Article

Adaptation Turning Points in River Restoration? The Rhine Salmon Case

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Abstract: Bringing a sustainable population of Atlantic salmon (*Salmo salar*) back into the Rhine, after the species became extinct in the 1950s, is an important environmental ambition with efforts made both by governments and civil society. Our analysis finds a significant risk of failure of salmon reintroduction because of projected increases in water temperatures in a changing climate. This suggests a need to rethink the current salmon reintroduction ambitions or to start developing adaptive action. The paper shows that the moment at which salmon reintroduction may fail due to climate change can only be approximated because of inherent uncertainties in the interaction between salmon and its environment. The added value of the assessment presented in this paper is that it provides researchers with a set of questions that are useful from a policy perspective (by focusing on the feasibility of a concrete policy ambition under climate change). Thus, it offers opportunities to supply policy makers with practical insight in the relevance of climate change.

Keywords: Atlantic salmon (*Salmo salar*); Rhine river; climate change; water temperature; adaptation turning points

1. Introduction

Atlantic salmon (*Salmo salar*) is again migrating into the Rhine river system [1], after it became extinct in the 1950s [2,3]. Reintroduction started when the Rhine state governments conceived and accepted the Rhine Action Plan in 1987. The first goal of the plan, to be reached in the year 2000, stated: "the Rhine ecosystem should be improved to such an extent that higher species, such as salmon and sea trout, again become indigenous" ([2], p.151). Rhine national governments as well as regional authorities and NGO's are involved in the implementation effort. Bringing back the salmon is more than a water policy objective; it is an inspiration for many small scale public and private initiatives along the Rhine streams and rivers [4]. Numbers of observed migrating salmon are low and we cannot speak of a sustainable population yet [1]. Therefore, reintroduction efforts continue to be high on the policy agenda [5].

The Rhine action plan proposes to restore the river water quality, parts of the connectivity and the morphology of a few selected spawning grounds to a state resembling the times when salmon were abundant [6]. It implicitly assumes that hydrological and temperature regimes of the river do not significantly change in the future. Future projections however show an increasing likeliness of extreme events [7] and changes in the hydrological [8,9] and temperature regime of the river [10–12]. This raises questions about changing habitat conditions for salmon. Will actual policy actions continue to lead to successful reintroduction of salmon?

This study focuses on salmon restoration policies in the Rhine under the pressure of climate change. The questions we aim to answer are: Can the reintroduction of the salmon in the Rhine fail as a result of climate change? If so, when? And what are adaptation strategies to prevent policy failure?

This paper presents results from a case study in the MEDIATION research project (Methodology for Effective Decision-making on Impacts and AdaptaTION) [13]. MEDIATION decided to focus on the salmon in the Rhine river because it is the symbol and indicator species of river restoration [2,5]. River restoration is of interest because it requires a multi scale policy approach involving ecological, morphological, hydrological, climate and governance knowledge. The subject of this study is a socio-ecological system, representing interconnections and feed backs between societal and ecological processes [14].

2. Methodology

This paper analyses the consequences of forcing the 'Atlantic salmon socio-ecological system' by climate change impacts on the rivers hydrological and temperature regime. Forcing of complex systems lead to nonlinear behavior with prolonged periods of stability alternated with sudden changes [15] or critical transitions [16].

Kwadijk *et al*. [17] applied theories on critical thresholds [18] and tipping points in the earth system [19] to water management systems in the Netherlands under pressure of climate change. Their aim is to find 'points where the magnitude of change due to climate change or sea level rise is such that the current management strategy will no longer be able to meet with the objectives' [17]. They call their approach 'adaptation tipping points'. Werners *et al*. [20] build on this approach, but take a more

socio-political perspective and define: 'an adaptation turning point is a situation in which a socio-political threshold is reached, due to climate change induced changes in the biophysical system'.

This paper uses a five step methodology developed from Kwadijk *et al.* [2] and Werners *et al.* [20] (Figure 1). Table 1 presents methods and tools used in every step.

Figure 1. Elements of the assessment of adaptation turning points and adaptation pathways. For detailed explanation of the steps, see Table 1. Step 1 is the scope of the assessment. The steps 2 and 4 in the left of the diagram represent the analysis of climate impacts, usually based on model simulation. Steps 3 and 5 are governance oriented. Both sides come together in an integrated analysis of a socio-ecological system. Iterations and feedbacks (e.g., from step 5; adaptation options to step 2; potential impacts of climate change) are part of the methodology.
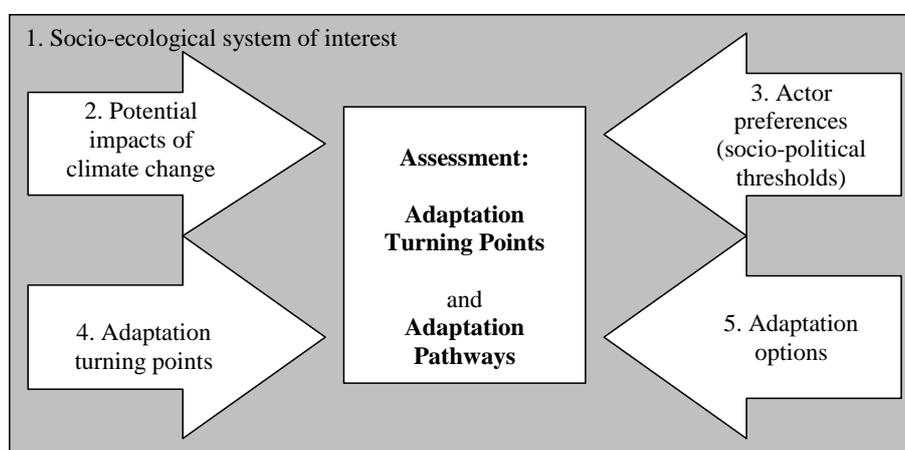

Table 1. The five steps of adaptation turning point methodology with presentation of methods used in this research [20], see Figure 1.

	Steps of adaptation turning points	Methods used in this study
1	Scope of the assessment: identify target region and socio-ecological sectors of concern.	Based on policy reports and literature Atlantic salmon was identified as an indicator species for ecological restoration of the Rhine. Salmon policies are explored at different scales, referring to policy objectives / standards / administrative arrangements. Sources are: • Literature • Four expert interviews • Results from Rhine restoration research conducted in 2008–2010 [21]
2	Identify key impacts of climate changes: (a) Create a list of possible consequences of climate changes for the region and the sectors of concern; (b) Prioritize climate change trends and impacts based on potential severity and likelihood using trends and extreme scenarios	Inventory of climate related factors potentially influencing the proliferation of Atlantic salmon on the basis of reports, scientific literature and four interviews with experts involved in the reintroduction policy: • A scientific adviser on salmon reintroduction to the ICPR; • A regional fishery association biologist; • A policy maker at the fishery authority at a German federal state level; • Chair of a local fishing association. Priority of factors is based on literature and expert judgment of potential declines in salmon populations. Physical water temperature limits for salmon were selected based on literature study.

Table 1. *Cont.*

	Steps of adaptation turning points	Methods used in this study
3	Select indicators and threshold values for socio-political objectives of concern: determine what situation is acceptable according to: (a) Analysis of policy objectives / standards / administrative arrangements, and (b) Public opinion.	Formal policy objectives from the ICPR on salmon restoration were taken as a basis for indicator and threshold identification [22,23].
4	Determine adaptation turning points: determine how much change a sector can handle, given the thresholds value independent from time. Next, translate turning points to timescale: Use projections of future climate (impact) to assess when the turning points are likely to occur.	• Water temperature was simulated on daily time step for both historic (1980–1999) and future climate (whole 21st century) using a coupled hydrological-water temperature model forced with bias-corrected Global Climate Model output. • Daily water temperature simulations were used in combination with critical water temperature limits for salmon to asses changes in the occurrence of exceeded water temperature thresholds for salmon (see Textbox 1 for further clarification).
5	Determine alternative adaptation strategies: assess what strategies actors may use to respond to adaptation turning points. Consider a different strategy or additional measures to postpone / resolve a turning point (methods depend on scale, score these alternatives based on policy targets). Assess how easy it is to switch between strategies in time (flexibility / 'no regret')	This assessment was based on: • Literature • An expert judgment by the researchers themselves.

3. Results

The following description of results is structured according to the five adaptation steps of Table 1.

3.1. Step 1: Description of the System of Interest and the Scope of the Research

The 'Rhine 2020-Programme on the sustainable development of the Rhine' [6] was adopted in 2001 by the ministers of the Rhine riparian states. This program sets the goals for the environmental protection and ecological restoration of the Rhine. The implementation of the program is integrated with Water Framework Directive policies and measures will serve both goals [5,6]. Furthermore, the Rhine 2020 program serves Habitat Directive (97/62/EC) and Birds Directive (97/49/EC) policies of the European Commission. The Rhine 2020 program focuses on ecosystem improvement, flood prevention and protection, water quality improvement, and groundwater protection. One resulting action plan is called Rhine Salmon 2020 [22]. This action plan sets the following objectives:

- 7,000 to 21,000 upstream migration individuals per year.
- Undisrupted migration possibilities up to Basel.
- Salmon stocking should be self-sustaining.
- Re-establishment of a self-sustaining, wild Atlantic salmon population in the Rhine until 2020 [22].

Since 1990, €50 million have been invested in the project. In total, investments of €528 million for the adaptation of infrastructure, like weirs and dams, and habitat restoration are planned for until 2015 [23].

Implementation of restoration measures is not without difficulty and at several policy levels stakeholders are opposing investments of public money in river restoration in general and contesting the need for restoration measures more specifically.

In the International Commission for the Protection of the Rhine (ICPR), the connectivity of the main river is a source of political deliberation on financing new fish passages. The Dutch government announced, for instance, to stop plans for the so-called ajar decision for the Haringvliet gate. The ajar decision will open the gates at the river mouth for North Sea fish to enter the Rhine. However, opening the gate will also lead to inflow of salt water into the delta, which works against local interests, which benefit from fresh water storage for farming and drinking water supply. The ICPR sent protest letters both to the Dutch government and parliament [24]. Under influence of international protests, the Dutch government reversed its decision in 2012 and decided to continue with preparation for a new Haringvliet gate management strategy.

Projects in tributaries at the local level often show comparable political difficulties [21]. Private weir owners, for instance, oppose the construction of fish passages because they do not want to lose water head for energy production. Habitat restoration such as re-meandering, flood plain and wetland construction asks for changes in land use, which is often at odds with the vested interests of farmers and other land users. On the other hand, many small NGOs collaborate with government agencies in setting up salmon nurseries and much effort is invested in terms of money and time to bring juvenile salmon to the rivers [4].

Maintaining a sustainable population of salmon in the Rhine is of concern both to formal policy makers and to representatives of civil society. In addition, given the high level of investments and the difficulties in project implementation actors need to be able to show success on the short term and a perspective for continuation of that success in the future.

3.2. Step 2: Climate Impacts on Rhine Salmon Habitats

This section explores linkages between climate change and the success of the reintroduction of Salmon. Rivers have to meet certain conditions for Atlantic salmon. A detailed description of necessary conditions can be obtained from Thorstad *et al*. [25], and Bardonnet and Baglinière [26]. In short, the following conditions have to be met:

(1). Connectivity from the river delta to the spawning grounds
(2). Appropriate spawning ground
(3). Flow regime, water levels and flow velocity
(4). Water quality (dissolved oxygen, temperature, occurrence of pollution, etc.)

Climate impact projections for the Rhine river basin show increasing winter discharge and decreasing summer discharge [6,9,27–29]. Furthermore, atmospheric warming in combination with projected reductions in summer flow is expected to increase river temperatures [10]. If we translate

these impacts to potential consequences for the proliferation of the salmon, and thus the success of achieving related policy objectives, we obtain the following factors [30–35]:

- Water temperatures may reach levels lethal for salmon and hamper upstream migration of salmon (Table 2).
- Periods of low water depth and low flow velocity in tributaries may inhibit spawning or nursery functions.
- Low oxygen levels may result in salmon mortality.

Considering all these factors water, temperature is the main generic river wide potential threat to salmon survival [36] (see as well studies on Pacific salmon [33–35]). The other factors do have potential impact on habitat conditions, but even if stress on the population may increase locally, it will not be as generic as a temperature change. In theory, water discharge influences especially the river entry of Atlantic salmon, but in larger rivers like the Rhine, water discharge is not physically limiting [37]. Negative effects of water discharge on spawning migration are restricted once Atlantic salmon has entered the river [25,37]. Therefore, we consider temperature in this study as the most important factor that can result in a policy turning point [36].

In literature diverse thermal boundary conditions for Atlantic salmon are found (Table 2).

Table 2. Overview of boundary conditions for Atlantic salmon considering water temperature (temperature tolerance values). The table shows values which are reported in literature.

Temperature level	Life stage	Value	References
Upper lethal temperature	not specified	25–28 °C	[30,38]
	parr (2–3 month)	28.7–29.2 °C	[1]
	parr (<2 years)	27.4–32.8 °C	[1]
	parr	33 °C	[39]
	adult	27.8 °C	[37,40]
	adult	30–32 °C	[1]
	adult	32–34 °C	[39]
Upstream migration (reduced)	adult	>20 °C	[25]
	adult	19.5 °C resp. 22 °C	[37]
	adult	23 °C	[1]
Upstream migration (ceased)	adult	24–25 °C	[1]
Signs of stress	not specified	22 °C	[30,38]
Growth (range)	not specified	7.8–24.6 °C	[32]
	not specified	0–25 °C	[31]
	not specified	6.0–22.5 °C	[30]
Growth (optimum)	not specified	18 °C	[32]
	not specified	16–20 °C	[41]
	not specified	18 °C	[30]
Food consumption (optimum)	not specified	19–21 °C	[41]
Feeding and growing	not specified	4.9–26.7 °C	[37,42]
Spawning	adult	0–8 °C	[39]
Egg survival	egg	0–16 °C	[39]

Thorstad *et al*. [25] point at the importance of the spawning migration for the survival of an Atlantic salmon population. Although the migration takes place during the whole year, the main migration takes place between spring and autumn in a time window of between 90 and 180 days [1]. Looking at upper temperature limits potentially threatening the reintroduction of the salmon, two boundary conditions from Table 2 are especially relevant:

(1). Short, but regularly occurring periods with potentially lethal temperatures between 25 °C and 33 °C.
(2). Long periods with mean water temperatures higher than 23 °C. In that case, the time window for salmon to migrate from the sea into the Rhine system might become too small to guarantee a sustainable population. It has been shown that *Salmonidae* reduce their upstream migration significantly in the Rhine above water temperatures of 23 °C. Upstream migration stops above 24–25 °C [1]. Other case studies show reduced spawning migration of Atlantic salmon above 19.5 °C [37], 20 °C [25], and 22 °C [37]. Reduced spawning success will lead to a declining population. A significant reduction in spawning migration for several years in a row will threaten the efforts to reintroduce a self-sustaining salmon population. However, it is largely unknown how migration depends on the duration and timing of the period of time that water temperatures are above a certain threshold value.

3.3. Step 3: Socio-Political Objectives of Concern

The success of the reintroduction is monitored by measuring the number of salmon swimming upstream [43]. Following the inventory of critical climate impacts in the last section, we conclude that a water temperature of 23 °C is a meaningful threshold value for a successful policy in this field. An alternative would be water temperatures above 28 °C, which leads to death, but as periods with temperatures above 23 °C are likely to occur earlier this threshold is chosen. Other threshold levels (Table 2) can easily be compared by the reader with our water temperature modeling results (Figures 2–4).

Figure 2. Mean annual cycles of projected daily river temperature for monitoring stations Koblenz, Bonn and Lobith for 1980–1999 and 2080–2099. The collared dotted lines show the results for the three GCMs individually and the thick line shows the overall GCM mean results for the control run (1980–1999) and for the SRES A2 and B1 scenario (2080–2099). Mean annual cycles in observed daily water temperature are shown in grey, except for station Bonn for which no data was available. The grey dotted line illustrates the 23 °C threshold level.
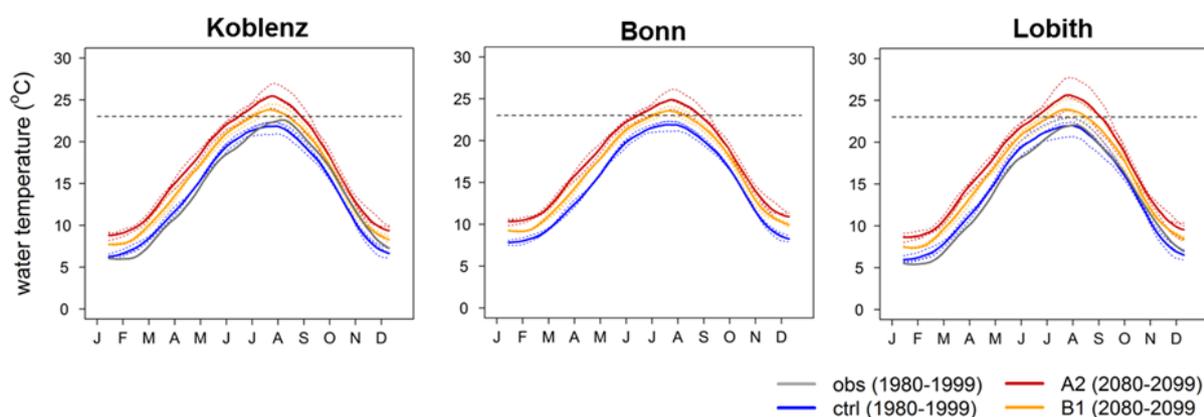
Figure 3 The number of days on which the simulated daily water temperature exceeds water temperature levels between 20 °C and 30 °C using simulated daily water temperature series for control period 1980–1999 and for SRES A2 and B1 scenario for 2080–2099. Solid lines show the mean and dashed lines the minimum and maximum for the GCM ensemble. The number of days was counted from the model data in 0.5 °C steps.
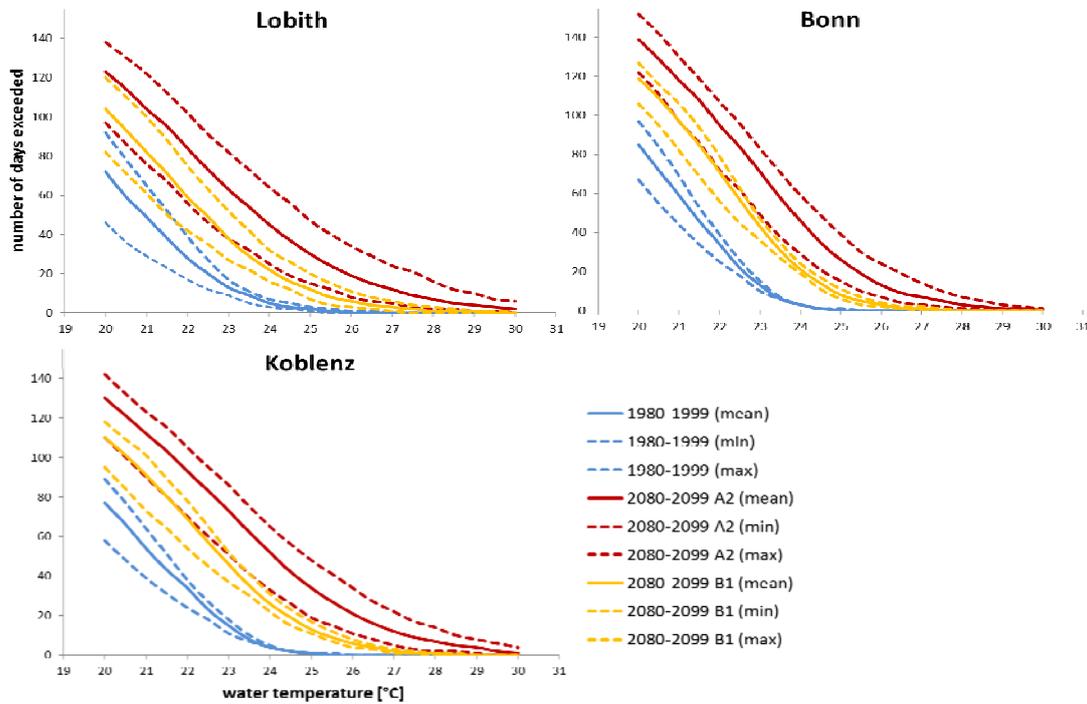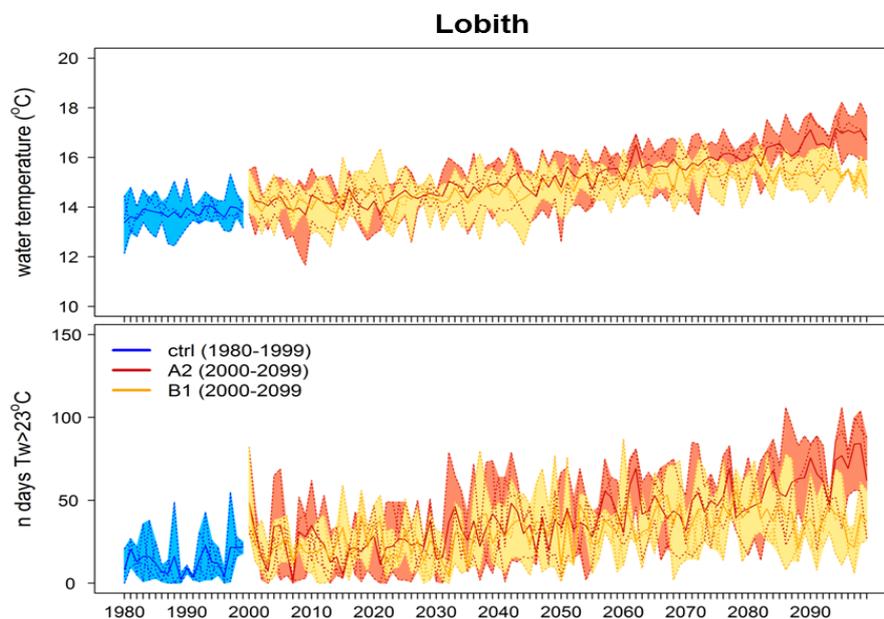

Figure 4. Long-term mean annual water temperature and number of days with daily water temperatures exceeding 23 °C at Lobith for 1980–2099. Dotted lines show the results for the three GCMs individually, colored polygons show the range in results across the GCMs and the thick line shows the overall GCM mean results for the control run (1980–1999) and for the SRES A2 and B1 scenario (2000–2099).

Salmon use the period from May/June until August/November for upstream migration [1]. The relevant period for upstream migration of salmon per year consists of 90 to 180 days. The threshold therefore is not just the 23 °C limit but the number of days with a water temperature in excess of 23 °C. There is not yet sufficient monitoring data on salmon migration in the Rhine in relation to water temperatures, to indicate a critical time window a sustainable salmon population needs for successful upstream migration. As we will discuss further below, this makes a precise determination of adaptation turning points related to salmon reintroduction complex.

3.4. Step 4: Adaptation Turning Points

In this step, actual adaptation turning points are determined and the question is: when does the number of days with a water temperature higher than 23 °C increases significantly? A significant increase is reached if the time window for spawning migration becomes too small to guarantee a sustainable salmon population. In order to assess the number of days with water temperatures in excess of 23 °C, we used simulations of water temperatures of three sections of the Rhine main stream (Lobith, Bonn, and Koblenz). Textbox 1 specifies the hydrological-water temperature modeling framework used in this study. The performance of the modeling framework for daily streamflow and water temperature simulations has previously been evaluated by van Vliet *et al.* [44], and shows a realistic representation of the observed water temperature conditions for the Rhine basin. For details about the application of this framework under the climate in the future, we refer to van Vliet *et al.* [45].

Textbox 1. The modeling framework.

The impact of climate change on daily water temperature of the Rhine basin was simulated by using the coupled VIC-RBM hydrological water temperature framework forced with bias-corrected output from three GCMs for both the SRES A2 and B1 scenario. A short description of the modeling framework and climate scenarios is given below. Details about the large-scale coupled hydrological-water temperature modeling framework and projected changes in water temperature under future climate are discussed in [12,44].

Daily water temperature projections were produced on daily timestep and 0.5° × 0.5° spatial resolution with the physically-based modeling framework VIC-RBM [12,45], which consists of the macro-scale hydrological model VIC [46] and the water temperature model RBM [47]. The water temperature model was modified to incorporate anthropogenic heat discharges from power plants by using gridded thermoelectric water use data sets [48,49] and represents thermal discharges as point sources into the heat-advection equation (for details see [12,44]).

The VIC-RBM framework was forced with bias-corrected output from three different Global Climate Models (GCMs) (CNCM3, ECHAM5 and IPSL) for both the SRES A2 and B1 emissions scenario [50], resulting in six climate change experiments. These GCM simulations from the CMIP3 archive were conducted for the 4th assessment report (AR4) of the IPCC [51]. For details of bias-corrected climate scenarios see [52]. The hydrological-water temperature model runs were performed on daily time steps for the periods 1980–1999 and 2000–2099.

Based on the daily water temperature simulations for all GCMs for the control and the 21st century, we calculated the mean number of days per year that water temperatures exceed the 23 °C water temperature limit for migration of salmon. To account for uncertainty in GCM output, the multi-model average and range in water temperature for the three selected GCMs for the control and A2 and B1 scenarios were calculated.

As the focus of our case study is on climate change, we assumed that water temperature would not be further increased by additional cooling water discharges, *i.e.*, increases in electricity supply in the river basin is assumed to be met without additional cooling water discharges (e.g., by using cooling towers rather than once-through cooling). The thermal pollution status of the Rhine River during the 21st century was therefore assumed to remain at the same level as in 2000.

Mean annual cycles of projected daily river temperature for 1980–1999 and 2080–2099 are presented for station Koblenz, Bonn and Lobith in Figure 2. Overall, the simulated water temperatures for the control simulations correspond well with the observed water temperatures for the 1980–1999 period for Koblenz and Lobith (no observed water temperature data was available for Bonn, located between Koblenz and Lobith). The mean number of days per year that water temperatures exceed the migration limit of salmon of 23 °C is slightly underestimated by the mean values for the control simulations compared to the observations for 1980–1999 (underestimation of three days for Lobith and five days for Koblenz; Table 3). However, the signal of change in the number of days with an exceedance of the 23 °C threshold under future climate for 2080–2099 is six times larger compared to the bias in the number of days with exceedances of water temperature thresholds.

Table 3. Mean number of days per year that daily water temperature exceeds migration (23 °C) and lethal (28 °C) water temperature limit using observed and simulated daily water temperature series for control period 1980–1999 and for SRES A2 and B1 scenario for 2080–2099. Both the mean and range [minimum–maximum] for the GCM ensemble is presented.

	n days Tw >23 °C							**n days Tw >28 °C**						
	obs	**ctrl**		**A2**		**B1**		**ods**	**ctr**		**A2**		**B1**	
Station		**mean**	**range**	**mean**	**range**	**mean**	**range**		**mean**	**range**	**mean**	**range**	**mean**	**range**
Lobith	16	13	[9–17]	63	[38–82]	38	[27–52]	0.0	0.0	[0.0–0.1]	7.0	[2.4–15.9]	1.3	[0.2–3.3]
Koblenz	22	17	[11–21]	73	[51–86]	46	[37–53]	0.0	0.0	[0.0–0.0]	6.9	[2.2–14.2]	0.7	[0.3–1.3]
Bonn	-	13	[10–16]	71	[49–83]	43	[36–48]	-	0.0	[0.0–0.0]	3.2	[1.2–7.1]	0.2	[0.1–0.3]

Projected changes in water temperature in the Rhine for 2080–2099 are generally larger for the GCM experiments based on the SRES A2 (medium-high) compared to B1 (low), because of the larger changes in projected meteorological forcing variables which affect water temperature (radiation and air temperature). The projected increase in water temperature for 2080–2099 is highest during summer, due to atmospheric warming in combination with strong reductions in summer low flow of the Rhine, which reduces the thermal carrying capacity of the river [10]. Figure 3 illustrates the increase in the number of days exceeding water temperatures between 20 °C and 30 °C. The number of days where the thermal limit for salmon migration (23 °C) is exceeded increases under future climate (Table 3; left). In addition, the probability that water temperature exceeds lethal limits (~28 °C) also increases (Table 3; right).

Long-term mean annual trends for 1980–2099 for Lobith show a distinct increase in mean annual water temperature and number of days with daily water temperatures exceeding 23 °C (Figure 4). The annual series are not fully linear and show inter-annual variability. Overall trends in mean water temperature and in number of days with water temperatures exceeding 23 °C for SRES B1 and A2 correspond closely until ~2060, but start to deviate with a much stronger increase for SRES A2 emissions scenario compared to B1 around the 2060s. The larger increase in water temperature for SRES A2 is due to the stronger projected change in climate compared to SRES B1 after the 2060s.

The current policy of re-establishing a wild Atlantic salmon population in the Rhine can no longer reach its goals if salmon is exposed to critical threshold conditions. When these conditions occur remains uncertain because a number of unknown factors exist. For example, the duration over which

the critical threshold is exceeded is a relevant factor, yet how it affects upstream migration is presently unknown. In addition, water temperature effects are locally variable and the adaptive capacity of Atlantic salmon is unknown. Notwithstanding, we see an increasing risk of exposure to critical threshold conditions: long periods with mean water temperatures higher than 23 °C. Thus, the time window for salmon to migrate from the sea into the Rhine system might become too small to sustain the population and the number of upstream migrating salmon might stay well under the policy goals of 7,000 to 21,000 individuals.

3.5. Step 5: Alternative Adaptation Strategies

Although we cannot indicate exactly when turning points in salmon policies will be reached, our analysis shows that a significant risk exists that salmon migration will be hampered before the end of the century. Thus, adaptation will be required in order to prevent failure of the reintroduction program. We have identified three types of adaptation strategies:

(1). Reducing exceedance of the water temperature threshold by reduction of anthropogenic warm water discharges in the river. Current river water temperature standards are based on research in the 1970s on toleration limits of cyprinid and not salmonid fish [53] and are set at a maximum of 28 °C. Water temperature in the 20th century increased with 1 °C–3.3 °C depending on the river branch [5,54]. Two thirds of this increase is attributed to point source discharge from industries and power plants and one third to climate change [11]. Reduction of point source discharge, enforced by more rigid standards, by investments in cooling towers or reductions of warm water discharges will have an effect on water temperature. The effect of this adaptation strategy is limited to the relative contribution of industry on water temperature. This adaptation strategy will therefore effectively delay reaching a turning point for salmon migration. Closing down power plants, e.g., due to the nuclear phase-out in Germany, will reduce the thermal load of the river. However, the reduction from the nuclear phase out will likely be compensated by the new construction of coal power plants along the German streams in the Rhine basin [55], introducing new unknown factors.

(2). An adaptive action relevant only for small streams in upper headwaters is replanting of trees and creation of shade. Mitigating impacts of warm water to salmon by creation of refuge cold spots for salmon along the river falls in the same category. For example at places with cool groundwater inflow, or deep stretches of the river.

(3). A third type of adaptation is to change policy objectives and socio-political preferences. For instance, to accept changes in ecosystems as a consequence of climate change and decide to take other species as an indicator for ecological improvements, where sturgeon might be a candidate.

4. Discussion

Our analysis shows that the risk of crossing thresholds for successful reintroduction of the salmon increases towards the end of this century. To reduce the uncertainty in when an adaptation turning point is reached, research is needed on the conditions for Atlantic salmon migration in the Rhine and

more specifically the time window needed for salmon to migrate upstream. There is limited understanding of the relationships between upstream migration at different river sections and climate related parameters, such as water temperature, as well as ecological responses, such as the behavior of salmon under stress. Research is needed on migration behavior of Atlantic salmon and on the capacity of salmon to adapt to changing temperature regimes [56] to better be able to assess the risk of policy failure. As Rhine salmon are new to the Rhine and originate from rivers in the Nordic countries, Ireland, Scotland and France [22,43], most of them are still used to more northern conditions and might be more vulnerable to high temperatures. Eliason *et al.* [57] show for sockeye salmon (*Oncorhynchus nerka*) that the cardio-respiratory physiology varies among populations. Speaking of the 'Rhine salmon' is a simplification in itself, as a sound analysis the 'homing' instinct of salmon, the strongly developed inclination of salmon to go back to where they were born, needs to be considered. Because of this instinct, isolated populations in different tributaries of the Rhine (Sieg, Mossel, Elsass, Main) can exist, each adapted to different climatic, hydrologic and ecological conditions [1]. Thermal optima in the end relate to the historic temperature range of the homing river [57].

A surprising outcome reported by the International Commission for the Protection of the Rhine was that monitoring of the salmon population during the extreme conditions of the summer of 2003 did not show significant decrease of migration [1]. Water temperatures in the Rhine and its main tributaries were above 23 °C for about three weeks and above 28 °C for several days in that summer [58]. Salmon apparently had found places with cool water, although little is known yet on where and how. Salmon are flexible: they may stay in the sea when the river water is too hot, and may enter the river later in the season. Longer periods with water temperatures above 23 °C narrow the time corridor for spawning migration and lead likely to reduced numbers of migration success.

In addition, little is known on the compounding effects of multiple-stress factors, like water temperature on top of for instance critical water depth and low oxygen [25,37]. Multiple stressors can threaten reintroduction before the 23 °C threshold is reached that this study reports on.

A first inventory of adaptation strategies shows that adaptive action is possible, but an appraisal of options in terms of costs and benefits is needed before choices can be made. In addition, an integrated approach to adaptation strategies, like increasing the base flow of the river by improving infiltration of rainwater in the river basin [59], can lead to positive synergy effects.

5. Conclusion and Recommendations

Salmon policies at the Rhine scale do have specific objectives, such as 7,000 to 21,000 upstream migration individuals per year and undisrupted migration possibilities up to Basel in Switzerland [22]. On many scales, efforts are made to provide the right habitat and connectivity conditions for salmon. A crucial element for a sustainable salmon population is the right conditions for upstream migration from the sea to spawning grounds and much money is spent to remove obstacles or make them passable. Monitoring the numbers of migrating salmon per year is used to assess success of reintroduction policies. The main spawning migration takes place between spring and autumn in a time window of between 90 to 180 days per year [1]. Research shows that Rhine salmon reduces migration significantly when the water temperature exceeds 23 °C. To assess whether climate change can threaten the success of the salmon reintroduction, this paper identified water temperature to define a

critical threshold. Projections of water temperature in the Rhine show an increase in the number of days per year that mean daily water temperature exceeds 23 °C. Between the control period 1980–1999 and the period 2080–2099, this is in the range of 15–64 days. Transient runs of water temperature project years where water temperature exceeds 23 °C for up to 100 days. Thus, our analysis suggests climate change may significantly affect the success of salmon reintroduction and does imply the need to rethink salmon policies or to start considering adaptive action.

We recommend to:

- Initiate or extent existing ecological research of Atlantic salmon in the Rhine on migration behavior in relation to water temperatures;
- To refine and extent transient analysis of water temperatures of Rhine summer water temperatures.
- To intensify policy discussion at the trans-boundary, national and regional levels on reducing impacts of low flow conditions and high water temperature in the Rhine river.

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Conflict of Interest

The authors declare no conflict of interest.

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