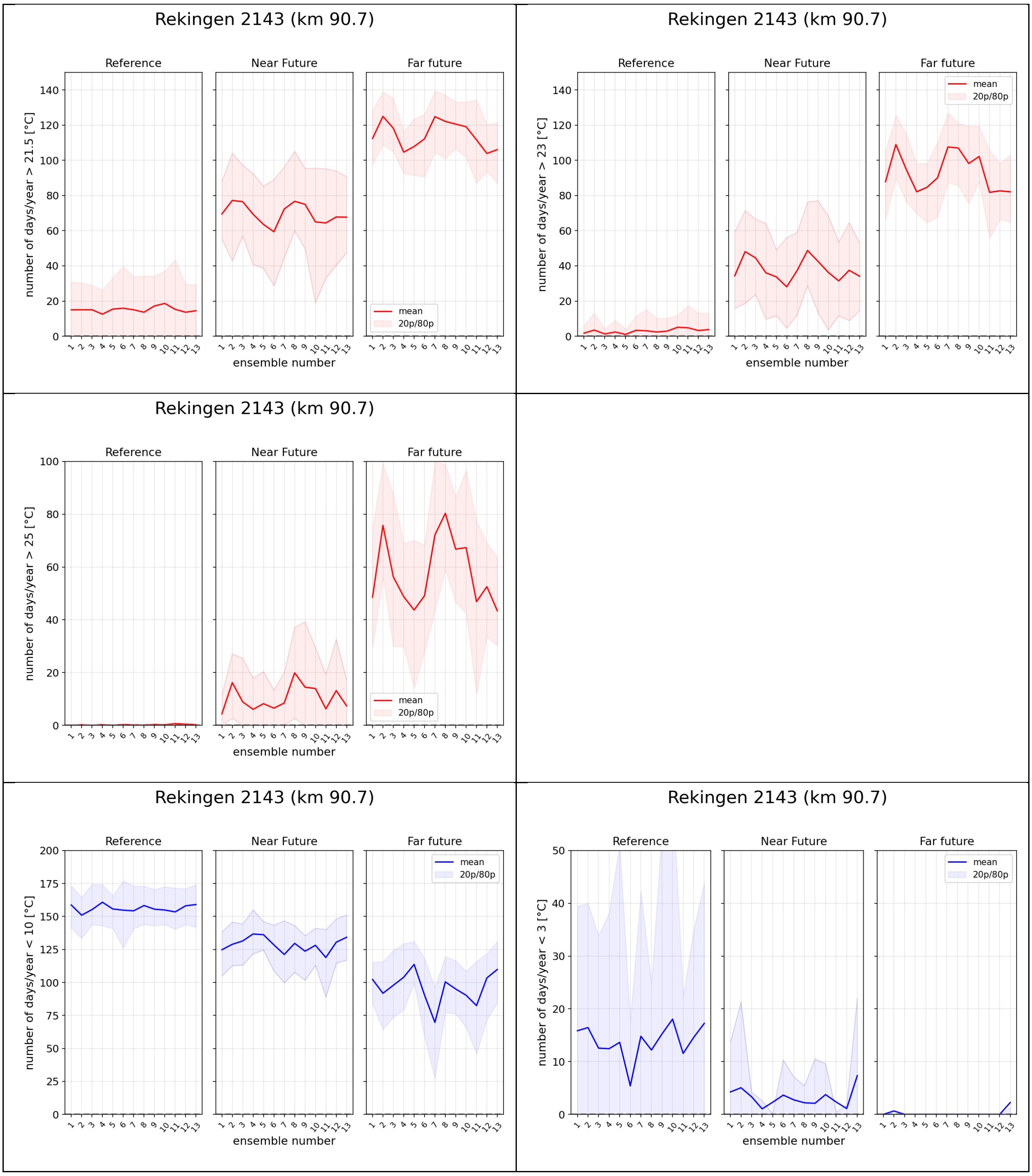
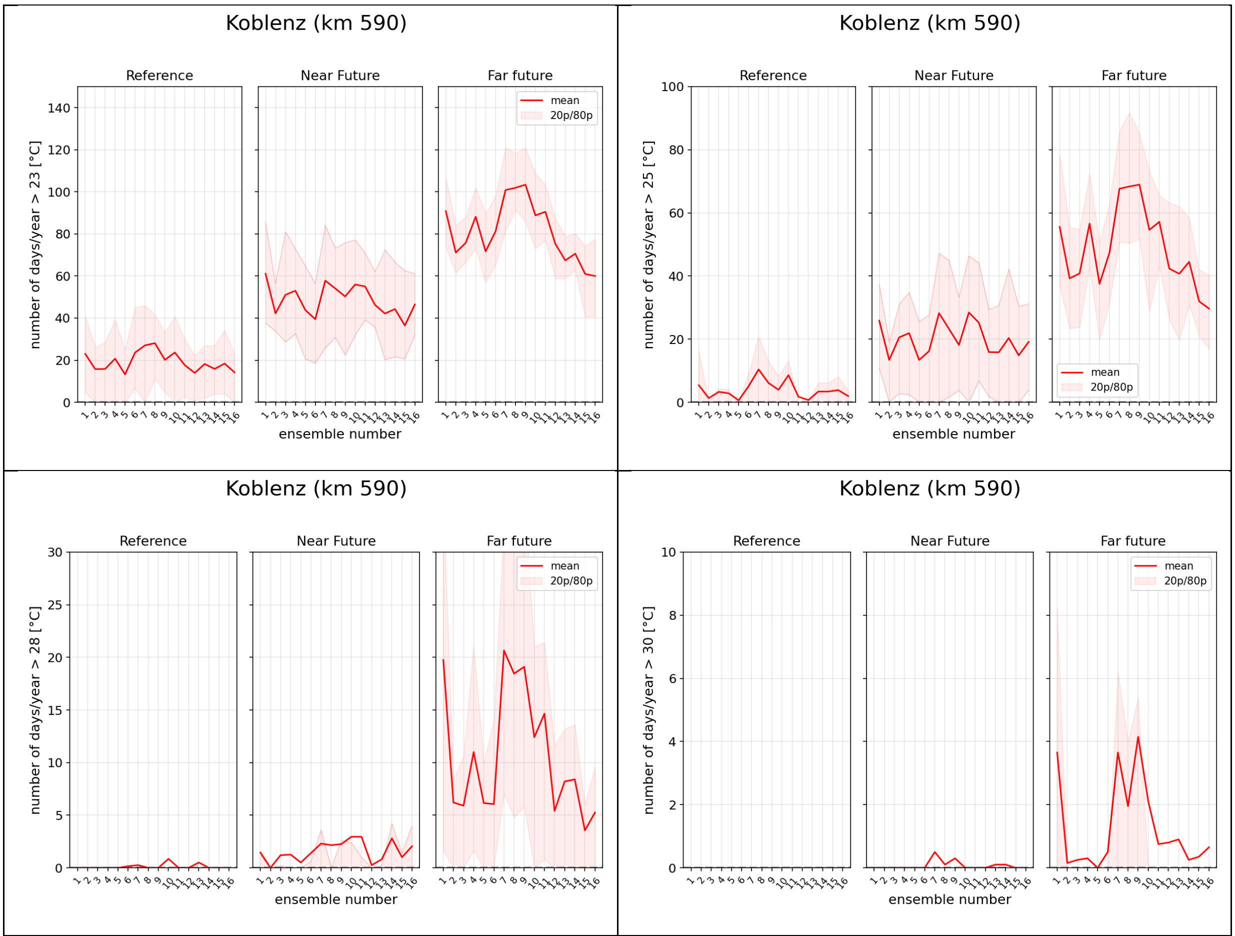


Figure 5-5 Number of days per year the water temperature is above 21.5 °C or 23 °C (upper panel), above 25 °C or 28 °C (middle panel) or below 10 °C or 3 °C (lower panel) in the reference, near and far future periods (three panels) at Rekingen (CH). Each panel shows 13 ensembles evaluated, see Table 5-1 . Each ensemble on the x-axis is presented by the average number of days per ensemble-year (20) a threshold is exceeded (line connects the points). The interannual variation is shown by the shaded area around the line covering 20 to 80 percentile values.

Figure 5-10shows the ensemble variation for days exceeding water temperature thresholds in 16 ensembles used to simulate wT at station Koblenz (D).

From the solid red line in Figure 5-10one can see (averages over the ensembles are listed in Table 5-4):

- an increase in warm days (> 25 °C), resulting in regular exceedance (20 d/y) in the near future to common exceedance of 40-60 d/y in the far future;
- a steady decrease in cool days (< 10 °C) from roughly five month/year to four month/year in the near future and three month/year in the far future;
- a seemingly exponential increase in hot days (> 28 °C), from rare at present to occasionally 10 d/y in the near future to on average 5-20 d/y in the far future (and regularly a month per year or more);
- a steady decrease in cold days (< 3 °C) with hardly any (on average 2-3 d/y) of such days remaining in the far future.



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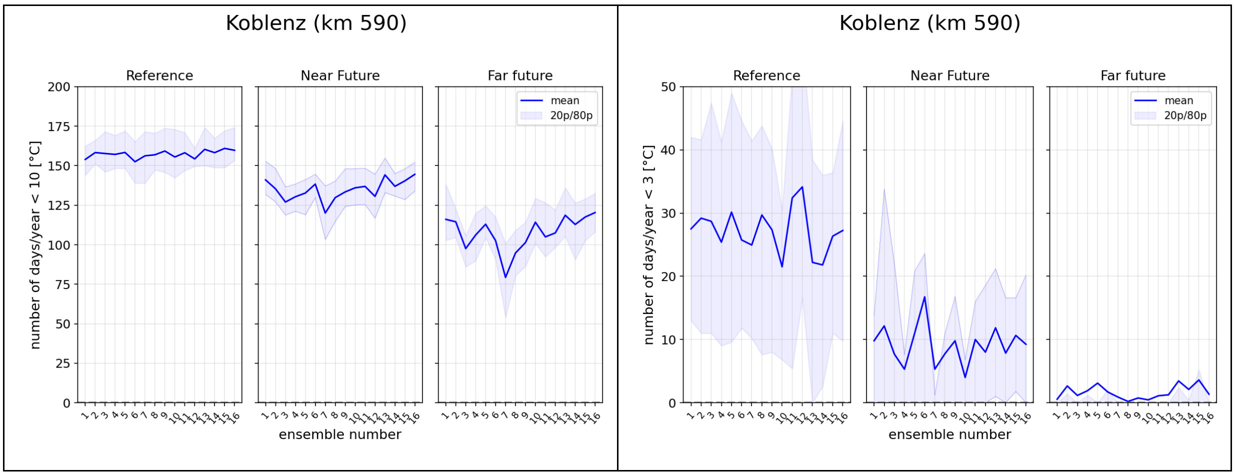


Figure 5-10 Number of days per year the water temperature is above 23 °C or 25 °C (upper panel), above 28 °C or 30 °C (middle panel) or below 10 °C or 3 °C (lower panel). Each panel shows 16 ensembles evaluated, see Table 5-1 . Each ensemble on the x-axis is presented by the average number of days per ensemble-year (20) a threshold is exceeded (line connects the points). The interannual variation is shown through the shaded area around the line covering 10 to 90 percentile value.

For the Netherlands, the ensemble variation is based on two ensemble members only and therefore is presented in Table 5-4, not graphically in this chapter.

5.5.2 Rhine profile for thresholds

The threshold statistics data are in Table 5-3, the variation caused by the ensemble variation (as shown in the previous chapter) is summarised by a minimum and maximum value.

As the simulated water temperature is not consistent at the national boundary crossings (chapter 5.4.5), neither are the thresholds in Table 5-3. The more extreme temperatures are affected most, and therefore shown here: see profiles for wT > 28 °C and wT < 3 °C in Figure 5-6. Note that the profiles for > 21.5 °C, > 23 °C and < 10 °C (not graphically shown) show more gradual wT changes in downstream direction.

Note that in Figure 5-6 at the boundary D-NL there is a stepwise increase towards warmer water in the far future, more than doubling the average number of days passing the 28 °C threshold for the far future (7 to 17 days per year).

Figure 5-6 and Table 5-4 show that the number of days < 3 °C is much higher in the German part compared to both the Swiss as well as the Dutch part of the Rhine. This is the case for the reference situation at Weil am Rhein (D) where the average number of days below 3 °C is 15 (ensemble variation 11-22) compared to Basel (CH) where only 5 days below 3 °C (ensemble range 1-11) are simulated.

At Bimmen (D) the number of days below 3 °C ranges from 20 to 32 compared 2-3 at Lobith (NL).

The reason for the large difference at the German-Dutch border is explained already in chapter 5.4.5: in the reference scenario the wT at Lobith is 1.9 °C to 2.1 °C warmer (due to inclusion of remains of heat inputs in the Dutch national approach), this temperature apparently corresponds to a 10-fold decrease in number of cold days.

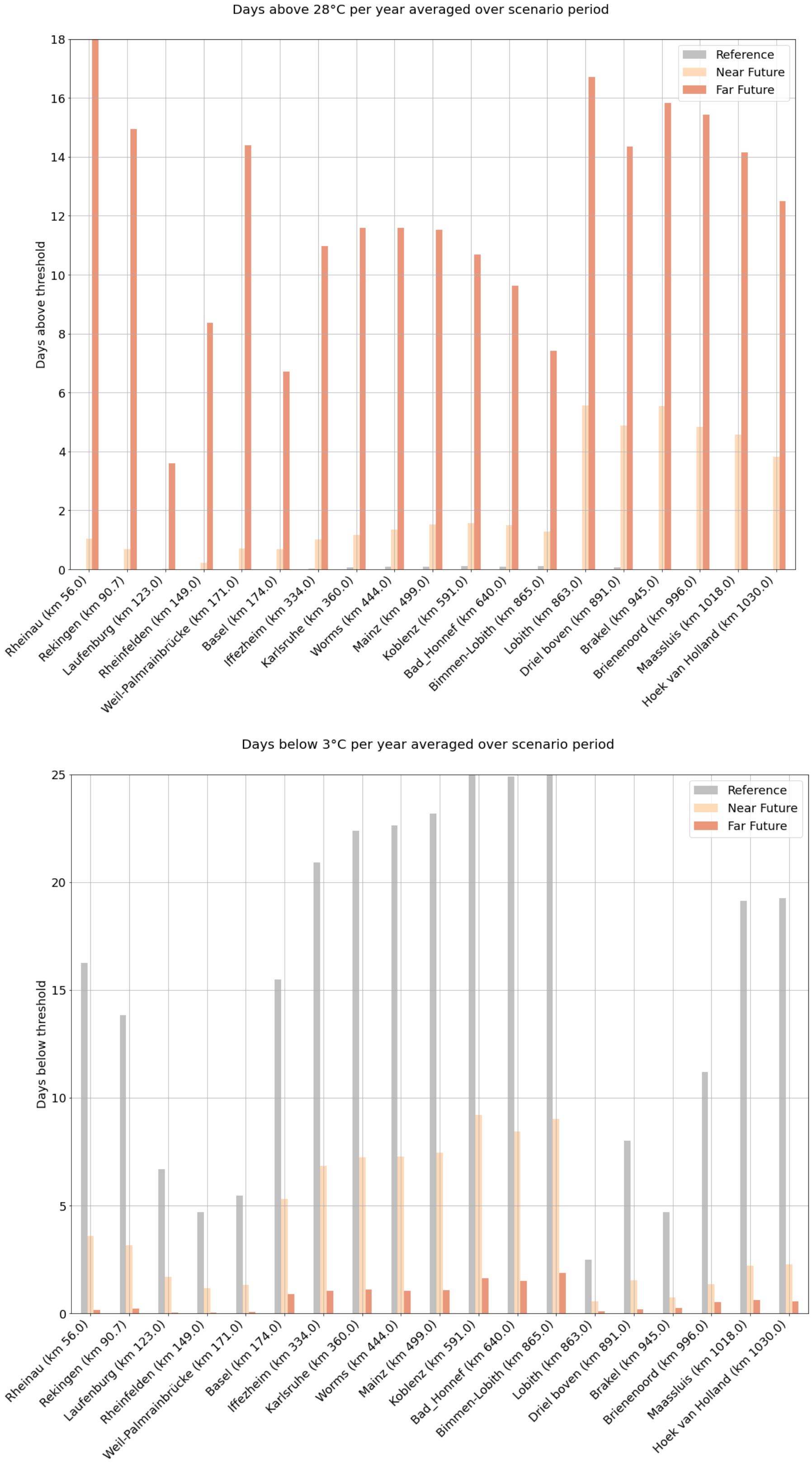


Figure 5-6 Number of days per year the water temperature is above 28 °C (top) and below 3 °C (bottom) for various Rhine stations (in downstream order but not scaled to distance). Each panel shows the interannual and ensemble averaged number of days per year for each station and scenario.

Table 5-3 Summary threshold statistics for national ensembles: average number of days (nod) for the threshold in each period of 20 years presented as the ensemble range (min-max).

	>21.5°C			>23°C			>25°C			>28°C			>30°C			<3°C			<10°C		
	ref	nf	ff	ref	nf	ff	ref	nf	ff	ref	nf	ff	ref	nf	ff	ref	nf	ff	ref	nf	ff
Rheinau 2392 (km 56)	14 - 20	64 - 84	108 - 128	1 - 6	34 - 58	87 - 114	0 - 2	6 - 27	50 - 91	0 - 0	0 - 3	3 - 50	0 - 0	0 - 1	0 - 28	11 - 20	1 - 7	0 - 2	156 - 164	127 - 140	89 - 117
Rekingen 2143 (km 90.7)	13 - 19	59 - 77	104 - 125	1 - 5	28 - 49	82 - 109	0 - 1	4 - 20	43 - 80	0 - 0	0 - 2	3 - 40	0 - 0	0 - 0	0 - 21	5 - 18	1 - 7	0 - 2	151 - 161	119 - 137	70 - 114
Laufenburg 2130 (km 123)	3 - 10	29 - 61	77 - 114	0 - 2	8 - 30	42 - 92	0 - 0	0 - 7	13 - 57	0 - 0	0 - 0	0 - 16	0 - 0	0 - 0	0 - 3	2 - 14	0 - 4	0 - 0	151 - 169	130 - 150	86 - 128
Rheinfelden 2091 (km 149)	11 - 16	54 - 74	99 - 120	0 - 3	22 - 45	75 - 103	0 - 0	2 - 15	31 - 73	0 - 0	0 - 1	1 - 34	0 - 0	0 - 0	0 - 12	1 - 8	0 - 3	0 - 0	141 - 149	115 - 129	78 - 111
Weil-Palmrainbr 2613 (km 174)	16 - 25	69 - 87	109 - 128	3 - 7	34 - 59	84 - 112	0 - 1	6 - 25	47 - 85	0 - 0	0 - 2	4 - 44	0 - 0	0 - 0	0 - 20	1 - 11	0 - 4	0 - 0	138 - 146	108 - 123	73 - 101
Basel (km 171)	14 - 31	41 - 66	70 - 114	2 - 12	20 - 41	47 - 91	0 - 3	4 - 19	16 - 57	0 - 0	0 - 3	1 - 16	0 - 0	0 - 1	0 - 5	11 - 22	2 - 10	0 - 3	134 - 146	89 - 123	41 - 91
Iffezheim (km 334)	26 - 45	54 - 82	82 - 123	7 - 24	32 - 59	61 - 104	0 - 7	9 - 28	29 - 70	0 - 0	0 - 3	3 - 21	0 - 0	0 - 0	0 - 6	17 - 27	3 - 14	0 - 3	142 - 154	107 - 137	64 - 110
Karlsruhe (km 359)	27 - 47	55 - 83	83 - 123	8 - 25	34 - 60	62 - 105	0 - 7	10 - 29	31 - 71	0 - 1	0 - 3	3 - 22	0 - 0	0 - 0	0 - 7	19 - 29	3 - 15	0 - 3	143 - 155	110 - 139	67 - 112
Worms (km 444)	30 - 49	58 - 85	83 - 123	11 - 26	35 - 61	62 - 105	0 - 9	12 - 29	32 - 71	0 - 1	0 - 3	3 - 22	0 - 0	0 - 0	0 - 6	18 - 29	3 - 15	0 - 3	147 - 157	114 - 142	72 - 114
Mainz (km 499)	33 - 52	61 - 87	84 - 125	14 - 29	37 - 63	63 - 107	1 - 10	13 - 30	32 - 72	0 - 1	0 - 3	4 - 21	0 - 0	0 - 0	0 - 5	18 - 30	3 - 15	0 - 3	149 - 159	114 - 141	71 - 114
Koblenz (km 590)	33 - 51	60 - 86	81 - 122	13 - 28	36 - 61	60 - 103	1 - 10	13 - 28	30 - 69	0 - 1	0 - 3	4 - 21	0 - 0	0 - 1	0 - 4	22 - 34	4 - 17	0 - 4	153 - 161	120 - 145	79 - 120
Bad-Honnef (km 640)	34 - 51	60 - 86	81 - 122	13 - 28	36 - 61	60 - 104	1 - 11	13 - 28	29 - 68	0 - 1	0 - 3	3 - 19	0 - 0	0 - 1	0 - 3	19 - 32	4 - 15	0 - 4	153 - 162	120 - 144	79 - 119
Bimmen (km 865)	31 - 50	57 - 82	74 - 119	11 - 25	34 - 56	52 - 99	1 - 10	9 - 24	24 - 62	0 - 1	0 - 2	3 - 17	0 - 0	0 - 1	0 - 3	20 - 32	4 - 15	0 - 4	155 - 163	122 - 147	84 - 124
Rhine-NWW_1_Lobith(km 863)	55 - 55	82 - 97	109 - 121	26 - 26	58 - 71	80 - 97	6 - 6	27 - 36	49 - 63	0 - 0	5 - 6	15 - 18	0 - 0	1 - 2	4 - 5	2 - 3	0 - 1	0 - 0	127 - 127	71 - 83	40 - 50
Rhine-NWW_2_Brakel(km 945)	52 - 52	80 - 93	104 - 116	25 - 25	56 - 66	78 - 90	6 - 6	26 - 32	47 - 58	0 - 0	5 - 6	15 - 17	0 - 0	1 - 1	4 - 4	5 - 5	0 - 2	0 - 1	134 - 134	79 - 92	58 - 61
Rhine-NWW_3_Vuren(km 951)	52 - 52	80 - 92	104 - 116	25 - 25	57 - 66	78 - 89	6 - 6	26 - 32	47 - 58	0 - 0	5 - 6	15 - 17	0 - 0	1 - 1	4 - 4	5 - 5	0 - 2	0 - 1	135 - 135	80 - 93	59 - 62
Rhine-NWW_4_Brienenoord_RO(km 995)	49 - 49	81 - 88	103 - 110	25 - 25	57 - 64	78 - 86	6 - 6	27 - 31	49 - 53	0 - 0	4 - 5	14 - 16	0 - 0	1 - 1	4 - 4	11 - 11	0 - 3	0 - 1	144 - 144	95 - 105	75 - 83
Rhine-NWW_5_Brienenoord(km 996)	49 - 49	81 - 88	103 - 110	25 - 25	57 - 64	79 - 86	6 - 6	27 - 31	49 - 53	0 - 0	4 - 5	15 - 16	0 - 0	1 - 1	4 - 4	11 - 11	0 - 3	0 - 1	144 - 144	95 - 105	75 - 83
Rhine-NWW_6_Maasluis(km 1018)	45 - 45	83 - 86	104 - 106	23 - 23	59 - 60	81 - 84	5 - 5	27 - 28	49 - 50	0 - 0	4 - 5	14 - 14	0 - 0	0 - 0	3 - 4	19 - 19	1 - 4	0 - 1	148 - 148	99 - 110	78 - 89
Rhine-NWW_7_HoekvanHolland(km 1030)	44 - 44	82 - 86	103 - 105	22 - 22	57 - 59	80 - 83	5 - 5	26 - 27	48 - 49	0 - 0	4 - 4	12 - 13	0 - 0	0 - 0	2 - 3	19 - 19	1 - 4	0 - 1	148 - 148	100 - 111	78 - 90

5.5.3 Summary projections from national ensembles

A summary of the water temperature projections based on the three national, ensemble weighted, approaches is given in Table 5-3. Table 5-4 shows threshold violations based on ensemble medians for the selected locations along the Rhine (summarizing the ensemble ranges as shown in Table 5-3).

Knowing the inconsistencies at the Swiss-German border and the German-Dutch border, the profiles presented do not meet the STEMP proposed approach for those parts of the Rhine influenced by the model boundary temperatures, this holds for: (1) the upper stretch of the German Rhine starting from Basel (estimated to have serious effect till Karlsruhe) and most part of the Dutch part of the Rhine.

In all sections of the Rhine, warmer water temperatures are projected for the near and far future compared to the reference. Details on this are further discussed in chapter 7 where a considered more meaningful summary of projections is based on simulations with a coupled model (see chapter 6.3, too).

Table 5-4 Summary threshold statistics for national ensembles: averaged number of days (nod) for the threshold in each period of 20 years presented as the ensemble median.

Variabele	>21.5°C			>23°C			>25°C			>28°C			>30°C			<3°C			<10°C		
Scenario	REF	NF	FF	REF	NF	FF	REF	NF	FF	REF	NF	FF	REF	NF	FF	REF	NF	FF	REF	NF	FF
Rheinau_2392_km-56	17	75	119	4	44	99	0	14	66	0	1	19	0	0	6	16	4	0	160	134	104
Rekingen_2143_km-90.7	15	70	114	3	38	93	0	10	58	0	1	15	0	0	4	14	3	0	156	129	96
Laufenburg_2130_km-123	6	50	99	1	20	71	0	3	32	0	0	4	0	0	0	7	2	0	159	136	110
Rheinfelden_2091_km-149	13	64	110	2	31	86	0	6	45	0	0	8	0	0	2	5	1	0	145	122	95
Weil-Palmrainbr_2613_km-174	21	78	120	4	44	98	0	12	61	0	1	14	0	0	4	5	1	0	141	117	87
Basel (km 171)	21	54	92	6	30	66	1	9	34	0	1	7	0	0	1	15	5	1	142	111	75
Iffezheim (km 334)	34	70	102	15	44	80	2	17	48	0	1	11	0	0	1	21	7	1	150	124	95
Karlsruhe (km 359)	36	71	103	16	46	81	2	18	49	0	1	12	0	0	2	22	7	1	151	126	97
Worms (km 444)	38	73	104	18	48	82	3	20	51	0	1	12	0	0	2	23	7	1	153	129	101
Mainz (km 499)	41	76	106	20	50	84	4	21	52	0	2	12	0	0	1	23	7	1	154	130	100
Koblenz (km 590)	41	74	103	19	49	81	4	20	49	0	2	11	0	0	1	27	9	2	157	135	108
Bad-Honnef (km 640)	41	75	104	19	49	81	4	20	48	0	1	10	0	0	1	25	8	1	158	134	105
Bimmen (km 865)	39	71	99	18	44	75	4	17	41	0	1	7	0	0	1	26	9	2	159	137	109
Rhine-NWW_1_Lobith (km 863)	55	90	115	26	65	88	6	31	56	0	6	17	0	1	5	2	1	0	126	77	45
Rhine-NWW_2_Brakel (km 945)	49	82	105	24	57	80	6	28	49	0	5	14	0	1	4	8	2	0	138	87	59
Rhine-NWW_3_Vuren (km 951)	52	86	110	25	61	84	6	29	53	0	6	16	0	1	4	5	1	0	134	85	60
Rhine-NWW_4_Brienenoord_RO (km 995)	49	84	106	24	60	82	6	29	51	0	5	15	0	1	4	11	1	1	144	100	79
Rhine-NWW_5_Brienenoord (km 996)	45	83	103	23	58	81	5	27	48	0	4	13	0	0	3	19	3	1	148	106	85
Rhine-NWW_6_Maasluis (km 1018)	45	83	103	23	58	81	5	27	48	0	4	13	0	0	3	19	3	1	148	106	85
Rhine-NWW_7_HoekvanHolland (km 1030)	44	82	102	22	57	80	5	25	47	0	4	12	0	0	2	19	3	1	148	107	86

5.5.4 Conclusion of national water temperature projections

Each country involved in this report already has worked on the simulation of climate change impacts on water temperature in the Rhine before. This resulted in different approaches and methods for the preparation of input data and the simulation itself. Consequently, the results are presented per country in this chapter.

In all sections of the Rhine, warmer water temperatures are projected for the near and far future. Notably, the frequency of days showing water temperature above 28 °C (and 30 °C) and below 3 °C is sensitive to relatively small differences in water temperature caused by methodological and at present does not show a consistent pattern for the different Rhine sections. Details on this are further discussed in chapter 7.

From a methodological point of view, a comparison between results for the different Rhine sections has to be done with care. When analysing/interpreting the data, the different ensemble sizes must be considered. The selection and number of ensemble members, and thus the sample size can have a clear impact on the comparability of the results between the different research teams and on the calculated statistics (extreme values and variability). While the main result shows a similar trend, the variability will be higher in larger model ensembles. It was also shown that the choice of the time periods, both in their point in time as well as their length, do have an impact on the results and must be considered when interpreting the data. Longer periods, i. e. 30 years like the common climate periods, are preferable for the analysis.

The Dutch approach differs in the definition of the reference scenario as it is based on measured rather than simulated climate as done in Germany and Switzerland. This leads to smaller variability in future predictions, the approach is in fact similar to the change-vector approach as followed in (ICPR, 2014). In the next round [KNMI23] Netherlands has adopted the same approach flowed by Germany and Switzerland.

At the national boundaries, the national approaches are not consistent. The upper boundary for the German model is out of phase compared to the Swiss simulation result that considers heat balance of upstream lakes. The upper boundary of the Dutch model, containing heat input remains, is too warm compared to the German simulation result. It is expected that this inconsistency will largely be resolved by coupling the models at their boundaries.

For future analyses of the whole Rhine basin, it is recommended to start the process of agreeing on time periods and ensemble members early on (chapter 8). That way a broader and consistent analysis will be made possible. A step in the direction of a basin-wide water temperature modelling approach is discussed in the following chapter 6.

6 First steps to a basin-wide approach

For a consistent and most meaningful basin-wide climate impact projection, a basin-wide model forced with the same climate ensemble(s) is the preferred option. The next best approach is to couple the national models at their boundaries, resulting in a so called "composite" or "coupled" basin model. This approach was chosen here since no basin-wide simulation model is available and the available time was too limited to set up such model. To run the composite basin model, in this study, only one climate model chain was available along the whole River Rhine ("common climate chain"). This limits the variability earlier shown for the national models (chapter 5) to the interannual variation as ensemble variation lacks. Details of the basin-wide model approach are described in the following chapter 6.1.

The basin-wide composite model uses only one ensemble member and thus results will differ from the results presented in chapter 5. In chapter 6.3, the effect of reducing the number of ensembles used is shown. In chapter 6.2, the water temperatures (and river discharge) at the national boundaries, focussing on the difference between the national and the coupled approach, are compared.

Simulation results from the basin-wide model using one common climate chain are presented in chapter 6.4 and are based upon the same stations that were validated (chapter 4) and presented in chapter 5.

6.1 Method

The basin-wide model is different from the national models in two key features, viz: (1) selects one climate chain ensemble member only to force the wT models and (2) replaces the national boundary estimates with upstream model results from the neighbouring nation.

6.1.1 Common climate chain

In chapter 5, the national climate change projections were based on different climate chain ensembles per country. This chapter focuses on national simulations that use one common climate chain. At the start of the research, this approach had been defined as the best meaningful way for a basin-wide assessment given the constraints of the project. The use of only one common climate chain reduces the variability in the national results but makes the impact of climate change more comparable between the different countries.

Only one common climate change projection was available in all three national climate change approaches (ECEARTH 1 RACMO). This common projection was included in each national ensemble and thus accepted by each country as (one of the) representative projections of the future climate 5.3. All results in this chapter are restricted to and based on the one common climate change projection available, viz. "ECEARTH 1 RACMO".

6.2 Upper boundaries of the national models

In the national approaches presented in chapter 5 as well as in the previous STEMP approach (ICPR, 2014), the water temperature conditions at the upper national model boundaries were based on empirical relations (air temperature to water temperature at model boundaries in QSim (D); air temperature and discharge to water temperature at model boundaries in SOBEK (NL)).

Here, the empirical boundary is compared to the modelled boundary for the Swiss-German border near Weil am Rhein (chapter 0) and for the German-Dutch border near Lobith (chapter 6.2.1).

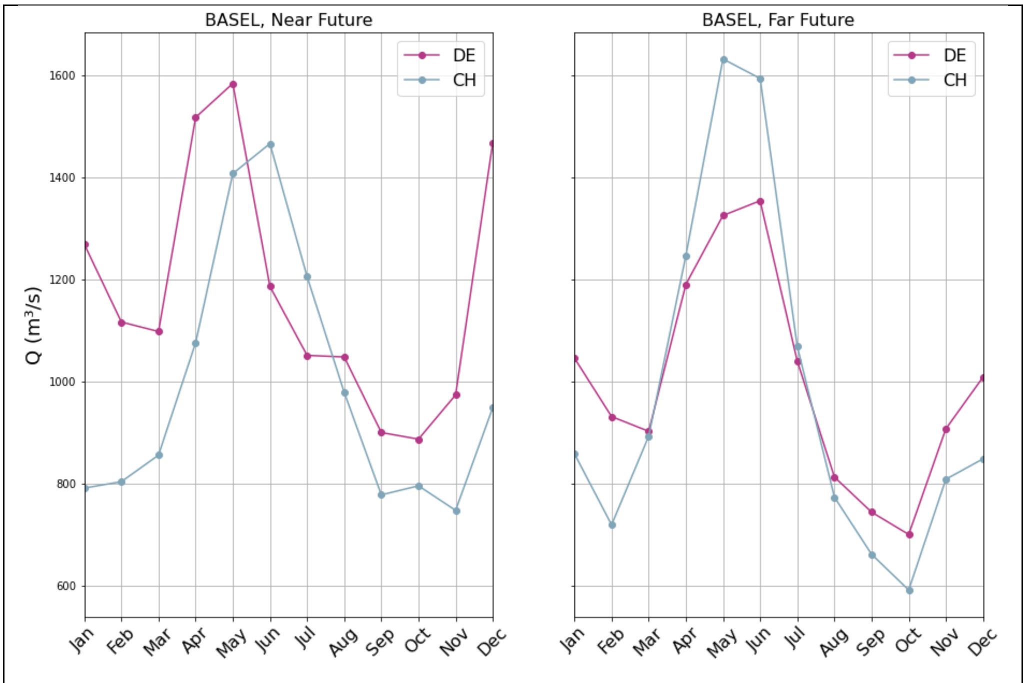
6.2.1 Empirical versus modelled result at Weil am Rhein (near Basel)

In Figure 6-1, the discharge from LARSIM and the water temperature derived from an empirical relationship with air temperature (German model approach) is compared to the Swiss model result for discharge (PREVAH at Rekingen station 2143) and water temperature (air2water at Weil am Rhein station 2613).

In the near future, the German estimate of discharge is 10 % higher and spring peaks occur one month earlier compared to the Swiss model approach. For the far future, the timing of the flows over the year is more synchronous, but spring flows are (much) higher in the Swiss model (1600 m^3/s) compared to little over 1300 m^3/s in the German approach. Late summer flows in the Swiss model reach as little as 600 m^3/s compared to 700 m^3/s in the German approach.

Comparing water temperatures of the two approaches at Weil am Rhein near Basel shows that the Swiss approach is colder from January to June and warmer from July to December. The crossing point that marks the different behaviour in the first part of the year compared to the second half occurs in June. Until June, the German approach is up to 2.5 °C warmer, after June the Swiss approach is up to 2.5 °C warmer, the patterns is similar for the near and the far future (Figure 6-1).

As argued in chapter 5.4.5, the likely explanation is that the Swiss semi-deterministic model (chapter 3.3.1) is more advanced, compared to the German relationship between air and water temperature, as it includes memory effects by including the reference temperature for deeper layers of lakes in the equations. This results in a slower warming of water coming from Switzerland before the summer and a slower cooling after summer.



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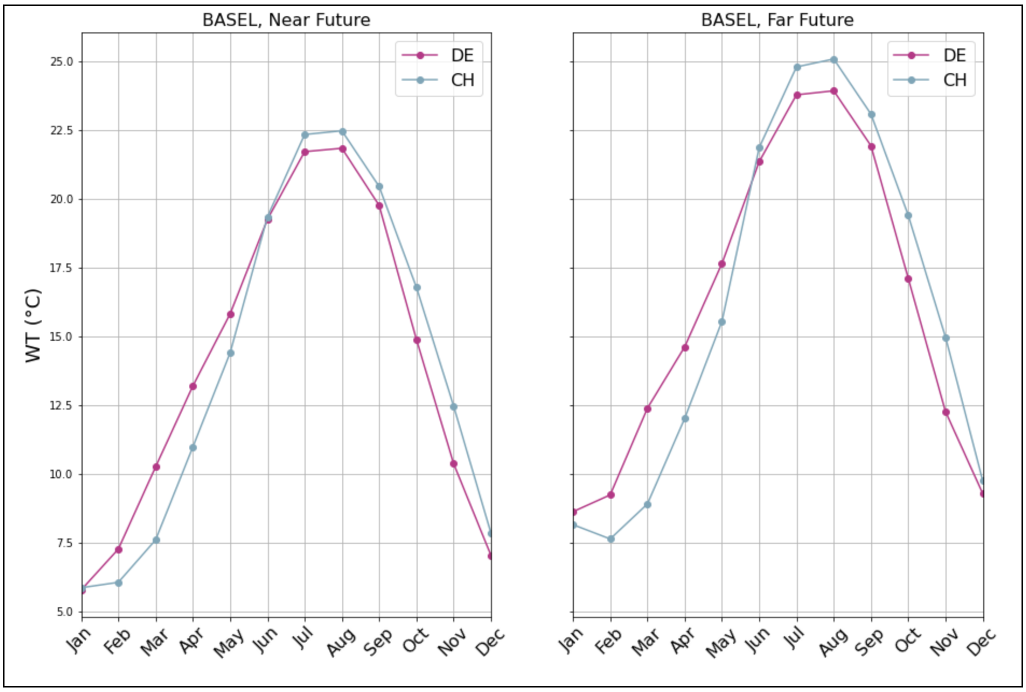


Figure 6-1 Model input at the upper boundary of the German model (station Weil am Rhein) computed by the German approach (D) and by the Swiss model approach (CH) for the common climate model chain ECEARTH 1 RACMO. Upper panel: average discharge Q (m^3/s), lower panel: average water temperature WT (°C) for near future (left) and far future (right).

6.2.2 Empirical versus modelled result at Lobith

Figure 6-2 shows the mean discharge over the agreed 20-year period in the near and far future for SOBEK's upper model boundary Lobith (Rhine-km 863). The German model shows the HYDRAX and QSim result at Bimmen (Rhine-km 865).

In fact, there are two German model results at Lobith, one based on the German national approach using an empirical relationship near Basel and one using the Swiss model result near Basel (the intended part of the composite basin-wide model). At Lobith, discharges from the composite model (D_CH) follow more or less a similar seasonal pattern as the German national model (D) and discharges show more or less similar values except during spring (April-June) where the discharges in the composite model are ±20 % higher compared to the national model (D vs D_CH in Figure 6-2).

The Dutch simulated national discharges [13, 14] show ±10 % lower minimum in September compared to the German simulated national discharges. There is also a one-month time shift (minimum discharge reached earlier in the Dutch national model), this time shift is more pronounced in the near future simulation. Winter discharges are ±10 % higher with the Dutch approach. Overall, the discharges are somewhat more extreme (lower in summer, higher in winter) in the Dutch compared to the German model results.

Note, when the national runs were made (back in 2018) the Netherlands used NL_WH (chapter 5.4.3) which shows much higher winter discharge (JFM) notably in the far future. It was replaced by WH_Dry because summer low flows were not extreme enough. NL_WH is used in this study as the 2nd ensemble (chapter 5) to assess variability in water temperatures.

The average water temperatures for Lobith from the different sources are shown in Figure 6-2 (lower panel). First, note that the two German approaches for wT are nearly identical. So, despite the differences in discharge and water temperature at the German upper boundary at Basel (between the national and composite model, Figure 6-1) there is limited to no effect remaining on water temperature simulated at Lobith.

There is a significant difference in water temperature at Lobith when comparing the results of the empirical relation used in the Dutch approach and the results simulated with the German model. Summer values in the Dutch approach are higher in both future projections (July +0.5 °C and August +1 °C). Winter values are much higher (up to almost 4 °C) compared to the German model result.

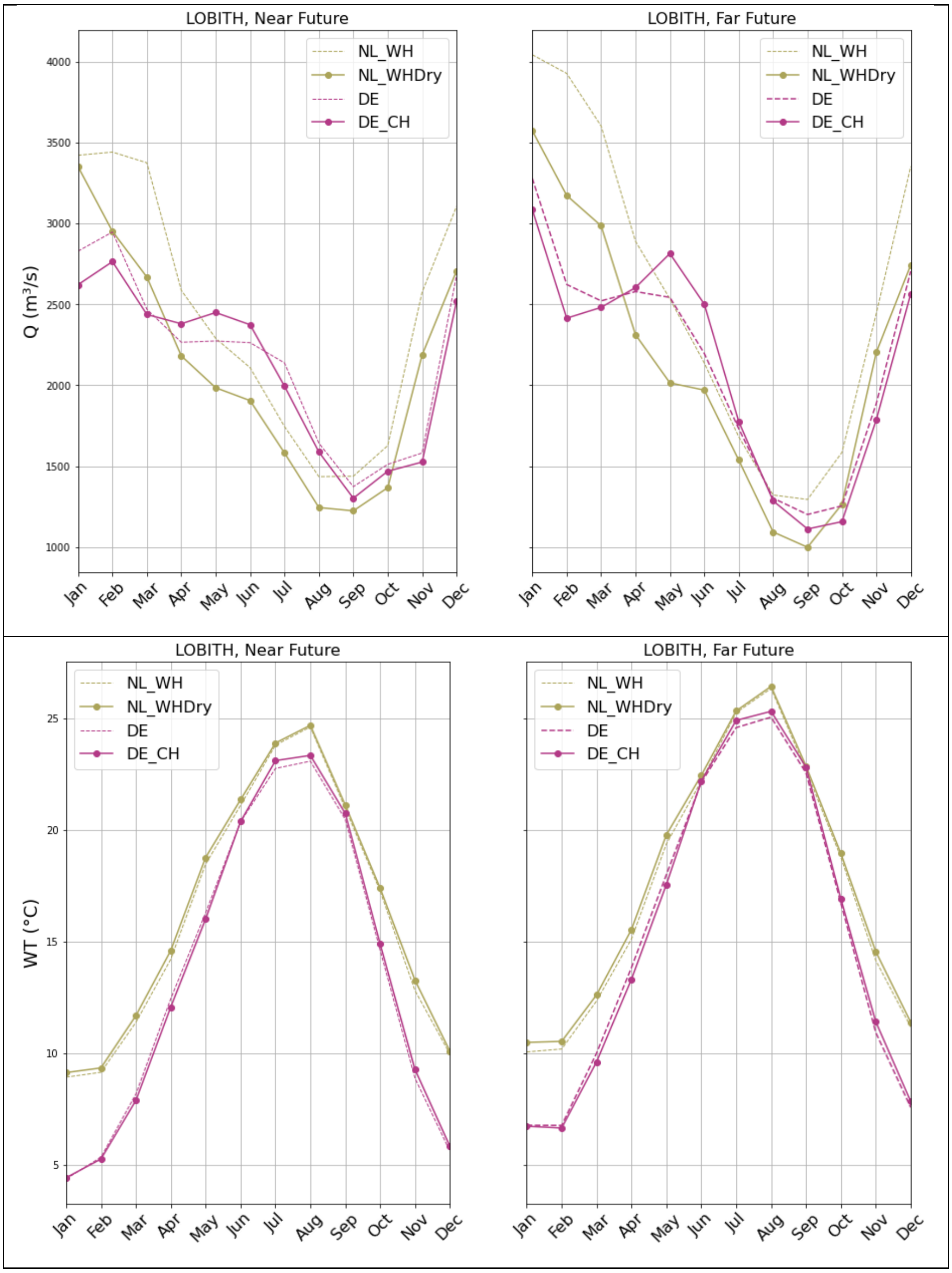


Figure 6-2 Model input at the upper boundary of the Netherlands model (Lobith) computed by the national approach (NL_WHDry) compared to the German model coupled to the Swiss model at Basel (DE_CH) and, as a reference, the national German model (DE). Upper panel: monthly averaged discharge Q (m^3/s), lower panel: monthly averaged water temperature WT (°C) for the near future (left) and the far future (right).

In the remainder of this chapter, plausible causes for the significantly higher wT in the Dutch national forcing compared to the German model result are investigated, notably the large difference during the winter half year.

Already in the reference scenario, water temperature at the Dutch and German boundary differs (Figure 6-3, left panel). In winter, values are 1-2 °C higher for the Netherlands. The Dutch reference values are based on measured wT values from the reference period, the German reference scenario is a model result based on the common climate chain (ECEARTH 1 RACMO).

As argued in chapter 5.4.5, the implicit inclusion of excess heat from upstream cooling water (present in the measured data defining the Dutch reference scenario) quantitatively explains the difference with the German simulation results in the reference scenario. Automatically, this explains the larger part of the difference in the future scenarios, too, because the Netherlands uses an approach in which the reference scenario is 'translated' to future scenarios thus including the excess heat that is present in the reference scenario.

Table 6-1 shows the additional difference (original Table 5-2 in chapter 5.4.5) for the future scenarios when corrected for the above explained difference in the reference scenario. The difference is still significant, notably in winter and in the near future.

Table 6-1 Difference in water temperature modelled at the Dutch border (Dutch empirical relation minus QSim) for near and far future after correction for the difference in the reference scenario (derived from Table 5-2 in chapter 5.4.5.*).*

	REF	NF	FF	REF	NF	FF	REF	NF	FF	REF	NF	FF
		WINTER			SPRING			SUMMER			FALL	
border D->NL	0	1.3	0.9	0	0.8	0.3	0	0.4	0.1	0	0.4	0.3

As the wT in the Dutch national approach is determined by 90-95 % by future air temperature (the remainder by future discharges). Figure 6-3 shows that the air temperature forcing the water temperature models in Germany in the future scenarios is lower than the air temperature used for the Netherlands. The largest differences are observed in winter and summer, this explains the remaining wT difference shown in Table *6-1*.

The remaining question is why the air temperature is different for the Netherlands and Germany for the future scenarios (Figure 6-3) as both are based on the same climate chain. The likely explanation is a methodological difference: the harmonisation of the scenario periods affects the forcing for the German model (chapter 5.3) but does not affect the Dutch forcing as it is based on a change vector relative to a 30 year period (1981-2010).

Additionally, part of the difference in air temperature may be real as there is a geographical air temperature gradient from east to west. Although the spatial scale (Kleve to De Bilt) is probably too small to be of practical relevance (not investigated), it points to a relevant disadvantage of using an empirical relationship for wT at a boundary based on one meteorological station only. The Dutch wT boundary is based on a local air temperature station in the Netherlands whereas the German model is based on several meteorological stations along the Rhine. The difference in the geographical position of the meteorological stations may cause a bias in the Dutch boundary (warmer winters, cooler summers, in line with Figure 6-3). At high flow conditions (winter) the bias is probably stronger as water at Lobith originates from further away, the 'memory' effect is not accounted for sufficiently by the empirical relationship used in the Netherlands (wT decreases with increasing discharge).

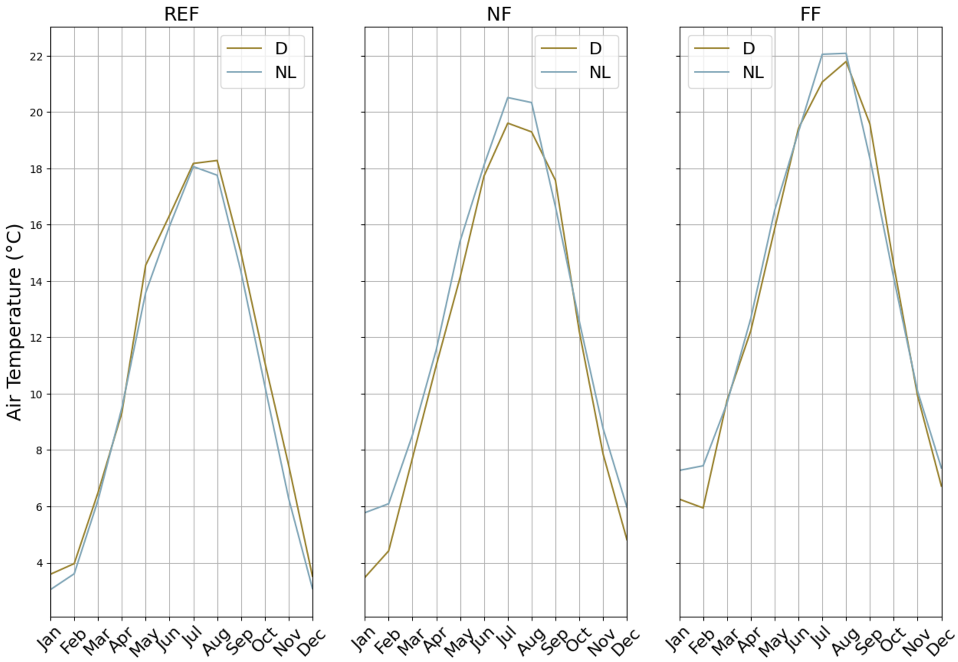


Figure 6-3 Comparison of input air temperature to the German QSim model at Kleve and the Dutch SOBEK model at De Bilt for the reference period, near future and far future.

In conclusion, the empirical relationship used to define wT for the upper boundaries of the German as well as the Dutch model are less suited than the modelled alternatives and are therefore replaced by the upstream model results in the basin-wide model (chapter 6.4).

6.2.3 Coupling at national boundaries ("composite model")

In the national approaches (chapter 5), upstream water temperature at the boundaries of the national models of Germany and the Netherlands were derived from simplified empirical relationships using air temperature as a proxy for water temperature. In the basin-wide approach presented here, the model results from the upstream neighbouring countries were used. This provides a better alternative as these models have more advanced relationships between atmospheric conditions and water temperature and have, at least for QSim, the option to exclude (by choice) direct heat inputs which is not possible using empirical relationships calibrated on measured water temperature that include, potential significant, remains of direct heat inputs.

Therefore, the national models were re-run (for the common climate chain ECEARTH 1 RACMO) replacing the national boundary estimates with the model result from the upstream national models. In this case:

- Germany used the Swiss model results at Weil am Rhein feeding QSim (air2water in CH, chapter 3.3.1) and
- the Netherlands used the German model (QSim, chapter 3.3.2) results at Lobith feeding SOBEK.

6.3 Common climate chain with national model boundaries

This chapter shows how water temperature projections change if based on the common climate chain "ECEARTH 1 RACMO" compared to results based on the national ensembles. The models still use their national boundaries (not coupled to upstream model). Thus, the change in water temperature projections presented here, is the result of the first step in harmonizing the national results (chapter 6.1.1).

The change in temperature resulting from the harmonization (national ensemble run minus run with one climate chain) is shown in Table 6-2. Largest differences occur at the national boundaries, further away from the upper model boundaries (indicated in yellow boxes) the climate impact on water temperature shows:

- Relatively small (0.1 °C to 0.2 °C) differences in the Netherlands as the common ensemble is not very different from the second ensemble member (chapter 5.4.3).
- Differences for CH and D having a higher and more diverse number of ensemble members range from -0.7 °C to +0.3 °C.
- The near future is colder for all seasons (-0.1 °C to -0.6 °C).
- The far future summer half year is mostly also colder (-0.2 °C to -0.7 °C) but the far future winter half year is mostly warmer (-0.3 °C to +0.3 °C).

The changes (Table 6-2) are relatively small and do not alter the seasonal temperatures profile presented earlier in Table 5-3 preserving the following features described in chapter 5.4.5 earlier: (1) temperature jump at the CH–D border in spring and fall, (2) temperature jump throughout the year at the D-NL border and (3) inconsistent longitudinal temperature profiles.

It is concluded that projected wT based on the one common ensemble member differs as expected (chapters 5.2 and 5.5.1) from that based on national ensembles, however, the differences are small compared to the influence inconsistent national boundaries have in a large part of the basin. It therefore seems justified to apply the common climate chain in the basin-wide model and use the results (chapter 6.4) as the currently best achievable tool for climate projections in the Rhine basin.

Table 6-2 Change in seasonal temperature (compared to Table 5-3) when national models are using the common climate chain (ECEARTH 1 RACMO) instead of their national ensembles (see Table 5-1).

National (Ensembles - Common)	T(°C)		T(°C)		T(°C)		T(°C)	
season	DJF		MAM		JJA		SON	
scenario	NF	FF	NF	FF	NF	FF	NF	FF
Rheinau_2392_km-56	-0.4	0.1	-0.2	-0.5	-0.6	-1.0	-0.3	0.0
Rekingen_2143_km-90.7	-0.4	0.2	-0.2	-0.1	-0.5	-0.8	-0.2	0.0
Laufenburg_2130_km-123	-0.6	0.0	0.3	0.2	-0.2	-0.4	-0.3	-0.1
Rheinfelden_2091_km-149	-0.5	-0.1	-0.4	-0.6	-0.5	-0.6	-0.2	0.0
Weil-Palmrainbr_2613_km-174	-0.4	0.1	-0.3	-0.5	-0.5	-0.7	-0.3	0.0
Basel (km 171)	-0.4	0.1	-0.3	0.0	-0.8	-0.8	0.1	0.5
Iffezheim (km 334)	-0.5	0.0	-0.1	0.1	-0.6	-0.5	-0.1	0.2
Karlsruhe (km 359)	-0.5	0.0	-0.1	0.1	-0.6	-0.4	-0.1	0.2
Worms (km 444)	-0.5	-0.1	-0.1	0.1	-0.5	-0.4	-0.1	0.2
Mainz (km 499)	-0.6	-0.2	-0.1	0.1	-0.5	-0.4	-0.1	0.2
Koblenz (km 590)	-0.6	-0.2	-0.2	0.0	-0.5	-0.3	-0.1	0.3
Bad-Honnef (km 640)	-0.6	-0.3	-0.2	0.0	-0.5	-0.3	-0.1	0.3
Bimmen (km 865)	-0.6	-0.3	-0.2	0.0	-0.5	-0.3	-0.1	0.3
Rhine-NWW_1_Lobith (km 863)	-0.1	0.1	0.2	0.3	0.4	0.4	0.2	0.2
Rhine-NWW_2_Brakel (km 945)	-0.1	0.1	0.2	0.2	0.3	0.3	0.1	0.1
Rhine-NWW_3_Vuren (km 951)	0.0	0.1	0.2	0.2	0.3	0.3	0.1	0.1
Rhine-NWW_4_Brienenoord_RO (km 995)	0.0	0.1	0.2	0.2	0.2	0.2	0.1	0.1
Rhine-NWW_5_Brienenoord (km 996)	0.0	0.1	0.2	0.2	0.2	0.2	0.1	0.1
Rhine-NWW_6_Maasluis (km 1018)	0.0	0.0	0.2	0.2	0.1	0.1	0.1	0.1
Rhine-NWW_7_HoekvanHolland (km 1030)	0.0	0.0	0.2	0.2	0.1	0.1	0.1	0.1

6.4 Results of the basin-wide model

A basin-wide simulation is possible because the national models share one common global and regional climate chain across CH, D and NL for emission scenario RCP8.5. The conditions at the upper boundaries of the national models (Basel, Germany and Lobith, the Netherlands) are taken from model results of PREVAH and air2water (CH) at Weil am Rhein and HYDRAX and QSim (D) at Bimmen, respectively. The simulations were run without direct heat input resulting from cooling water discharges.

Details of the setup of the basin-wide model are described in chapter 6.1 and consequences of harmonizing the national models are described in chapter 6.3 (one common climate chain, "ECEARTH 1 RACMO") and in chapter 6.2 (coupling at national boundaries).

Thus, the basin-wide water temperature projections presented here are based on three coupled, but conceptually and by implementation different, national hydrological and water temperature models. Their climate forcing is consistent across the river basin.

6.4.1 Seasonal water temperature

Summary statistics for seasonal water temperature projections are given in Table 6-3. The layout of the table is the same as the summary statistics table for the national ensembles to ease comparison (Table 5-2).

The basin-wide temperatures show a consistent longitudinal profile (compared to the national results in Table 5-2). At the national boundaries there is smooth transition from one national model to the other. Model results show plausible seasonal patterns along the Rhine: In summer and spring the water in Switzerland is relatively cold and warms up in the middle (German) part of Rhine followed by slight cooling towards the North Sea in the Netherlands. In autumn and winter the opposite is modelled, relative warm water from Switzerland (note it contains remains of direct heat inputs) cools down flowing through Germany and the Netherlands.

Table 6-3 Summary statistics showing range in quarterly averaged Rhine water temperature (°C) for the three scenarios in the basin-wide run. Quarters per column: winter-DJF, spring-MAM, summer-JJA and autumn-SON. Colours are relative per column indicating longitudinal temperature gradient (per scenario and per season).

COUPLED (common ensemble)		T(°C)			T(°C)			T(°C)			T(°C)	
season		WINTER			SPRING			SUMMER			AUTUMN	
scenario	REF	NF	FF	REF	NF	FF	REF	NF	FF	REF	NF	FF
Rheinau_2392_km-56	5.1	6.1	8.4	9.0	10.2	11.9	19.4	21.8	24.5	14.3	16.9	19.9
Rekingen_2143_km-90.7	5.1	6.2	8.6	9.6	10.8	12.7	19.5	21.7	24.4	14.0	16.6	19.4
Laufenburg_2130_km-123	5.5	6.4	8.3	9.4	10.2	11.4	18.7	20.8	23.1	14.2	16.5	18.9
Rheinfelden_2091_km-149	5.7	6.6	8.5	10.3	11.0	12.2	19.4	21.4	23.9	14.3	16.6	19.2
Weil-Palmrainbr_2613_km-174	6.0	6.9	9.0	10.7	11.5	12.7	19.8	22.0	24.6	14.7	17.1	19.8
Iffezheim (km 334)	5.1	6.0	8.0	11.1	11.7	13.0	20.6	22.6	25.0	14.3	16.5	18.9
Karlsruhe (km 359)	5.0	5.8	7.9	11.2	11.8	13.1	20.7	22.7	25.1	14.2	16.3	18.7
Worms (km 444)	4.9	5.7	7.7	11.4	12.0	13.3	20.8	22.7	25.0	14.0	16.0	18.3
Mainz (km 499)	4.8	5.6	7.6	11.5	12.2	13.6	21.0	22.8	24.9	13.9	15.8	18.1
Koblenz (km 590)	4.5	5.2	7.2	11.5	12.1	13.5	21.0	22.7	24.8	13.6	15.3	17.5
Bad-Honnef (km 640)	4.6	5.3	7.3	11.5	12.1	13.7	21.0	22.6	24.6	13.6	15.3	17.5
Bimmen (km 865)	4.5	5.2	7.1	11.5	12.0	13.5	20.9	22.3	24.2	13.4	15.0	17.1
Rhine-NWW_2_Brakel (km 945)	4.3	5.1	7.0	11.4	12.0	13.5	20.9	22.4	24.2	13.2	14.9	16.9
Rhine-NWW_3_Vuren (km 951)	4.3	5.1	7.0	11.4	12.0	13.5	20.9	22.4	24.2	13.2	14.9	16.9
Rhine-NWW_4_Brienenoord_RO (km 995)	3.9	5.1	6.9	11.2	12.2	13.5	20.9	22.7	24.3	13.1	14.9	16.8
Rhine-NWW_5_Brienenoord (km 996)	3.9	5.1	6.9	11.2	12.2	13.5	20.9	22.7	24.3	13.1	14.9	16.8
Rhine-NWW_6_Maasluis (km 1018)	3.8	5.3	7.0	11.1	12.1	13.4	20.8	22.7	24.3	13.1	15.1	16.9
Rhine-NWW_7_HoekvanHolland (km 1030)	3.8	5.3	7.1	11.0	12.1	13.4	20.8	22.6	24.2	13.2	15.2	17.0

6.4.2 Longitudinal plot

Figure 6-4 and Figure 6-5 show the longitudinal profiles of the Rhine from Switzerland to the mouth at the North Sea through a selection of stations along the Rhine at the corresponding distance (Rhine kilometre).

Figure 6-4 shows the increase of water temperature relative to the reference period. The average temperature increase in the three parts of the Rhine (CH, D, NL) varies between +1.1 °C and +1.8 °C for the near future and from 2.9 °C to 4.2 °C in the far future. The highest temperature increase occurs in Switzerland. The average warming signal is similar to what was reported in the previous STEMP analysis in 2014 (ICPR, 2014).

The plot indicates a significant amount of spread in the warming signal. The 90th percentile (corresponding to roughly a month per year) varies between 4 °C and +4.5 °C in the near future and between +5 °C and +7 °C in the far future. Note that negative warming (cooler compared to the reference) is simulated for the lower 25 percentile of the data in the near future and (only in Germany) 10 percentile data in the far future.

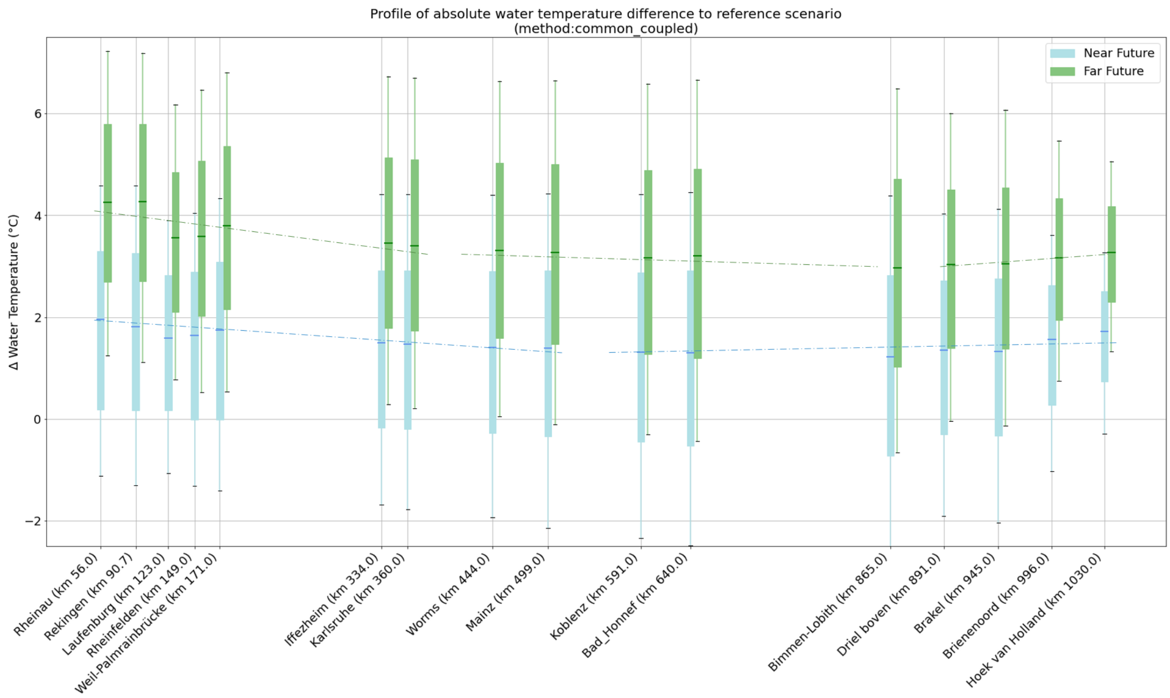


Figure 6-4 Longitudinal water temperature profile of the Rhine from simulation without heat input using the basin-wide model shown as temperature difference between the near future (2045-2065) and far future (2080-2100) and the reference period (1990-2010). The boxplots show the period median (horizontal solid line), the first and the third quartile (borders) and the 10 and 90 percentile data (whiskers).

Figure 6-5 shows the longitudinal plot for absolute water temperature and the variation for each station as boxplots. In the reference scenario, temperatures show a gradual increase to warmest temperatures in the Middle Rhine followed by cooling towards the Lower Rhine and Delta Rhine. Within the future scenario, warmest temperatures occur in the Upper Rhine.

In large parts of the Rhine, the 90th percentile of water temperature in the near future reaches 25 °C (WFD critical water temperature for good ecological status). In the far future, the 95th percentile of water temperature is close to 27 °C.

Evaluation of critical threshold values is presented in the next chapter.

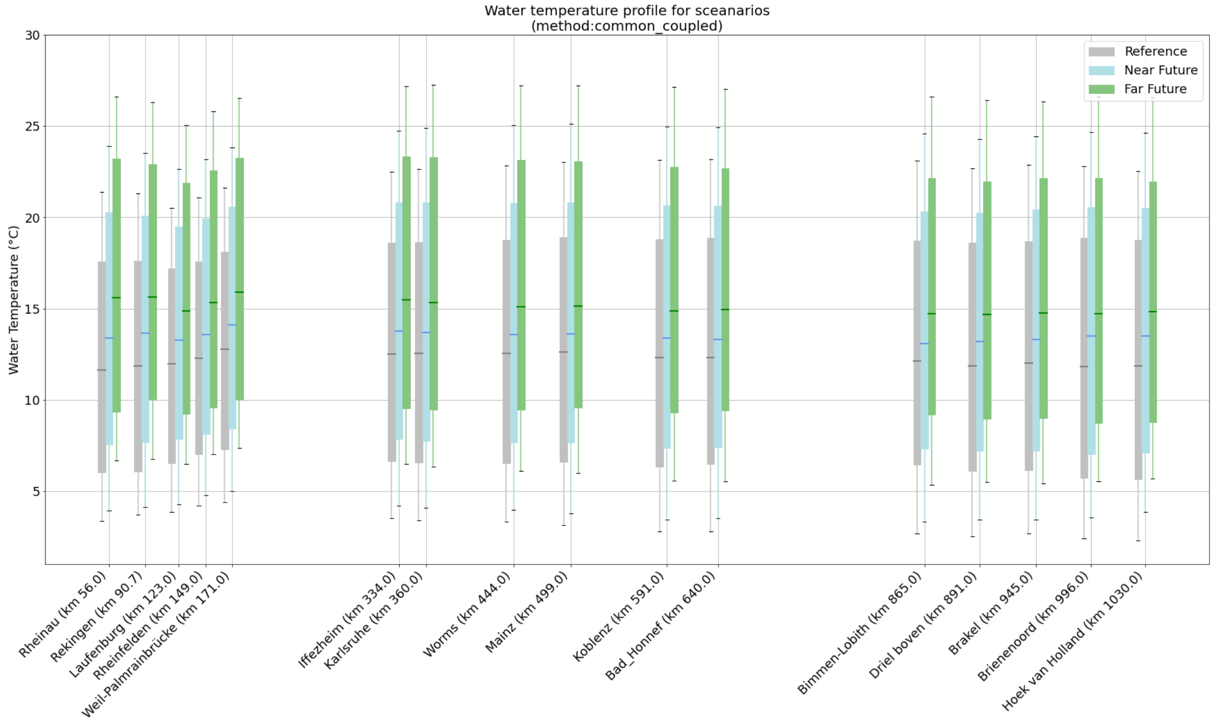


Figure 6-5 Longitudinal water temperature profile of the Rhine from simulation without heat input using a basin-wide model shown as temperature in the reference period (1990-2010), the near (2045-2065) and far future (2080-2100). The boxplots show the period median (horizontal solid line), the first and the third quartile (borders) and the 5 and 95 percentile data (whiskers).

6.4.3 Water temperature against thresholds

This chapter evaluates threshold violations for the basin-wide approach. Next to the number of days per year when a threshold is passed, also the longest period of the threshold violation is evaluated. All water temperature thresholds relevant in the Rhine countries were evaluated, viz. 21.5 °C, 23 °C, 25 °C, 28 °C and 30 °C (number of days above) and 3 °C and 10 °C (number of days below).

Figure 6-6 shows the variation within the scenario periods for the threshold temperature value below 3 °C. Both, the number of days per year and the longest period strongly vary per year within each scenario. The dashed horizontal line indicates average number of days and average consecutive days that will be shown per station in Figure 6-7.

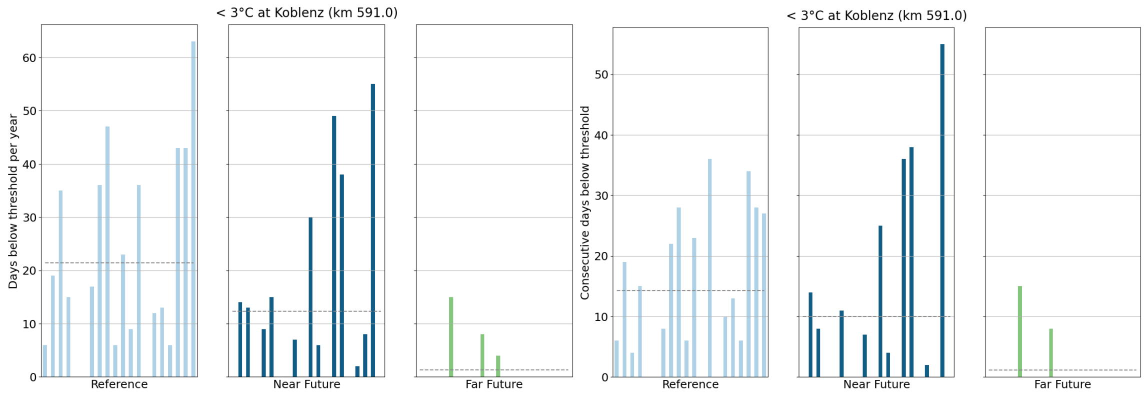


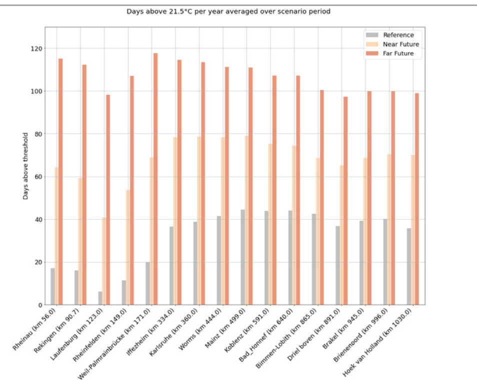
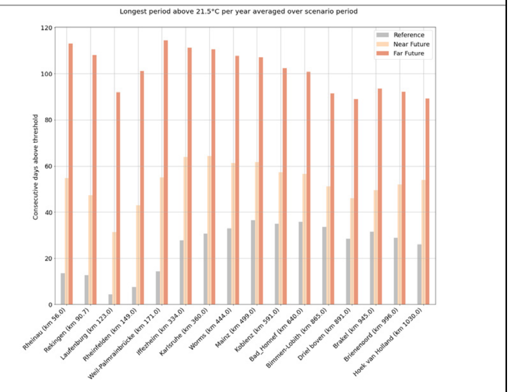
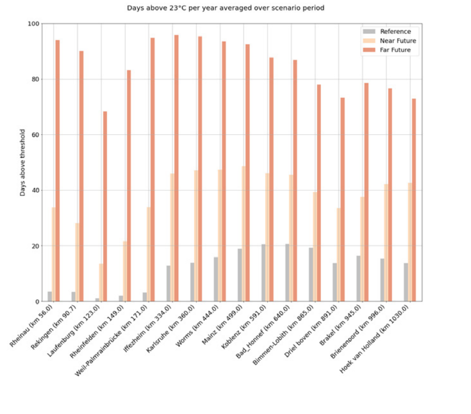
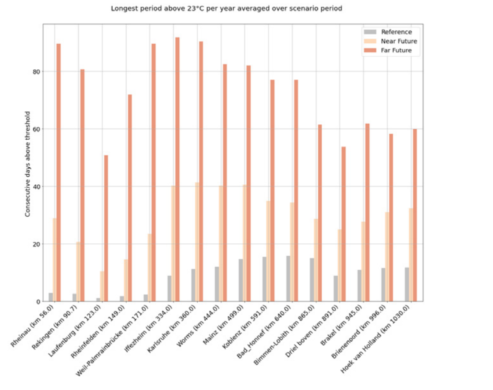
Figure 6-6 Number of days per year (left) and longest consecutive period in days (right) the water temperature is below 3 °C in the reference period, the near and far future for Koblenz. Each panel shows the variation of the 20 years in each of the periods (columns) and the average (dotted line).

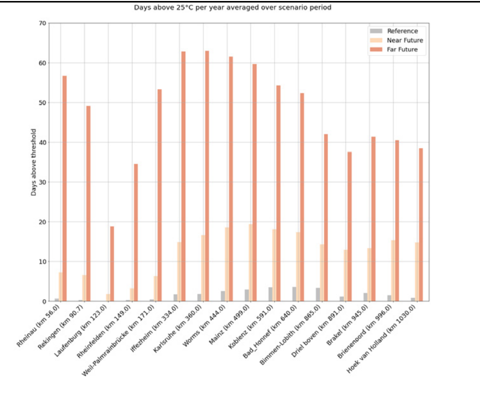
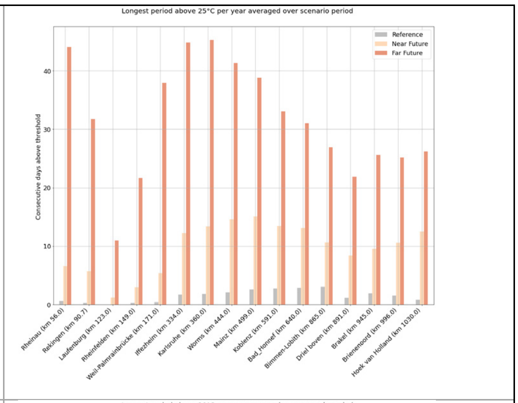
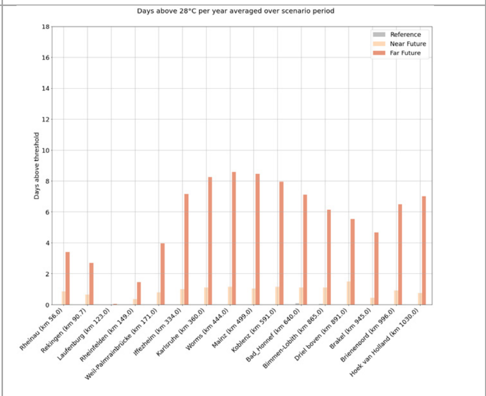
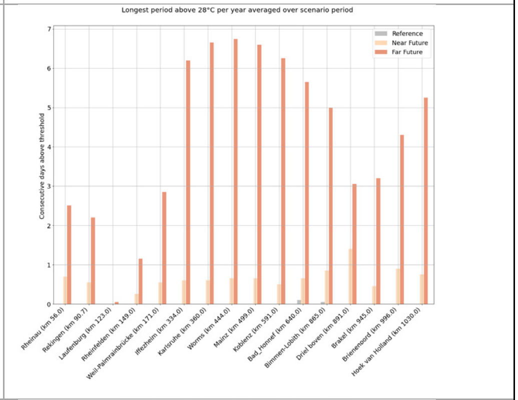
Figure 6-7 shows annual averaged number of days, the indicated threshold are violated and the consecutive number of days the threshold is exceeded for several stations along the Rhine. The following observations are made:

- All thresholds for temperatures > 21.5 °C are exceeded longer and more frequently in the future scenarios.
- The 25 °C threshold is exceeded longer than 10 days in near future and up to a month in the far future.
- The 28 °C threshold is not exceeded yet in the near future, but will be exceeded in the far future for periods up to 7 days.
- The 30 °C threshold is essential not exceeded in the near and far future.
- Water temperatures below 3 °C are absent in a major part of the Rhine in the far future. Duration of periods with wT below 3 °C decrease from a maximum of 14 days (range 1-10) in the reference period to a maximum of 10 days (range 1-10) in the near future and less than 2 consecutive days in the far future.

Remains of direct heat inputs are still included in the simulations for the upper part of the Rhine (included in the semi-deterministic Swiss water temperature model). It is likely that the lower water temperatures notably in winter are therefore elevated resulting in a relatively low number of days with below 3 °C compared to the German part of the Upper Rhine.

The number of days < 3 °C in the near future in the German part of the Rhine is influenced by the bias caused by the harmonisation (chapter 6.3).

Threshold (°C)	**Number of days per year**	**Longest period days**
> 21.5 °C		
> 23 °C		

<table>
<tr><td>> 25 °C</td><td>
</td><td>
</td></tr>
<tr><td>> 28 °C</td><td>
</td><td>
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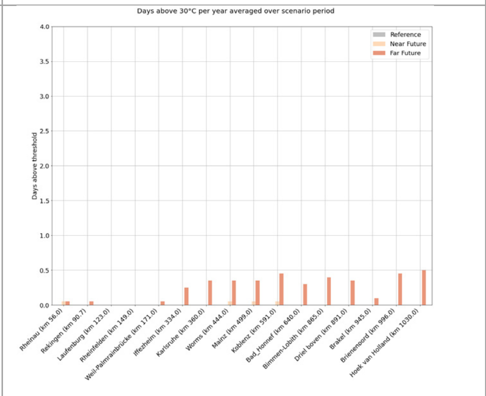
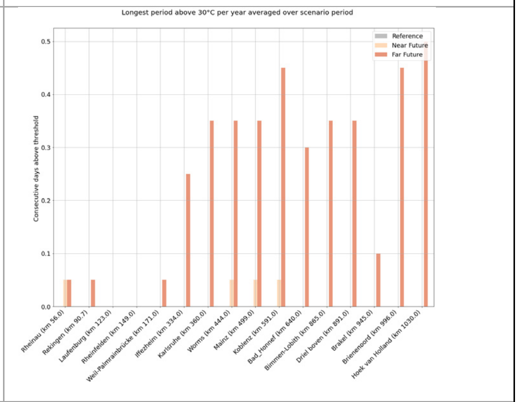
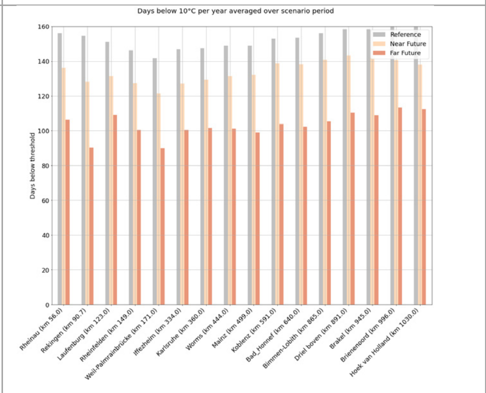
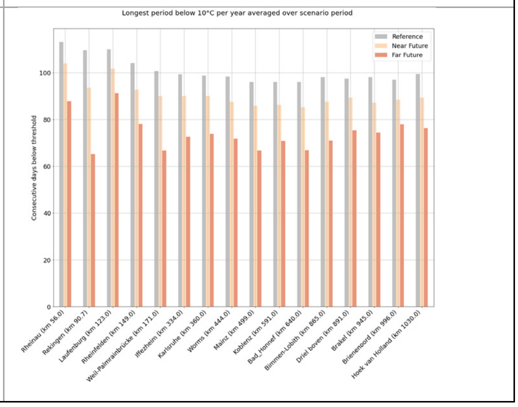
<tr><td>> 30 °C</td><td>
</td><td>
</td></tr>
<tr><td>< 10 °C</td><td>
</td><td>
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< 3 °C

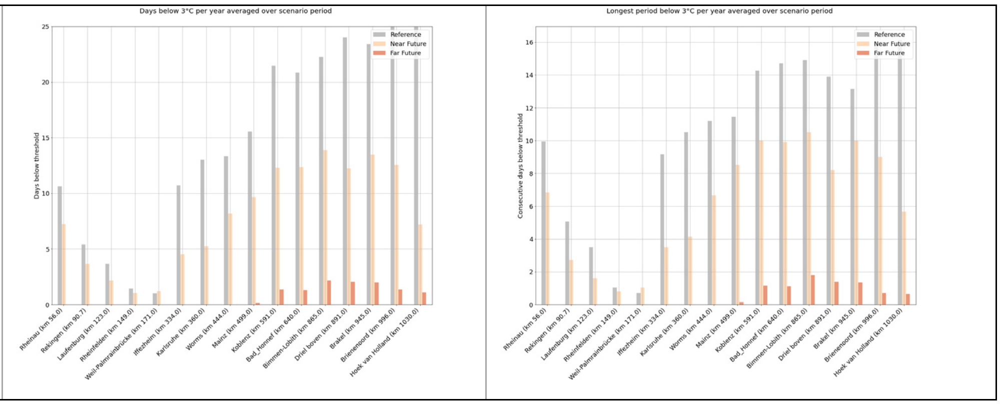

Figure 6-7 Annual averaged number of days per year (left column) and averaged longest consecutive period in days (right column) the water temperature is above 21.5 °C, 23 °C, 25 °C, 28 °C, 30 °C and below 3 °C, 10 °C in the reference period, the near future and far future along the Rhine. Each panel shows the average across 20 years in each scenario per station (distance not to scale).

6.5 Evaluation basin-wide approach

The basin-wide Rhine model is composed of three coupled national models describing hydrology and water temperature forced with one common climate chain ensemble member. This leads to a more consistent water temperature profile along the Rhine compared to the national approaches which cause inconsistencies at the national boundaries.

The climate forcing signal that is applied in the basin-wide approach is affected by the combination of shortening the evaluation period from the common climate change approach of 30 years to 20 years in combination with a shift of the reference period to more recent (warmer) years. The applied climate forcing in the basin-wide model is, notably in the near future, cooler (-0.1 °C to -0.6 °C, chapter 6.3) compared to the ensemble based projection used in the German national approach.

Despite using the same climate chain ensemble member, the basin-wide water temperature result is biased by a (remaining) methodological difference between the Netherlands and Germany and Switzerland in using this climate chain ensemble. The German and Swiss approach use projected climate chain results for the reference period and rely on bias correction to correct differences in the mean and variability between climate model and observations. The Dutch results (in this study based on KNMI 2014) use a “change vector” derived from a 30-year climate model added to a reference based on measurements. This is done to avoid a bias correction.

The basin-wide approach has the advantage that inconsistencies at the national boundaries are avoided (following from the fact they are coupled) and that it allows to make future projections excluding the influence of remains of direct heat inputs in the Netherlands. Simulations for the upper part of the Rhine are still influenced by remains of direct heat inputs as these cannot be excluded from Swiss water temperature model as it is a semi-deterministic model based on water temperature measurements.

So, the basin-wide approach in its current implementation is not ideal yet but is nevertheless preferred to the method of combining the three national approaches to a Rhine wT profile (as done in chapter 5).

7 Conclusions

The best estimate for temperature projections for the Rhine basin as a whole at this point, are based on the basin-wide approach (chapter 6) with some nuances based on climate chain ensemble results of the national approaches (chapter 5).

7.1 Data summary

Table Table *7-1* summarises the projected warming for the near (2045-2065) and far future (2080-2100) relative to the reference period (1990-2010) under the highest emission scenario RCP8.5 without direct heat inputs. Table 7-2 summarises the effect the relative warming has on the number of days that relevant thresholds for absolute water temperature are exceeded in the reference and future scenarios.

Table Table *7-1* shows that in all sections of the Rhine, warmer water temperatures are projected for the near and far future:

- In the near future, basin-wide annual average wT increase varies from +1.1 °C to +1.8 °C.
- In the far future, basin-wide annual average wT increase varies from +2.9 °C to +4.2 °C.

Warming is asymmetric, meaning that summer and autumn warm faster than the annual average and winter and spring warming is slower (colours in Table Table *7-1*).

Table 7-1 Seasonally averaged Rhine water temperature increase (dT, °C) for near and far future scenarios in the basin-wide model. Seasons per column: winter-DJF, spring-MAM, summer-JJA and autumn-SON and annual average. Colours are relative per scenario indicating both seasonal and longitudinal temperature gradients.

scenario	NF-REF					FF-REF				
season	WINTER	SPRING	SUMMER	AUTUMN	YEAR	WINTER	SPRING	SUMMER	AUTUMN	YEAR
Rheinau_2392_km-56	1.0	1.1	2.4	2.6	1.8	3.4	2.8	5.1	5.6	4.2
Rekingen_2143_km-90.7	1.0	1.1	2.2	2.6	1.7	3.5	3.0	4.9	5.4	4.2
Laufenburg_2130_km-123	0.9	0.8	2.1	2.3	1.5	2.8	2.0	4.4	4.7	3.5
Rheinfelden_2091_km-149	0.9	0.7	2.1	2.3	1.5	2.8	1.8	4.6	4.9	3.5
Weil-Palmrainbr_2613_km-174	0.9	0.7	2.2	2.4	1.6	3.0	2.0	4.8	5.1	3.7
Iffezheim (km 334)	0.9	0.6	2.0	2.1	1.4	2.9	1.9	4.4	4.6	3.5
Karlsruhe (km 359)	0.8	0.6	2.0	2.1	1.4	2.9	1.9	4.3	4.5	3.4
Worms (km 444)	0.8	0.6	1.9	2.0	1.3	2.8	1.9	4.1	4.3	3.3
Mainz (km 499)	0.8	0.6	1.8	1.9	1.3	2.8	2.1	3.9	4.2	3.2
Koblenz (km 590)	0.7	0.6	1.7	1.7	1.2	2.7	2.0	3.8	3.9	3.1
Bad-Honnef (km 640)	0.7	0.6	1.6	1.7	1.1	2.7	2.1	3.6	3.9	3.1
Bimmen (km 865)	0.7	0.5	1.4	1.6	1.1	2.6	2.1	3.3	3.7	2.9
Rhine-NWW_2_Brakel (km 945)	0.9	0.7	1.5	1.6	1.2	2.8	2.1	3.3	3.6	3.0
Rhine-NWW_3_Vuren (km 951)	0.9	0.7	1.6	1.6	1.2	2.8	2.1	3.3	3.6	3.0
Rhine-NWW_4_Brienenoord_RO (km 995)	1.2	0.9	1.7	1.8	1.4	3.0	2.3	3.4	3.7	3.1
Rhine-NWW_5_Brienenoord (km 996)	1.2	0.9	1.7	1.8	1.4	3.0	2.3	3.4	3.7	3.1
Rhine-NWW_6_Maasluis (km 1018)	1.5	1.0	1.8	2.0	1.6	3.2	2.3	3.5	3.8	3.2
Rhine-NWW_7_HoekvanHolland (km 1030)	1.5	1.1	1.8	2.0	1.6	3.2	2.4	3.5	3.8	3.2

Table 7-2 shows that threshold indicators for warmer water temperatures are exceeded more frequently for the future scenarios. The opposite holds for indictors for cooler water temperatures which occur less frequently in future:

- The > 25 °C threshold is exceeded 1-2 weeks per year in the near future.
- The > 28 °C threshold is exceeded 1 ± 0.5 week per year in the far future.
- The > 30 °C threshold is not exceeded in the scenarios.
- The < 3 °C threshold is still undercut 1-2 weeks in the near future (compared to 1-3 weeks in the reference scenario), but rarely in the far future scenario.

Table 7-2 Summary threshold values for common climate projection in composite the basin-wide model without direct heat inputs for selected stations. Values represent the (rounded) average number of days per year calculated from a 20-year simulation of daily temperatures.

Variabele		> 21.5 °C			> 23 °C			> 25 °C			> 28 °C			> 30 °C			< 3 °C			< 10 °C	
Scenario	REF	NF	FF	REF	NF	FF	REF	NF	FF	REF	NF	FF	REF	NF	FF	REF	NF	FF	REF	NF	FF
Rheinau_2392_km-56	17	64	115	3	34	94	1	7	57	0	1	3	0	0	0	11	7	0	156	136	106
Rekingen_2143_km-90.7	16	59	112	3	28	90	0	7	49	0	1	3	0	0	0	5	4	0	155	128	90
Laufenburg_2130_km-123	6	41	98	1	14	68	0	2	19	0	0	0	0	0	0	4	2	0	151	131	109
Rheinfelden_2091_km-149	11	54	107	2	22	83	0	3	35	0	0	1	0	0	0	1	1	0	146	127	101
Weil-Palmrainbr_2613_km-174	20	69	118	3	34	95	0	6	53	0	1	4	0	0	0	1	1	0	142	121	90
Iffezheim (km 334)	36	78	114	13	46	96	2	15	63	0	1	7	0	0	0	11	5	0	147	127	100
Karlsruhe (km 359)	39	79	114	14	47	95	2	17	63	0	1	8	0	0	0	13	5	0	147	129	101
Worms (km 444)	42	78	111	16	47	94	3	19	61	0	1	9	0	0	0	13	8	0	149	131	101
Mainz (km 499)	45	79	111	19	49	93	3	19	60	0	1	8	0	0	0	16	10	0	149	132	99
Koblenz (km 590)	44	75	107	20	46	88	3	18	54	0	1	8	0	0	0	21	12	1	153	139	104
Bad-Honnef (km 640)	44	75	107	21	46	87	4	17	52	0	1	7	0	0	0	21	12	1	154	138	102
Bimmen (km 865)	43	69	100	19	39	78	3	14	42	0	1	6	0	0	0	22	14	2	156	141	105
Rhine-NWW_2_Brakel	39	69	100	16	38	79	2	13	41	0	0	5	0	0	0	23	13	2	158	142	109
Rhine-NWW_3_Vuren	39	69	99	16	38	79	2	13	41	0	0	5	0	0	0	24	14	2	159	142	109
Rhine-NWW_5_Brienenoord	40	70	100	15	42	77	1	15	40	0	1	7	0	0	0	27	13	1	160	141	113
Rhine-NWW_4_Brienenoord_RO	40	70	100	15	42	76	1	15	40	0	1	6	0	0	0	27	13	1	160	141	113
Rhine-NWW_6_Maasluis	37	70	99	14	43	74	1	15	40	0	1	7	0	0	1	28	7	1	161	138	113
Rhine-NWW_7_HoekvanHolland	36	70	99	14	43	73	1	15	39	0	1	7	0	0	1	28	7	1	161	138	112

7.2 Comparison to previous assessment

A meaningful comparison of the findings of the current study to the previous STEMP study (ICPR, 2014) is complicated as the previous results included a significant influence of direct heat input and moreover, the reference periods are not the same.

Previous results were therefore corrected for heat inputs in Table 7-3; the comparison to the current projections then leads to the following conclusions for the mean annual water temperature between Worms and Lobith:

- The temperature in the currently used reference temperature scenario is colder (as it includes colder years 1990-2000[7]).
- The current dT signal for the near future is higher resulting in an almost similar absolute near future temperature.
- The current far future temperature projection is somewhat colder (-0.1 °C to -0.3 °C).

Table 7-3 Difference in yearly averaged water temperature projections in the current study (2024) compared to the previous STEMP study in 2014 (ICPR, 2014). Results for 2014 are based on (ICPR, 2014): Table 4.2 using Ref0 (no heat input) and corrected values for NF and FF using Ref-Ref0).

		REF			NF			FF		
		2014	2024		2014	2024		2014	2024	
Worms	T °C	13.1	12.8	-0.3	14.1	14.1	0.0	16.3	16.1	-0.2
Koblenz		13.0	12.6	-0.4	14.0	13.8	-0.1	16.0	15.7	-0.3
Lobith		12.7	12.6	-0.1	13.6	13.6	0.0	15.6	15.5	-0.1
Worms	dT °C				0.9	1.3	0.4	3.2	3.3	0.1
Koblenz					1.0	1.2	0.2	3.0	3.1	0.1
Lobith					0.9	1.1	0.2	2.9	2.9	0.0

In Table 7-4, a comparison between the current and the previous assessment for threshold values 28 °C and 3 °C is made. Basel was not modelled in the previous study, it was the upper boundary of the German model and based on an empirical relationship, it is nevertheless included here as it was presented as a modelling result at the time.

[7] Warming trends in data report [ref] show e. g. +1.15 °C, +0.63 °C and +0.37 °C/decade warming in the period 1980-2000 for Worms, Koblenz and Lobith respectively.

The current threshold projections compared to the previous values shows the following (Table 7-4):

- In the reference scenario, except for Basel, projections are similar for both thresholds. The difference in the mean annual wT of several tenth of degrees (Table 7-3) has limited impact on both thresholds.
- The slightly cooler reference in the current simulations suggests somewhat cooler summers (less number of days > 28 °C) and at the same time warmer winters (less number of days < 3 °C).
- In the near future, the 28 °C threshold violation is very similar to the earlier projections.
- In the far future, there is a (relatively) small reduction in the number of days > 28 °C which is in line with the mean annual cooling (Table 7-3) except, again, for Basel where a significantly stronger effect of warming is projected in the current study.
- In the near future, the number of days < 3 °C has increased in the current study. This was not observed in the mean annual water temperature (Table 7-3) but confirms the cooler near future results, notably in the German part of the Rhine.
- In the far future, the number of days < 3 °C has deceased in the current study.

Table 7-4 Difference in number of days the thresholds are passed for the current study (2024) compared to the previous STEMP study in 2014 (ICPR, 2014). Results for 2014 are based on (ICPR, 2014): Figure 4-4 (> 28 °C) and Figure 4-3 (< 3 °C) applying a rough correction using the difference between Ref (including direct heat input) and Ref0 (no heat input) to correct values for NF and FF). Numbers in bold indicate relative changes > 50 %.

		REF			NF			FF		
		2014	2024		2014	2024		2014	2024	
Basel	nod >28 °C	2	0	**-2**	7	6	-1	31	53	**22**
Koblenz	nod >28 °C	4	3	-1	18	18	1	59	54	-4
Lobith	nod >28 °C	3	3	0	15	14	0	49	42	-7
Basel	nod<3 °C	0	1	**1**	1	1	**1**	0	0	0
Koblenz	nod<3 °C	17	16	-1	4	10	**6**	3	0	**-3**
Lobith	nod<3 °C	23	21	-2	9	12	3	7	1	**-6**

7.3 Methodological findings

The national model approaches available at the start of this study were too different to directly use them to construct a basin-wide temperature profile. It was therefore necessary to harmonise (1) the climate chain members and use only one common member, (2) the length of the evaluation period, (3) the reference period start and end date and (4) the conditions at the national boundaries.

As all ensemble members are possible futures, the selection of only one member is assumed to show one of these possible futures. As within this study it was not possible to simulate several ensemble members across all Rhine sections. The chosen common climate chain was assumed to be representative of the model ensemble. Reducing the evaluation period from 30 years, which is the regular definition of climate, to the harmonised 20-year period used here causes different results. Within shorter periods, single cold or warm years have a larger impact on the average than within longer periods. It was e. g. demonstrated that ensemble member ECE-R1_RAC_RCP85 in the 20-year runs is less "mainstream" when comparing its position to the one in the 30-year runs at Lobith. Projections for the near future are therefore colder (estimated -0.1 °C to -0.6 °C, chapter 6.3).

The reference period used here (1990-2010) is colder compared to the previous STEMP study (2000-2010) but e. g. warmer compared to what is normally used in Germany because it includes even older (and thus colder) years. This is not a methodological problem, but it complicates comparisons, notably when comparing temperature differences between reference and future(s).

The harmonisation of the national boundaries was a significant methodological improvement. Only after coupling of the national models, a consistent basin-wide temperature profile with plausible seasonal patterns along the Rhine was simulated.

The basin-wide approach has the advantage that inconsistencies at the national boundaries are avoided (following from the fact that they are coupled) and that it allows to make future projections excluding the influence of remains of direct heat inputs in the Netherlands. Simulations for the upper part of the Rhine were still influenced by remains of direct heat inputs as these could not be excluded from the Swiss water temperature model as it is a semi-deterministic model based on water temperature measurements.

Despite using the same climate chain ensemble member, the basin-wide water temperature projections are biased because of a (remaining) methodological difference between the Netherlands and Germany and Switzerland in using this common climate chain ensemble. The German and Swiss approach use projected climate chain results for the reference period and rely on bias correction to correct differences in the mean and variability between climate model and observations. The Dutch results (in this study based on KNMI 2014) uses a "change vector" derived from 30-year climate model added to a reference based on measurements. This is done to avoid a bias correction.

So, the basin-wide approach in its current implementation is still not ideal yet but is nevertheless preferred to the method of combining the three national approaches to a Rhine wT profile (as done in chapter 5).

8 Recommendations

For a successful harmonisation of models projecting effects of climate change in the Rhine basin, it is key to have an early agreement on time periods and climate chain ensemble members to simulate. A similar recommendation can be found in the HCLIM reporting. As discharges are relevant for water temperature models, too and need harmonisation, too (ICPR, 2024), an early coordination with HCLIM is recommended.

Scenario periods used in the previous assessment (10 years) as well as the current assessment (20 years) were based on pragmatic choices that had to be made after national studies were already finished. Periods shorter than the desirable standard 30 years in climate studies introduce bias in the results. Upfront harmonisation of scenario periods may prevent this.

Rather than simulating one climate chain as done in this study within the basin-wide model, a better coverage of uncertainty is obtained by simulating multiple climate chains as is done in the national approaches.

Riparian states should make sure to include climate chains representative for the scale of the Rhine catchment in their national analysis. Focus on the national scale only does not serve transboundary modelling of water temperature (and hydrology). During the national evaluation of ensemble members analysis, countries could consider the performance of each member of their climate chain selection on a basin-scale, too.

Methods to reflect climate change should be the same in the participating countries. The current disbalance between Germany and Switzerland using simulated time series and the Netherlands using constant climate change vectors is unfavourable as it hampers easy comparison of model results.

Upper model boundaries of the national water temperature models should not be located at the national boundaries as is common practice for water temperature now. This implies (1) shifting the model boundaries over a significant distance (several hundreds of km) upstream resulting in overlapping national models (this approach was followed in the previous STEMP study (ICPR, 2014)) or (2) replacing the national boundaries by the neighbouring national model results as done in this study or (3) development of one basin covering model. For other reasons, see below, the first option is preferred.

It is recommended for a basin-wide assessment to harmonise the national water temperature models in the sense that all models should have a similar amount of detail in their model concept. The national water temperature models combined in the basin-wide approach are conceptually different and vary in the amount of deterministic detail included. At present, the Dutch and German models are deterministic models whereas the Swiss model is semi-empirical and cannot distinguish remains of heat inputs, as QSim and SOBEK do. Harmonisation of the model concept may increase comparability of the results and is therefore recommended. Deterministic models are better suited for modelling influence of remains of direct heat inputs, but this may no longer be relevant in the future. In that situation, a basin-wide model composed of either three deterministic or three semi-empirical concepts are possible. Alternatively, a model ensemble of different water temperature models would be possible but would cause a large workload of applying all models to all Rhine sections.

The temperature models should be better validated, and probably calibrated, too for their lower temperature range. The current models seem to underestimate for example the winter water temperatures below 3 °C.

Overlapping models are preferred (as done in the previous assessment (ICPR, 2014). There is added value in comparing not only the performance of the national models against measurements but also comparing their future projections as done in the previous assessment (ICPR, 2014). Geographically overlapping models are therefore preferred, allowing inter model comparison that can bring model bias or variability in future projections to light.

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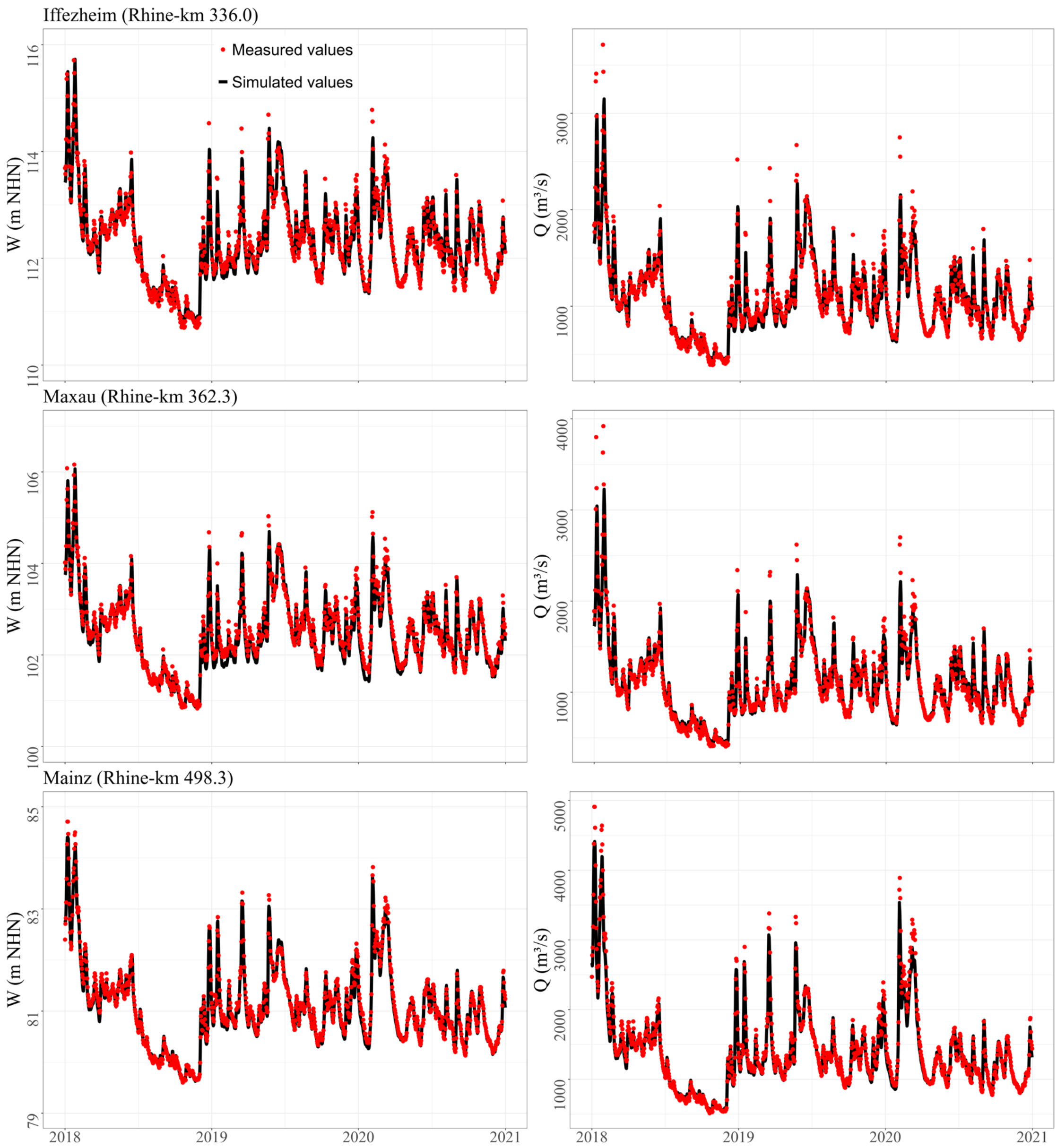
10 Appendix: Validation results (per model)

In this appendix, firstly calibration (2018) and validation (2019-2020) of the HYDRAX simulations for water levels and discharges at different gauging stations along the Rhine are presented. Following that the simulation results for the validation period (2018-2020) are compared to measurements of water temperature at selected Rhine stations (in downstream order), respectively for Switzerland, Germany and the Netherlands, each country uses its own simulation model.

10.1 Hydrodynamics

Validation of the hydrodynamic models is reported for Germany (HYDRAX) only.



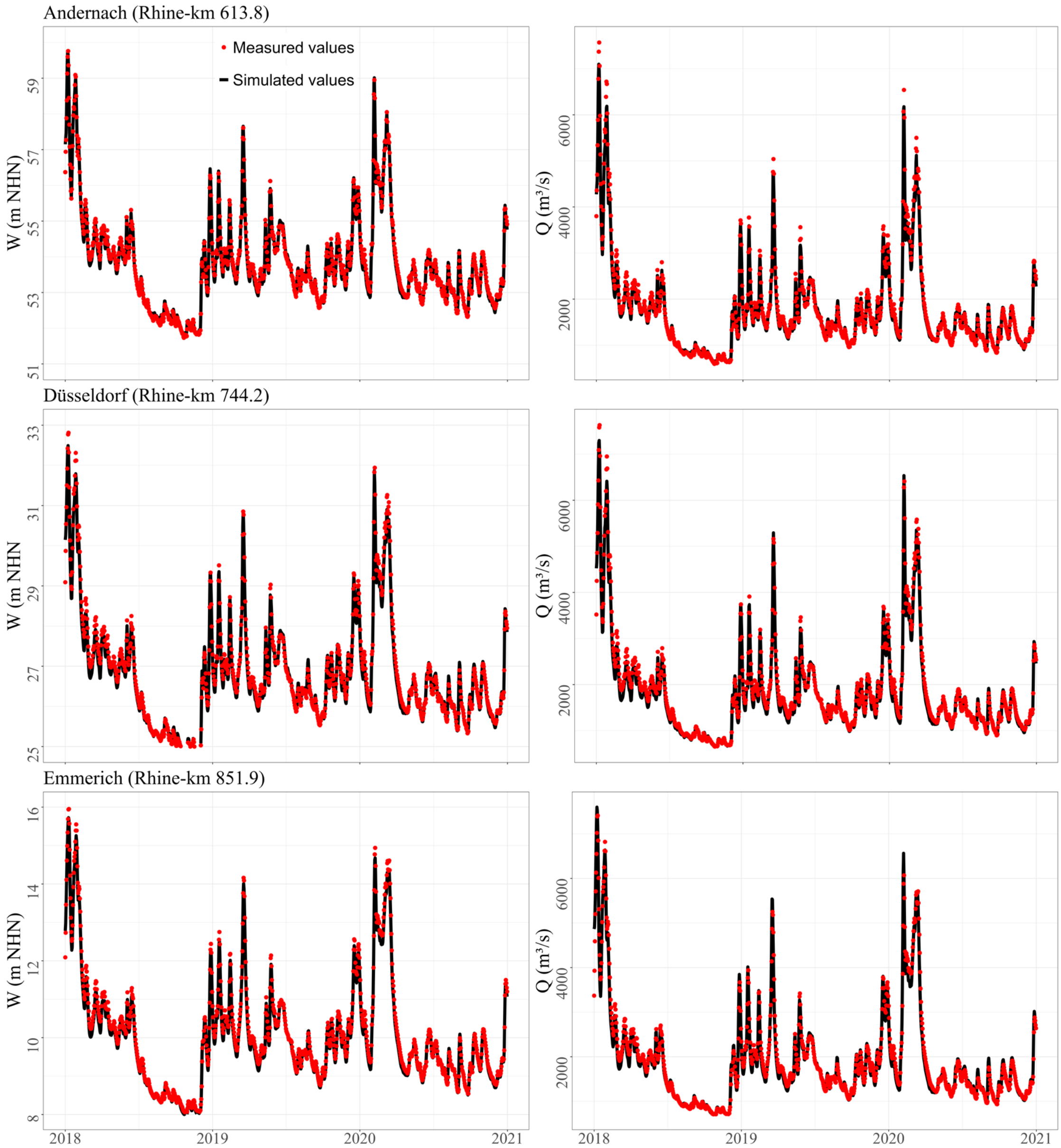


Figure 10-1 Graphical comparison of HYDRAX simulations and measurements (2018-2020) of water level and discharges at different hydrological gauging stations along the Rhine. The flow data from 2018 was used for HYDRAX calibration whereas validation was performed with flow data from 2019-2020.

Table 10-1 Performance metrics for HYDRAX simulated water levels and discharges during validation (2019-2020).

	W				Q				
Gauging station	**RMSE [m NHN]**	**MAE [m NHN]**	**NSE**	**R²**	**RMSE [m NHN]**	**MAE [m³/s]**	**MAPE [%]**	**NSE**	**R²**
Iffezheim	0.17	0.12	0.92	0.93	105.35	64.46	5.25	0.90	0.91
Maxau	0.18	0.13	0.93	0.95	86.30	53.35	4.32	0.94	0.94
Mainz	0.10	0.07	0.98	0.98	101.53	63.44	3.85	0.96	0.98
Andernach	0.11	0.08	0.99	0.99	112.25	75.25	3.75	0.98	0.99
Köln	0.13	0.09	0.99	0.99	106.12	73.84	3.72	0.99	0.99
Düsseldorf	0.15	0.11	0.98	0.99	128.29	94.12	4.78	0.98	0.99
Emmerich	0.13	0.10	0.99	0.99	157.98	105.75	5.05	0.97	0.97

10.2 Switzerland – air2water

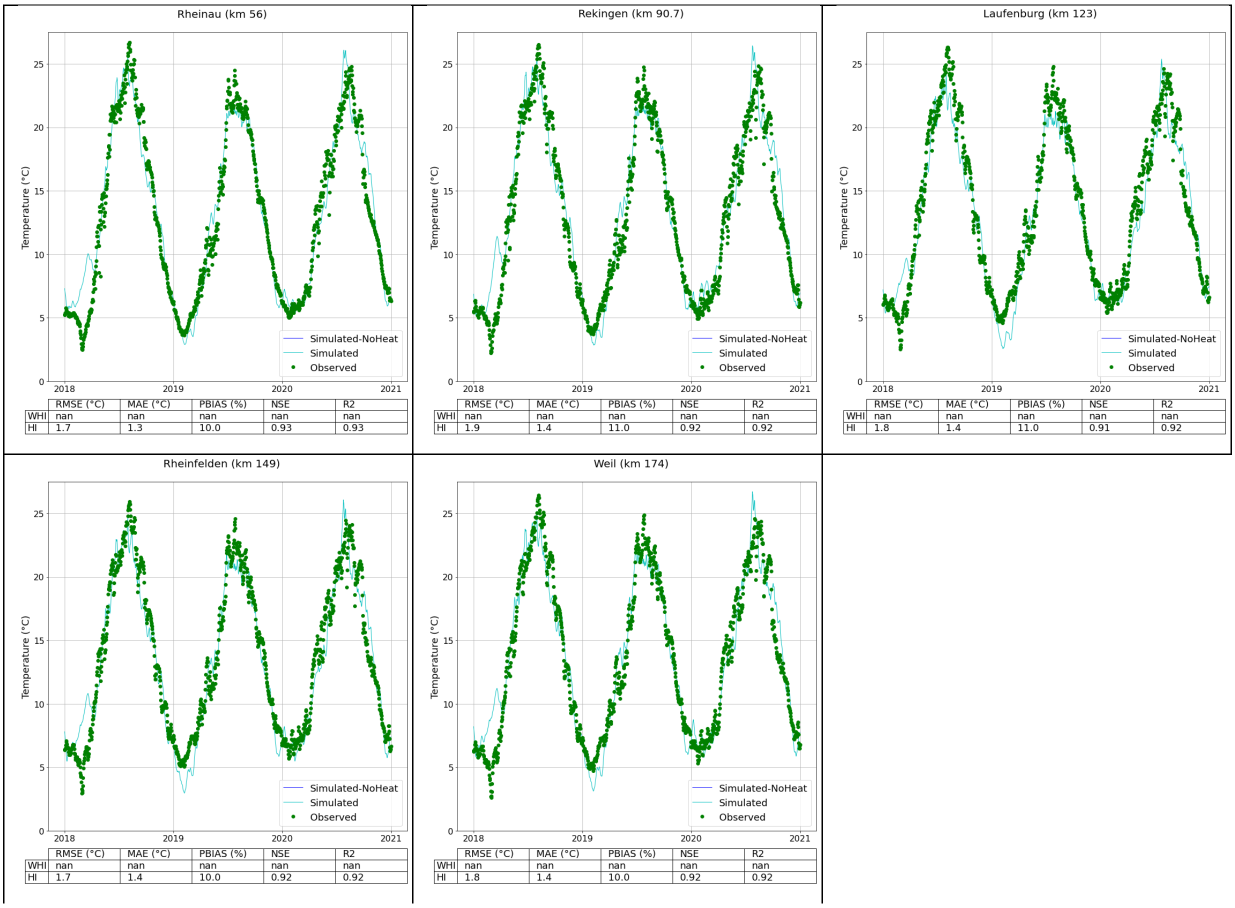


Figure 10-2 Comparison between measurements (green dots) and simulations without (WHI) and with heat input (HI) (blue lines) of water temperatures (2018-2020) at different stations along the Rhine including model statistics based on measurements and simulation.

10.3 Germany – QSim

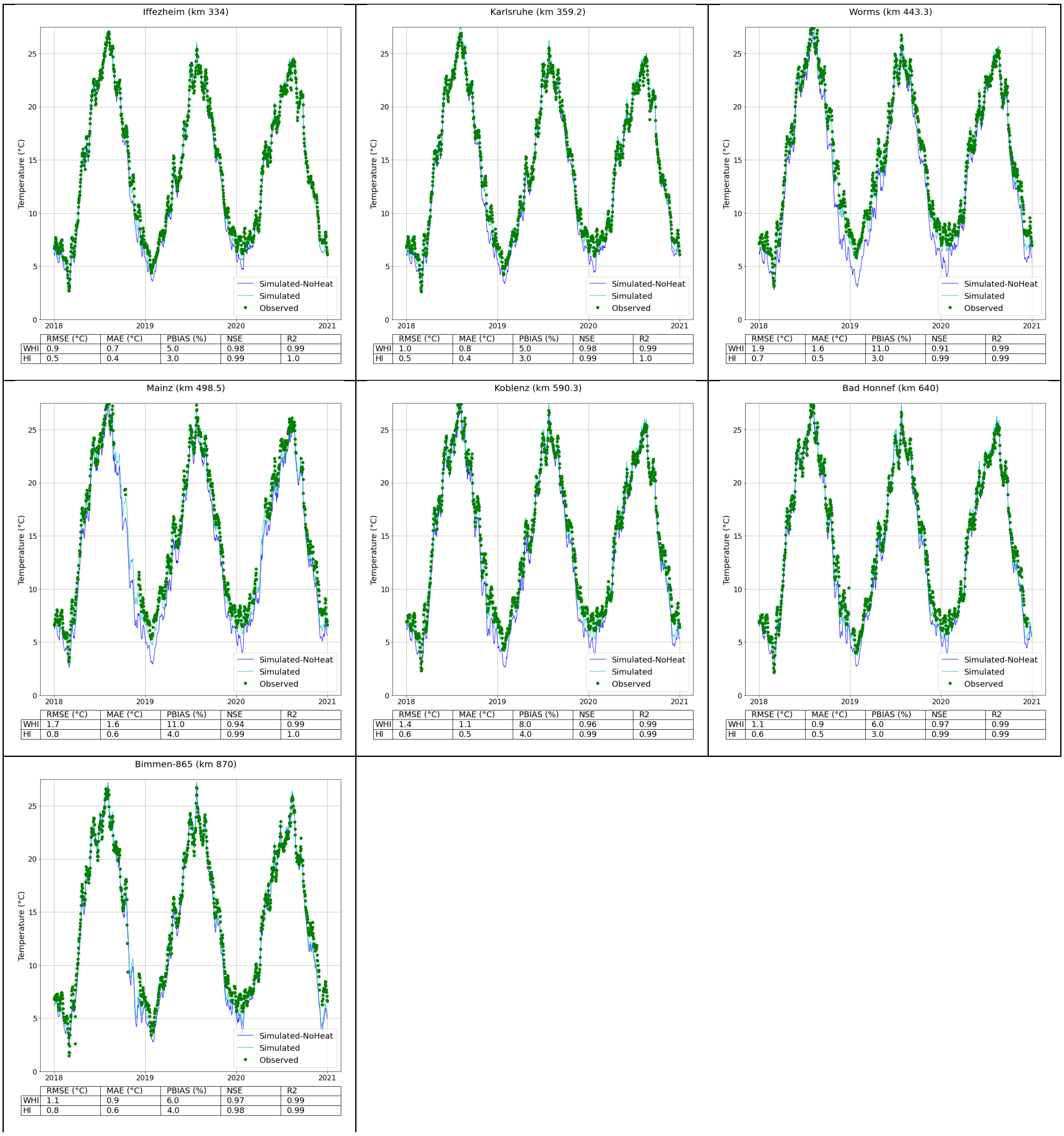
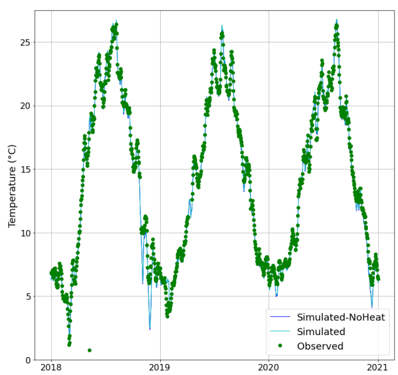


Figure 10-3 Comparison between measurements (green dots) and simulations without (WHI) and with heat input (HI) (blue lines) of water temperatures (2018-2020) at different stations along the Rhine including model statistics based on measurements and simulation.

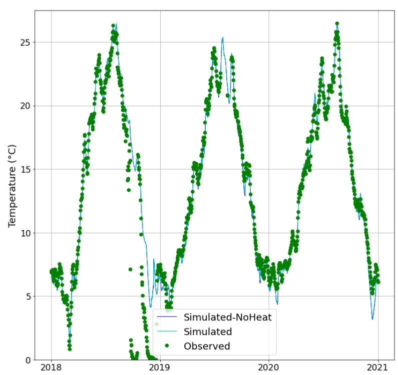
10.4 The Netherlands – SOBEK

Driel (km 891.1 - Nederrijn)



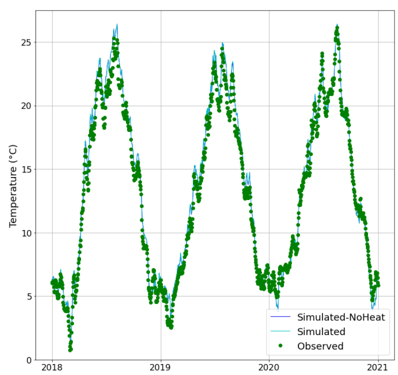
	RMSE (°C)	MAE (°C)	PBIAS (%)	NSE	R2
WHI	0.9	0.5	3.0	0.98	0.98
HI	0.9	0.5	3.0	0.98	0.98

Amerongen (km 922.0 - Nederrijn)



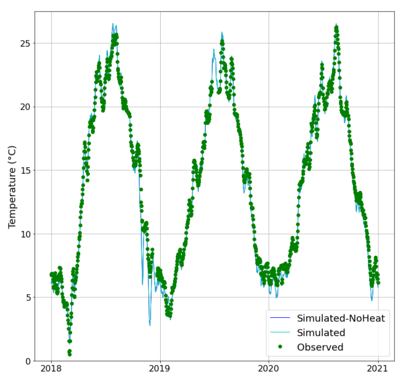
	RMSE (°C)	MAE (°C)	PBIAS (%)	NSE	R2
WHI	2.7	1.2	9.0	0.84	0.85
HI	2.8	1.1	9.0	0.84	0.85

Hagestein (km 946.7 - Lek)



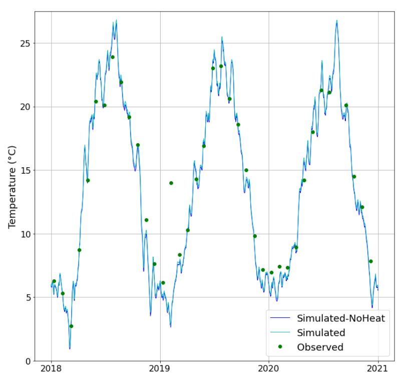
	RMSE (°C)	MAE (°C)	PBIAS (%)	NSE	R2
WHI	0.9	0.7	6.0	0.98	0.99
HI	0.9	0.8	6.0	0.98	0.99

Brienenoord-RO (km 995.2 - Nieuwe Maas)



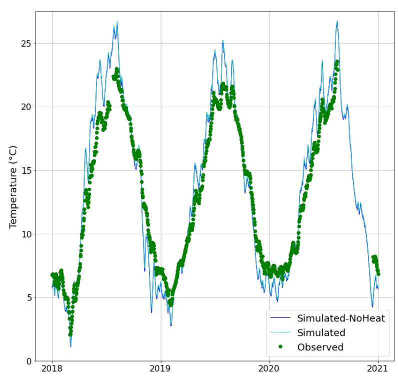
	RMSE (°C)	MAE (°C)	PBIAS (%)	NSE	R2
WHI	0.7	0.5	3.0	0.99	0.99
HI	0.7	0.5	3.0	0.99	0.99

Maasluis (km 1018.5 - Nieuwe Waterweg)



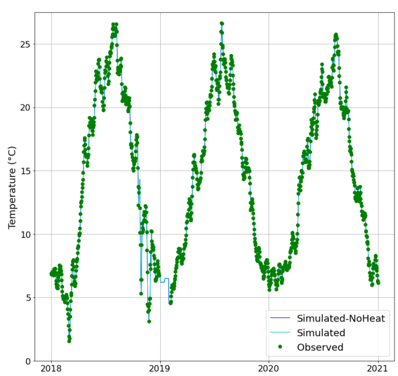
	RMSE (°C)	MAE (°C)	PBIAS (%)	NSE	R2
WHI	2.0	1.0	7.0	0.89	0.93
HI	2.0	1.0	7.0	0.89	0.93

HoekvanHolland (km 1030.1 - Nieuwe Waterweg)



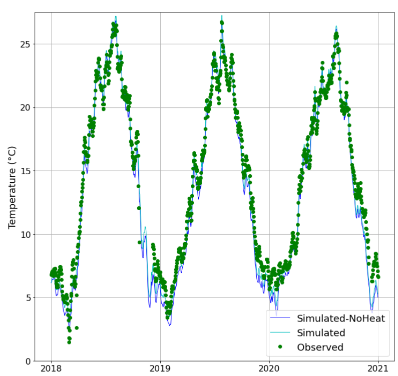
	RMSE (°C)	MAE (°C)	PBIAS (%)	NSE	R2
WHI	1.8	1.5	11.0	0.9	0.96
HI	1.8	1.5	12.0	0.89	0.96

Lobith (km 863.2 - Rhine)



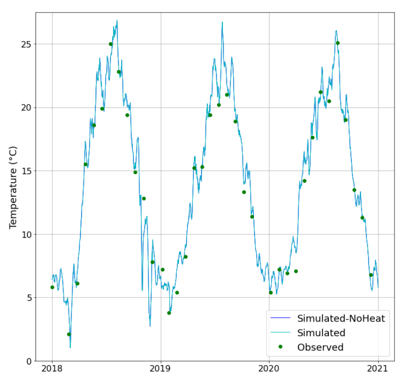
	RMSE (°C)	MAE (°C)	PBIAS (%)	NSE	R2
WHI	0.5	0.3	2.0	0.99	0.99
HI	0.5	0.3	2.0	0.99	0.99

Bimmen-865 (km 870)



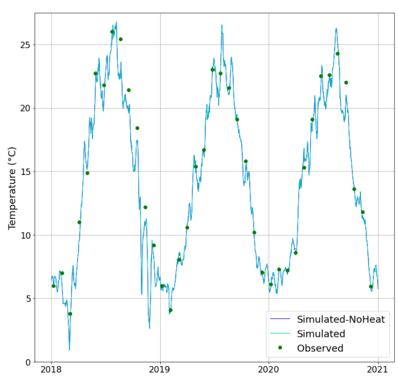
	RMSE (°C)	MAE (°C)	PBIAS (%)	NSE	R2
WHI	1.1	0.9	6.0	0.97	0.99
HI	0.8	0.6	4.0	0.98	0.99

Brakel (km 945.3 - Waal)



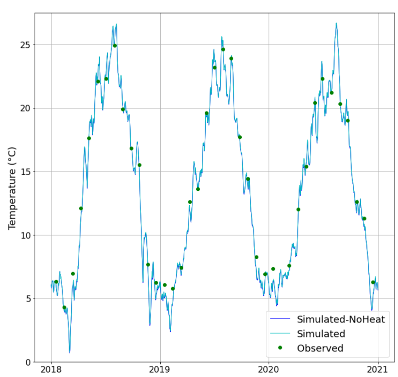
	RMSE (°C)	MAE (°C)	PBIAS (%)	NSE	R2
WHI	1.1	0.9	7.0	0.97	0.98
HI	1.1	0.9	7.0	0.97	0.98

Vuren (km 951.7 - Waal)



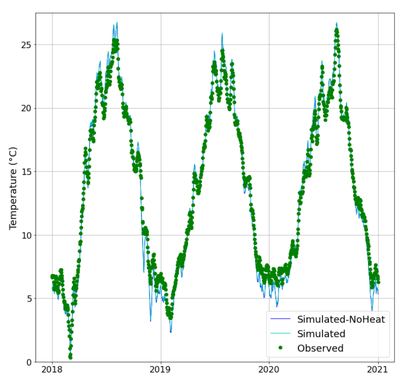
	RMSE (°C)	MAE (°C)	PBIAS (%)	NSE	R2
WHI	0.9	0.6	4.0	0.98	0.99
HI	0.9	0.6	4.0	0.98	0.99

Puttershoek (km 984.4 - Oude Maas)

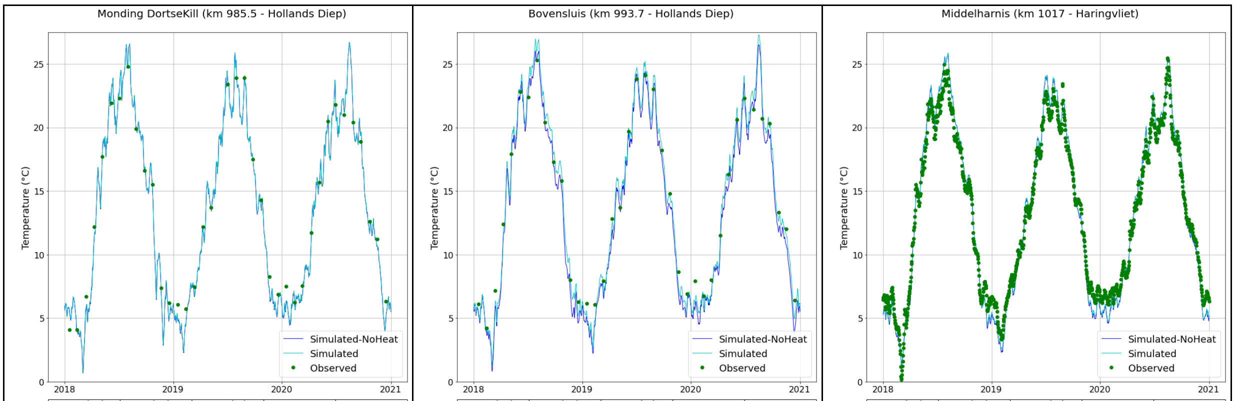


	RMSE (°C)	MAE (°C)	PBIAS (%)	NSE	R2
WHI	0.7	0.5	4.0	0.99	1.0
HI	0.6	0.5	4.0	0.99	1.0

Beerenplaat (km 996.1 - Oude Maas)



	RMSE (°C)	MAE (°C)	PBIAS (%)	NSE	R2
WHI	0.8	0.6	5.0	0.98	0.99
HI	0.8	0.6	5.0	0.99	0.99



	RMSE (°C)	MAE (°C)	PBIAS (%)	NSE	R2
WHI	0.8	0.6	4.0	0.99	0.99
HI	0.7	0.6	4.0	0.99	0.99

	RMSE (°C)	MAE (°C)	PBIAS (%)	NSE	R2
WHI	1.1	0.9	6.0	0.97	0.99
HI	0.8	0.7	5.0	0.98	1.0

	RMSE (°C)	MAE (°C)	PBIAS (%)	NSE	R2
WHI	1.0	0.8	6.0	0.98	0.99
HI	0.9	0.8	6.0	0.98	0.99

Figure 10-4 Comparison between measurements (green dots) and simulations without (WHI) and with heat input (HI) (blue lines) of water temperatures (2018-2020) at different stations along the Rhine including model statistics based on measurements and simulation.