



Climate change adaptation and mitigation measures for alluvial aquifers - Solution approaches based on the thermal exploitation of managed aquifer (MAR) and surface water recharge (MSWR)

Epting Jannis^{a,*}, Love Råman Vinnå^a, Affolter Annette^a, Scheidler Stefan^a, Oliver S. Schilling^{b,c}

^a Applied and Environmental Geology, Hydrogeology, Department of Environmental Sciences, University of Basel, CH-4056 Basel, Switzerland

^b Hydrogeology, Department of Environmental Sciences, University of Basel, CH-4056 Basel, Switzerland

^c Department Water Resources and Drinking Water, Eawag - Swiss Federal Institute of Aquatic Science and Technology, CH-8600 Dübendorf, Switzerland

ARTICLE INFO

Keywords:

Managed Aquifer Recharge MAR
Managed Surface Water Recharge MSWR
Thermal groundwater exploitation
Renewable energy
Climate change adaptation

ABSTRACT

As climate change adaptation strategies, both Managed Aquifer (MAR) and Surface Water Recharge (MSWR) are not only highly suitable tools to mitigate negative effects on water resources but also bear large potential for concomitant exploitation of thermal energy. They should thus form an integral part of any sustainable water resources management strategy. However, while at global scale general water resource adaptation and mitigation measures are discussed widely, measures that build on thermal exploitation of MAR and MSWR, and which are readily adaptable to various different local and regional scale conditions, have yet to be developed.

Here, based on systematic numerical analyses of the sensitivity of groundwater and surface water recharge as well as water temperatures to climate change, we present adaptable implementation strategies of MAR and MSWR with concomitant exploitation of their thermal energy potential. Strategies and feasibility benchmarks for the exploitation of hydrologic and energetic potentials of MAR and MSWR were developed based on three hydrologically and hydrogeologically contrasting urban study sites near the city of Basel, Switzerland. Our studies show projected trends in the number of days when surface water temperatures exceed 25 °C examined for various streamflow and climate scenarios.

We illustrate that local hydrogeologic settings and hydrological boundary conditions as well as legal aspects affect to which degree MAR and MSWR are suitable solutions as climate change adaptation measures. Optimal situations for exploiting the potential of seasonal heat storage in MAR and MSWR exist where subsurface travel times between the injection and the withdrawal or exfiltration point are between 4 and 8 months and legal limits allow a sufficiently large temperature spread. In such settings, the exploitable water flux and temperature spread of MAR and MSWR reaches a heat potential of 14 to 20 MW (i.e., corresponding to 3 to 7 wind power plants), and energetic exploitation becomes a suitable tool either for local low-temperature heat applications such as heating and hot water or for ecological use as a heat and water buffer in rivers affected by seasonal droughts. As a positive side effect, climate-induced warming of groundwater resources and temperature increases in drinking water withdrawals would be mitigated simultaneously.

1. Introduction

The expected quantitative and qualitative impacts of climate change (CC) on surface water (SW) and groundwater (GW) resources (IPCC, 2014) emphasize the need for regional mitigation and adaptation strategies.

SW systems are among the most sensitive systems to CC (Watts et al.,

2015), with high water temperatures having a range of adverse effects on both society and ecosystems (Bradford and Heinonen, 2008; Poff et al., 1997; Price et al., 2011; Rolls et al., 2012; van Vliet et al., 2012). Due to CC, the seasonal amplitude of river flow will change and an increase in low-flow conditions during summer months can be expected in the future (Brunner et al., 2019). More frequent low flows and continuous warming trends over the last four decades (Michel et al., 2020)

* Corresponding author.

E-mail address: jannis.epting@unibas.ch (E. Jannis).

<https://doi.org/10.1016/j.watres.2023.119988>

Received 8 November 2022; Received in revised form 13 April 2023; Accepted 20 April 2023

Available online 25 April 2023

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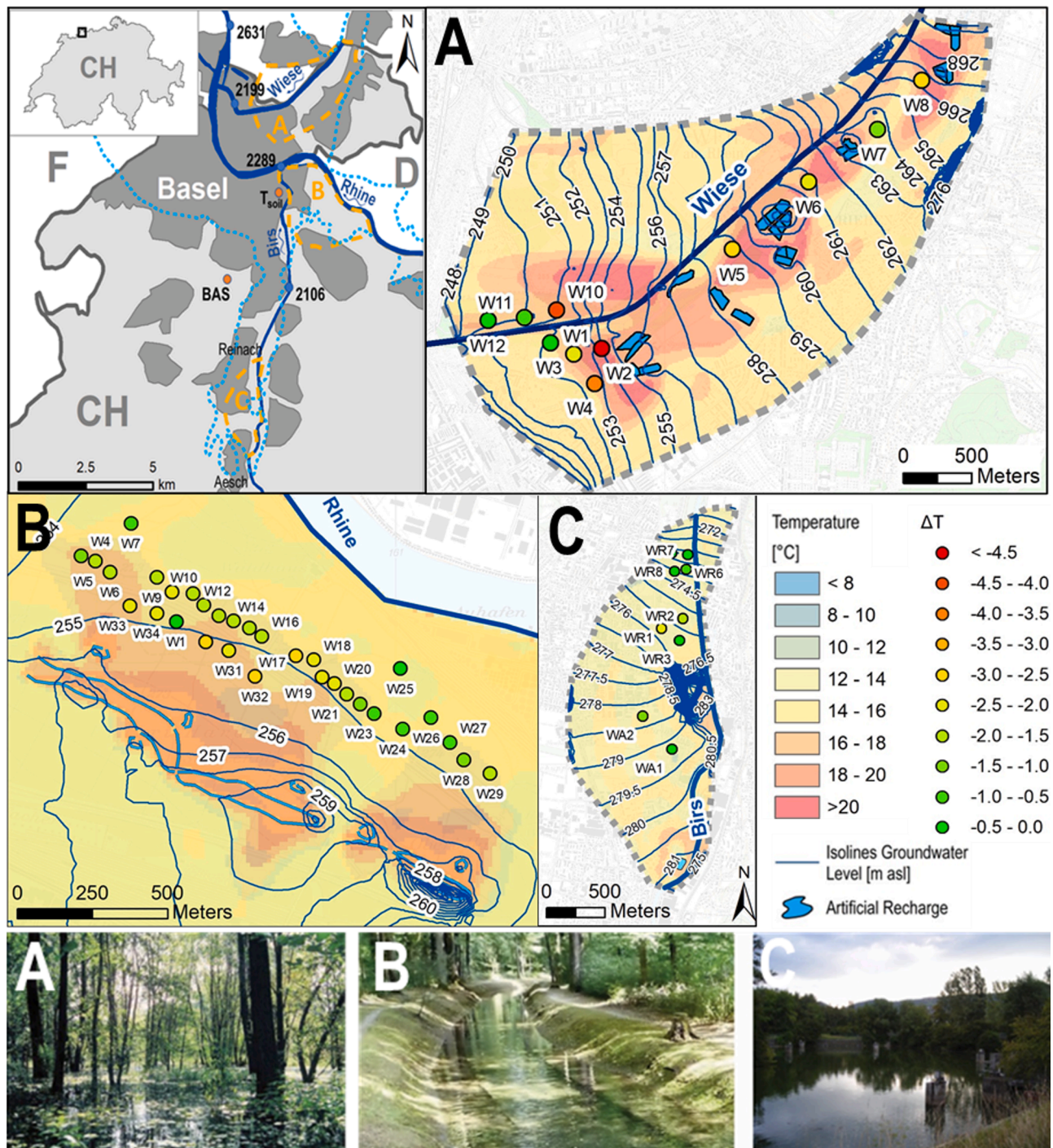


Fig. 1. Upper left: Study areas in the agglomeration of the city of Basel, Switzerland (CH), bordering France (F) and Germany (D), including governmental river monitoring stations (numbered blue dots, with numbers indicating the official station IDs), a governmental meteorological station (BAS), and the location of soil temperature measurements (T_{soil} ; orange dots). Also shown are the case study areas A-C (dashed orange lines) and the delineation of the alluvial aquifers (dashed light blue line). Upper figures A-C: Maps of the Lange Erlen (A), Hardwald (B) and Lower Birsvalley (C) study areas, including hydraulic and thermal groundwater recharge in autumn and temperature change at the drinking water wells (W #; A-Aesch & R-Reinach) resulting from the infiltration of comparatively “colder” recharge water to the reference state in 2000. Lower figures A-C: Photos of the three infiltration systems at the three study sites.

impact the health of stream ecosystems (e.g., favoring the spread of fish diseases) and their services (e.g., impairing the water usage for industrial cooling; Bourqui et al. (2011)). Severe low flows and heatwaves in Europe during the years 2003, 2011, 2015 and 2018 led to substantial economic losses due to limited water availability for households, industry, agriculture, hydropower, and river transportation (Florinancic et al., 2020; MunichRe, 2009; Stahl et al., 2016). Anthropogenic SW and

GW withdrawals can further exacerbate low water levels in rivers. Most importantly, agricultural water extractions from streams and groundwater are expected to skyrocket until 2100 due to a dramatic increase in the demand of water for irrigation purposes (Bierkens and Wada, 2019; Wada and Bierkens, 2014).

As seasonally reduced runoff and increased water abstraction will strongly reduce SW infiltration and GW exfiltration during certain

Table 1

Selection of climate projections (GCM – Global Change Models) for air temperature (T_{air}), river discharge (Q) and temperature (T_{riv}). For each climate scenario the model that minimized and maximized each variable (T_{air} , Q and T_{riv}) was selected (see Table A1-3 in the Appendix). For the groundwater flow and heat-transport modeling the selected climate projections were combined with the emission scenarios (RCP – Regional Climate Projections; EUR11 – 11 km; EUR44 – 44 km resolution).

Parameter	Min	Max
Air temperature (T_{air})	DMI-HIRHAM_ECEARTH_EUR11	KNMI-RACMO_HADGEM_EUR44
Discharge (Q) & River temperature (T_{riv}) data	DMI-HIRHAM_ECEARTH_EUR11	SMHI-RCA_ECEARTH_EUR44
Groundwater scenarios (S)	S1: DMI-HIRHAM_ECEARTH_EUR11_RCP2.6 S2: DMI-HIRHAM_ECEARTH_EUR11_RCP4.5 S3: DMI-HIRHAM_ECEARTH_EUR11_RCP8.5	S4: SMHI-RCA_ECEARTH_EUR44_RCP2.6 S5: SMHI-RCA_ECEARTH_EUR44_RCP4.5 S6: SMHI-RCA_ECEARTH_EUR44_RCP8.5

periods, it is crucial for a robust CC adaptation strategy to also assess the resulting changes in the heat budgets of – and thermal dynamics between – SW and GW bodies (Keery et al. (2007)). Rising GW temperatures can be associated with negative effects on water quality (Sprenger et al., 2011), problems with drinking water production, and possible clogging of drinking water wells by precipitated manganese and iron (Hunt et al., 2002). GW temperatures are moreover an important factor for river water temperatures close to GW exfiltration zones (Caissie, 2006), and can serve as an indicator for depletion of soil moisture storage reducing aquifer recharge and streamflow (Jaeger and Senéviratne, 2011; Vidal et al., 2010).

At global scale, climate projections show a significant and continued increase of air temperature, with the Alpine country of Switzerland being most strongly affected and having witnessed an increase in air temperature since 1894 of +2 °C, which is more than twice the global average of +0.9 °C (CH2018, 2018). There are clear indications that climate warming is also impacting SW and GW temperatures (IPCC, 2014). Beside consequences for SW and GW quality, aquatic ecosystems, and ecological aspects in general, heat discharges from industry into rivers are increasingly at risk of exceeding biologically relevant and legally binding temperature thresholds in summer (a phenomenon that could already be observed in Switzerland and throughout central Europe during the extremely dry summer of 2022).

MAR and MSWR provide opportunities to adapt to CC, meet quantitative and qualitative water resources requirements, and to operationally protect sites that produce drinking water (Bouwter, 2002). MAR, therefore, offers an alternative to surface storage by storing excess water underground during periods of low demand or high availability (Händel et al., 2014). Knowledge about the residence times of artificially infiltrated water and its flow paths is essential to developing adequate GW management and protection schemes (Bekele et al., 2014). However, artificial GW recharge with river water (not including bank filtration) currently accounts for only 3.8% of drinking water in Switzerland (SVGW, 2020) and is not considered in water management and adaptation planning for CC impacts. While on the European level MAR is an important water resources management tool, due the strict GW quality regulations artificial recharge with river water is also only marginally contributing to the total MAR (Hannappel et al., 2014; Sprenger et al., 2017).

To quantify the sensitivity of MAR and MSWR to CC, in Epting et al. (2022) we investigated the role of artificial GW recharge and the associated temperature imprinting of aquifers under consideration of selected climate and water supply operation projections.

High-resolution 3D numerical GW flow and heat-transport modeling allowed quantifying and differentiating between different recharge components. Seasonal shifts in natural GW recharge and operation strategies related to artificial GW recharge were revealed as important factors affecting the long-term quantity and quality of GW resources. Importantly, increased artificial GW recharge in summer and natural infiltration of SW during high flow periods, which will occur more often in winter, were moreover shown to strongly impact both GW recharge and temperatures. The estimated future increase of groundwater demand during droughts will likely be tackled by increasing artificial groundwater recharge with surface water, which is predicted to become warmer and therefore will likely increase groundwater temperatures and the temperature of the extracted drinking water even further (Epting et al., 2022). In Epting et al. (2021), we demonstrated that under selected CC scenarios at the end of the century, a shift in precipitation and river flood events from summer to winter months likely results in an increase in groundwater recharge in comparatively cool seasons, which in turn will tend to naturally cool groundwater. Possibilities to limit the temperature increase of SW and of GW by artificial recharge with SW must thus be considered in order to guarantee sustainable water management strategies involving MAR and MSWR.

To bridge this gap, we present adaptable implementation strategies of MAR and MSWR with concomitant exploitation of their thermal energy potential under various geologic and hydrogeologic conditions from present day into the future (2100) under the consideration of different CC projections. Strategies and feasibility benchmarks for the exploitation of hydrologic and energetic potentials of MAR and MSWR were developed based on three hydrologically and hydrogeologically contrasting urban study sites near the city of Basel, Switzerland.

2. Material & methods

2.1. Study areas

In the urban agglomeration of the city of Basel, Switzerland, there are three areas where river water is used for artificial GW recharge (Fig. 1). In the Lange Erlen and in the Hardwald study areas (A&B) water of the river Rhine is used. The drinking water wells located in these study areas each produce about half of the drinking water for the city of Basel. At the site of the Aesch recharge plant in the Lower Birsvalley study area (C), water from the river Birs is used for artificial GW recharge, supplying the drinking water for the municipalities of Aesch and Reinach. In the three study areas, different methods of artificial recharge are implemented (Hannappel et al., 2014): (1) infiltration fields (Lange Erlen; average recharge 44'023 m³ d⁻¹, extraction 49'680 m³ d⁻¹), (2) infiltration trenches and ponds (Hardwald; average recharge 85'000-100'000 m³ d⁻¹, extraction 40'000 m³ d⁻¹), and (3) infiltration systems with filter layers and injection wells (Lower Birsvalley; average recharge 12'960 m³ d⁻¹, extraction 27'648 m³ d⁻¹).

2.2. Climate projections, river discharge and water temperature modeling

To evaluate future climate-related changes to the rivers and the different groundwater recharge components, three climate projections developed within CH2018 have been selected (CH2018-Project-Team, 2018; CH2018, 2018; Feigenwinter et al., 2018). The three selected projections cover the full range of expected precipitation, air and river temperature variations (Table 1 and Table A1 in the appendix). For each of the projections, the emission scenarios RCP 2.6 (4 scenarios, limitation of warming to 2 K compared to the pre-industrial state), RCP 4.5 (6 scenarios) and RCP 8.5 (7 scenarios) were studied (Table 1).

Three groundwater flow and heat-transport models were setup using the numerical model FeFlow (DHI) to study GW recharge via naturally infiltrating SW and via artificial GW recharge, and to investigate associated temperature effects (Fig. 1). The model setup and calibration procedures are described in detail in Epting et al. (2022). To summarize,

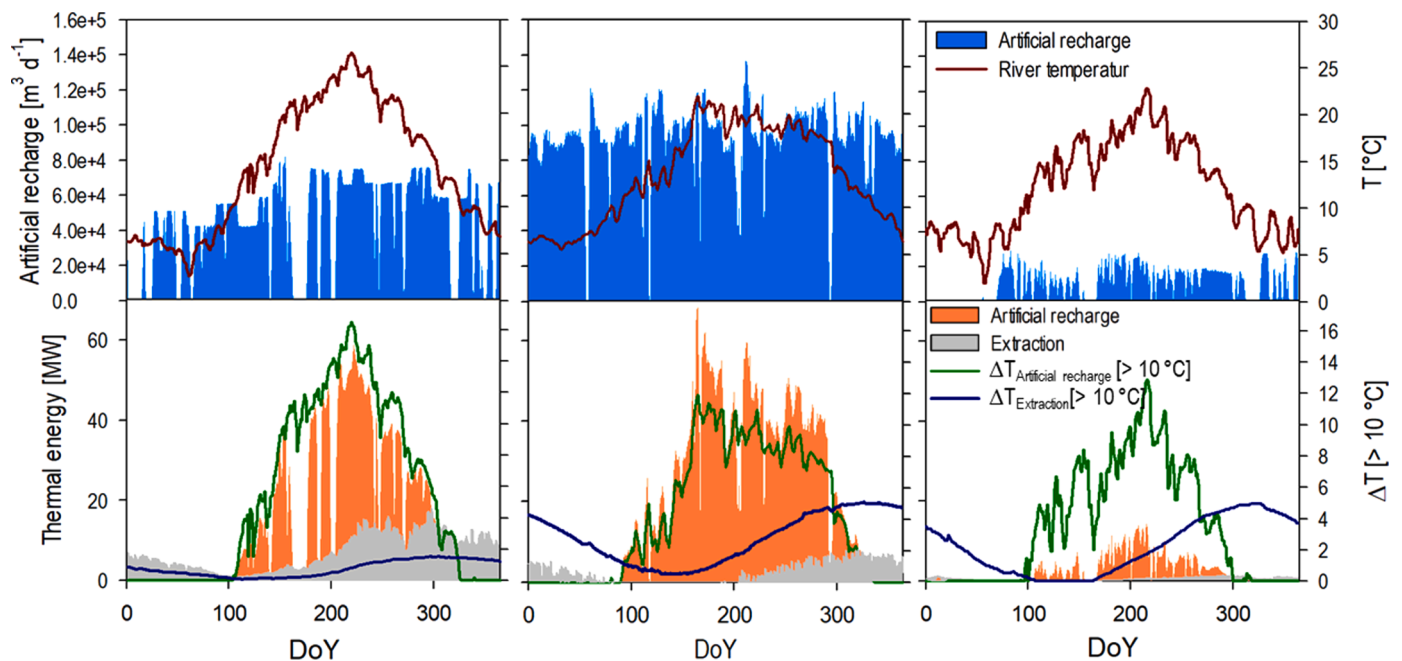


Fig. 2. Derivation of the theoretical thermal potential from the recharge and extraction water of the drinking water wells in the Lange Erlen (left, river station 2199) the Hardwald (middle, river station 2289) and the Lower Birsvalley (right, river station 2106) study areas. Top: Artificial recharge volumes (sum of all systems) and measured river temperatures. Bottom: Extraction of thermal energy from the artificial recharge (sum of all systems) and from the extraction water (sum of all wells), shown together with the temperature spread of the recharge and extraction water.

for the groundwater models future river flow boundary conditions were assigned from the PREVA-WSL models (Brunner et al., 2019), while future river temperature boundary conditions were based on simulations with the air2stream river temperature models (Piccolroaz et al., 2016; Toffolon and Piccolroaz, 2015). Specifically, air2stream was run from 1980 to 2099 for up to 18 regional to global coupled climate models using river flow projections from the PREVA-WSL models (Brunner et al., 2019) with emission scenarios RCP2.6, RCP4.5 and RCP8.5. Ultimately, to obtain a robust range of predictive uncertainty, the boundary conditions for the groundwater models were based on both the lower and upper bounds of the projected river flows and temperatures (i.e., by selecting the projections of the two climate models that resulted in the maximum and minimum river flows and temperatures, see Table 1). The river temperature projections were also used to define the thermal boundary condition of the artificially recharged river water. Further boundary conditions were defined based on continuous hydraulic and temperature measurements in groundwater observation wells as well data on groundwater recharge and exactions of the water suppliers. The groundwater models were subsequently calibrated using the pilot point methodology (Doherty, 2003; Doherty, 2015; Schilling et al., 2022) as implemented in FePEST, (Doherty, 2003; Doherty, 2015) using records of water temperature and hydraulic head measurements; for more details on the modeling, see Epting et al. (2022).

2.3. MAR & MSWR

2.3.1. Thermal use of recharge and extraction water

The thermal potential of GW depends mainly on flow velocities, GW thickness, thermal properties of the subsurface and the possible use of a temperature spread. To calculate the theoretical thermal potential in the artificial recharge and extraction water from the drinking water wells in the study areas, a potential heat extraction was calculated based on equation 1 and assuming that both the recharged water and the extracted drinking water should remain ≤ 10 °C (corresponding to the “natural state” of GW temperature in the study areas).

$$E_i = C_f \cdot q_i \cdot \rho_w \cdot \Delta T \quad (\text{Eq. 1})$$

with the available energy (E_i [J d⁻¹]), heat capacity of water (C_f [J kg⁻¹ K⁻¹]), flow rate (q_i [m³ d⁻¹]), density of water (ρ_w [kg m⁻³]) and the possible use of a temperature spread (ΔT [K]). In addition, the extent to which the temperatures of the extracted water at the drinking water wells are reduced by the infiltration of the “colder” recharge water was assessed.

For a thermal use of the extracted water of the drinking water supply, the phase shift of the temperature and the flow time between the locations of GW recharge and GW extraction are relevant. Since heat extraction is attractive especially in the winter months (heating & hot water), a phase shift of about half a year is ideal. Therefore, in a first step, the arrangement of individual extraction wells and recharge locations was evaluated with respect to the induced phase shifts, and, in a second step, the theoretical heat recovery of the recharge and extraction water was quantified.

2.3.2. Regeneration of “warmed” SW

Two conceptual approaches were considered in the evaluation of the regeneration of “warmed” SW: (A) direct heat extraction from the rivers Rhine, Wiese and Birs and (B) targeted exfiltration of comparatively “cold” GW for selected river sections to have the effect of “cooling” river temperatures.

2.3.2.1. Thermal use of SW. The thermal use of GW resources in Switzerland is subject to important regulations. The temperature may not be changed by more than ± 3 K through the introduction or extraction of heat compared to the “natural state” of GW 100 m down-gradient of the impact (GSchV, 1998). In addition, no heated water may be discharged or water for cooling withdrawn if the temperature of the SW body in question exceeds 25 °C.

Therefore, in scope of our investigations, in a first step, the projected development of the number of days on which SW temperatures exceed 25 °C was evaluated for the various watercourses and climate scenarios studied. In a second step, for the climate projections with the lowest (scenario S1) and the largest (scenario S6) impacts of CC (Table 1), the amount of energy that would have to be extracted from the different

Table 2
Simulated changes in the extraction temperatures of the drinking water wells (W #) in the Lange Erlen (A), Hardwald (B) and Lower Birsvalley (C; A-Aesch & R-Reinach) study areas compared to the current state as a result of the infiltration of recharge water which is always $\leq 10\text{ }^{\circ}\text{C}$.

A: Lange Erlen	W 1	W 2	W 3	W 4	W 5	W 6	W 7	W 8	W 10	W 11	W 12
$\Delta T\text{ [K]}$	-2.1	-4.5	0.0	-3.5	-2.6	-2.0	-1.2	-2.9	-4.5	-0.9	-0.1
B: Hardwald	W 1	W 4	W 5	W 6	W 7	W 9	W 10	W 11	W 12	W 13	W 14
$\Delta T\text{ [K]}$	0.0	-1.3	-1.5	-1.8	-0.8	-1.6	-2.1	-2.0	-2.0	-2.0	-1.8
	W 15	W 16	W 17	W 18	W 19	W 20	W 21	W 22	W 23	W 24	W 25
$\Delta T\text{ [K]}$	-1.8	-2.0	-2.5	-2.4	-2.4	-2.2	-1.9	-1.4	-1.0	-0.8	-0.3
	W 26	W 27	W 28	W 29	W 30	W 31	W 32	W 33	W 34		
$\Delta T\text{ [K]}$	-0.6	-0.9	-1.2	-1.7	-2.5	-2.2	-2.8	-2.5	-2.3		
C: Lower Birsvalley	W A1	W A2	W R1	W R2	W R3						
$\Delta T\text{ [K]}$	-0.3	-1.2	-2.3	-1.9	-0.4						
	W R4	W R5	W R6	W R7	W R8						
$\Delta T\text{ [K]}$	0.0	-0.5	-0.3	0.0	0.0						

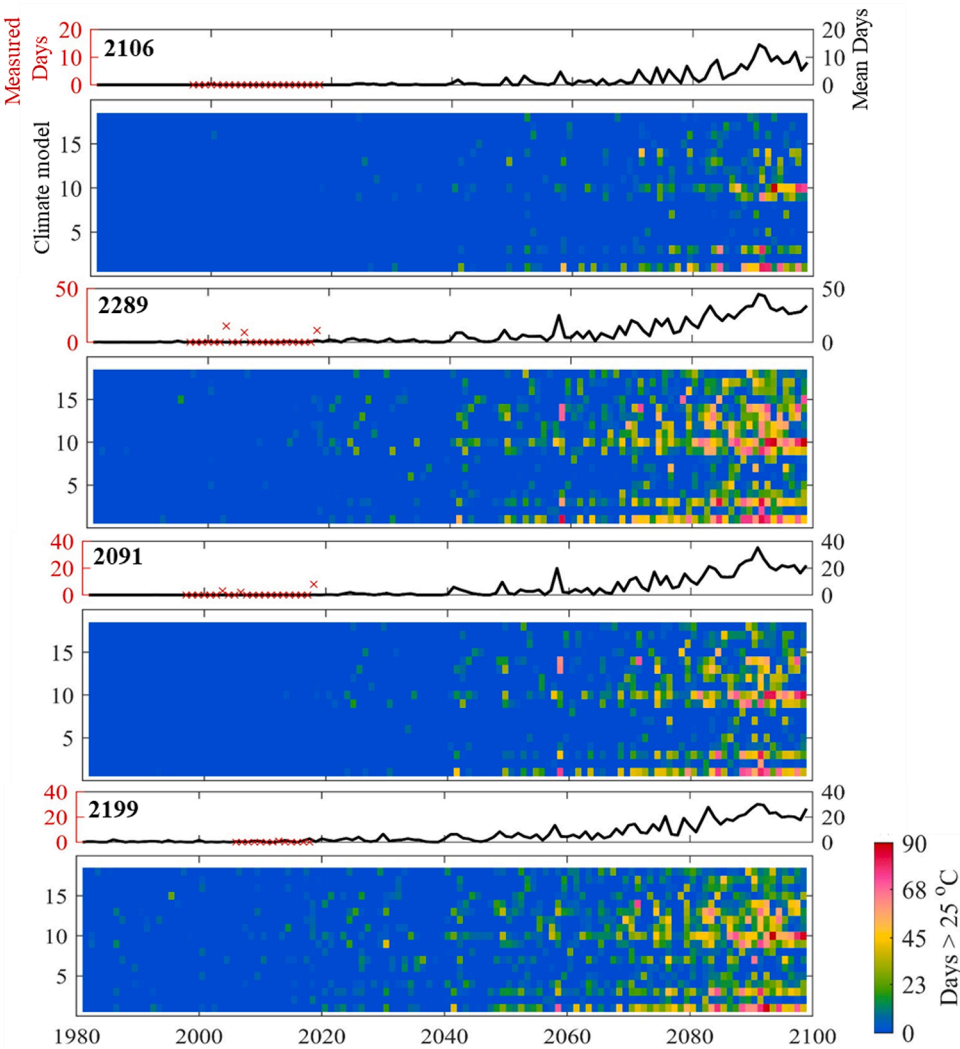


Fig. 3. Development of the total number of days per year on which river water temperatures exceed the thermal threshold ($> 25\text{ }^{\circ}\text{C}$). Results were simulated with the air2stream model for climate scenario RCP8.5 at the river monitoring stations 2106 (Birs), 2289 (Rhein), 2091 (Rheinfelden) and 2199 (Wiese). Bottom figures: Simulation results using air temperature and river flow from 18 climate models. Top figures: Mean threshold values from bottom figures (black line) and exceedance threshold from in-situ measurements (red crosses).

Table 3

Minimum, average and maximum values of (1) energy (E) extracted from the different SW and (2) water volumes (Q_2) that would have to be added to the rivers to maintain water temperatures $< 25^\circ\text{C}$. Energy in kW and water quantities in $\text{m}^3 \text{d}^{-1}$, except for the Rhine for which they are given as MW and $\text{m}^3 \text{s}^{-1}$.

		Wiese (2199)			Rhein (2289)			Rheinfelden (2091)			Birs (2106)		
		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Scenario 1	E	20	3'631	24'108	535	1'289 MW	2'018 MW	-	-	-	341	2'092	3'554
		kW	kW	kW	MW						kW	kW	kW
	Q_2	28	4'555	29'608	8.4	19.7	30.4	-	-	-	467	2'837	4'807
		$\text{m}^3 \text{d}^{-1}$	$\text{m}^3 \text{d}^{-1}$	$\text{m}^3 \text{d}^{-1}$	$\text{m}^3 \text{s}^{-1}$	$\text{m}^3 \text{s}^{-1}$	$\text{m}^3 \text{s}^{-1}$				$\text{m}^3 \text{d}^{-1}$	$\text{m}^3 \text{d}^{-1}$	$\text{m}^3 \text{d}^{-1}$
Scenario 6	E	20	6'228	48'916	20	3'090	11'035 MW	21	2'503 MW	8'847 MW	588	10'901	53'343
		kW	kW	kW	MW	MW		MW			kW	kW	kW
	Q_2	28	7'226	56'468	0.3	43.0	127.0	0.3	35.7	107.1	804	13'736	58'432
		$\text{m}^3 \text{d}^{-1}$	$\text{m}^3 \text{d}^{-1}$	$\text{m}^3 \text{d}^{-1}$	$\text{m}^3 \text{s}^{-1}$	$\text{m}^3 \text{s}^{-1}$	$\text{m}^3 \text{s}^{-1}$	$\text{m}^3 \text{s}^{-1}$	$\text{m}^3 \text{s}^{-1}$	$\text{m}^3 \text{s}^{-1}$	$\text{m}^3 \text{d}^{-1}$	$\text{m}^3 \text{d}^{-1}$	$\text{m}^3 \text{d}^{-1}$

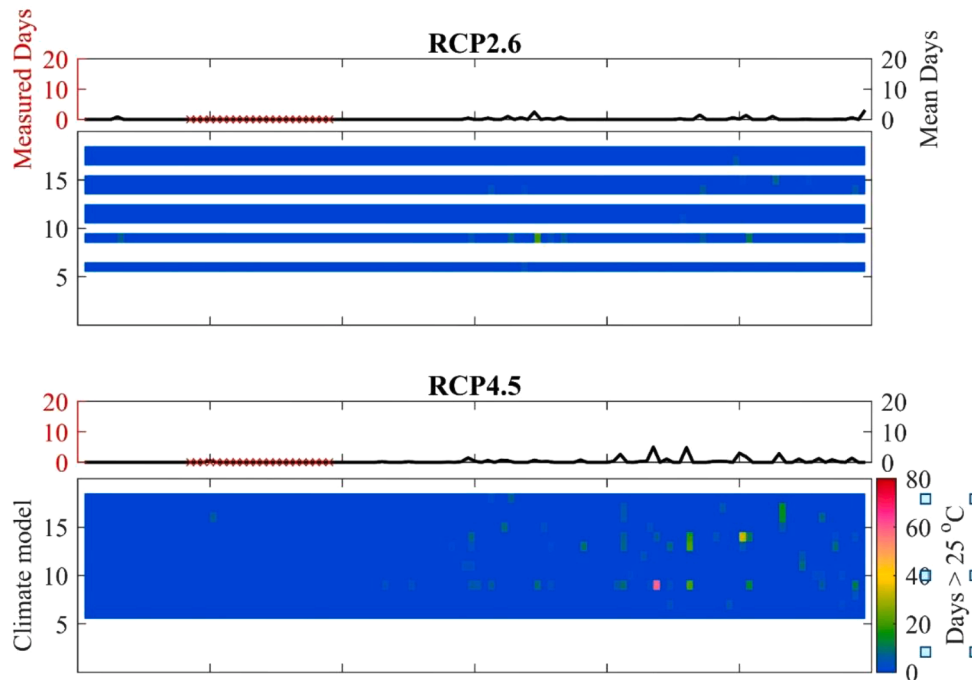


Fig. A1. Projected development of the total number of days per year on which the surface water temperatures are $> 25^\circ\text{C}$ at station 2106 (Birs) for three climate scenarios RCP2.6 and RCP4.5 (top: annual mean values from all climate models - black line; measurements - red crosses; bottom - simulation results of the individual climate models).

rivers to keep the SW temperatures below 25°C was evaluated according to [equation 1](#).

2.3.2.2. Groundwater exfiltration. In order to be able to estimate how much water, for example via MSWR, would have to be added at a defined temperature in order to cool temperatures of a receiving SW body below 25°C , a simple mixing analysis (Richmann's law, which is here used as a form of End Member Mixing Analysis (EMMA); e.g. (Bertrand et al., 2014; Christophersen and Hooper, 1992; Cook and Herczeg, 2000; Cook et al., 2018; Schilling et al., 2019; Schilling et al., 2021)) was performed, which allows a separation by a mass balance of a n-component system. With n tracers (assuming water temperatures to be conserved and unaffected by external sources and the instantaneous mixing of the exfiltrating groundwater with the river water), n+1 water components can be separated. A prerequisite is that all tracers (in our case the temperatures) of the different water components are distinct. The following equations apply:

$$Q = Q_1 + Q_2 \quad (\text{Eq. 2})$$

and

$$Q \cdot c = Q_1 \cdot c_1 + Q_2 \cdot c_2 \quad (\text{Eq. 3})$$

with Q [$\text{m}^3 \text{d}^{-1}$] the total discharge (the discharge of the respective river, including the mixed water or the exfiltrating groundwater), c the concentration of the tracer in the total discharge (the desired final temperature of 25°C after mixing the water components), $Q_1, 2$ [$\text{m}^3 \text{d}^{-1}$] the discharge from storage elements 1 and 2 (the river discharge and the amount of added groundwater) and $c_1, 2$ the concentrations of the tracer in storage elements 1 (the temperature of the river water) and 2 (the temperature of GW, given as 10°C , see above). Resolved for Q_2 , the amount of mixed water with a defined temperature of 10°C which would have to be added to keep the SW temperatures below 25°C , gives:

$$Q_2 = Q \cdot \frac{c - c_1}{c_2 - c_1} \quad (\text{Eq. 4})$$

3. Results

3.1. Thermal use of recharge and extraction water

[Fig. 2](#) shows the calculated theoretical thermal potential (based on

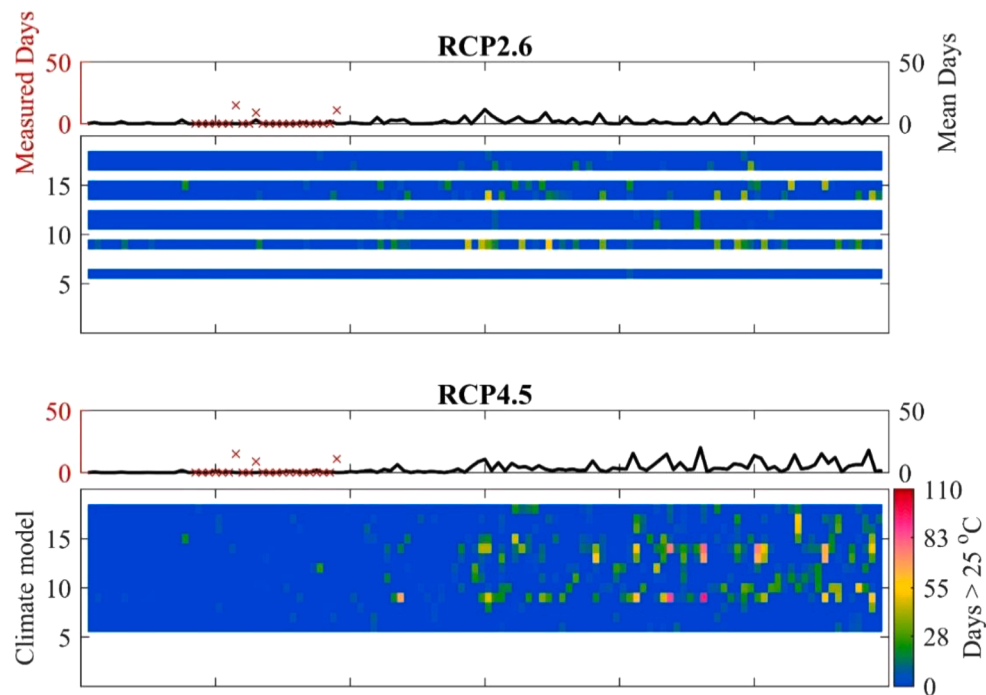


Fig. A2. Projected development of the total number of days per year on which the surface water temperatures are $> 25^{\circ}\text{C}$ at station 2289 (Rhein) for three climate scenarios RCP2.6 and RCP4.5 (top: annual mean values from all climate models - black line; measurements - red crosses; bottom - simulation results of the individual climate models).

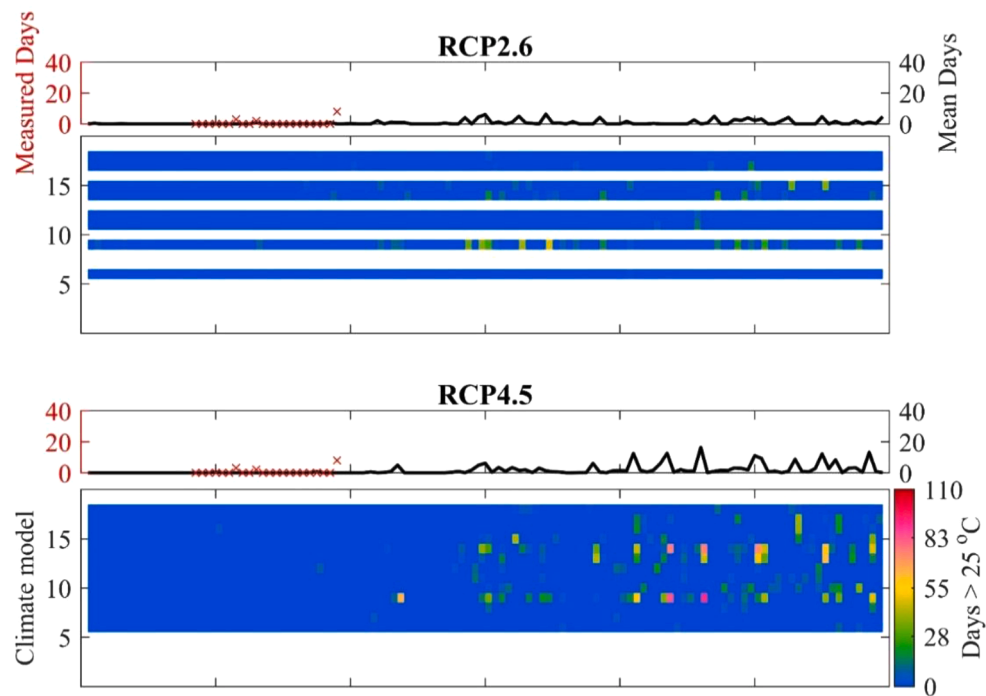


Fig. A3. Projected development of the total number of days per year on which the surface water temperatures are $> 25^{\circ}\text{C}$ at station 2091 (Rheinfelden) for three climate scenarios RCP2.6 and RCP4.5 (top: annual mean values from all climate models - black line; measurements - red crosses; bottom - simulation results of the individual climate models).

Eq. 1) in the artificial recharge and extraction water of the drinking water wells in the study areas under the assumption that both the recharge water and the extracted drinking water should always be $\leq 10^{\circ}\text{C}$. Accordingly, in the Lange Erlen study area, up to 59 MW could be extracted from the artificial recharge water in the summer half-year and 14 MW as an annual average. Theoretically, up to 18 MW and on

average 7 MW could be extracted from the extraction water, especially in the late summer and autumn months. The infiltration of the “cooled” recharge water would result in reduced temperatures of the extracted water of the drinking water wells by an average of 2.2 and a maximum of 4.5 K (Table 2).

In the Hardwald study area, up to 69 MW could be extracted from the

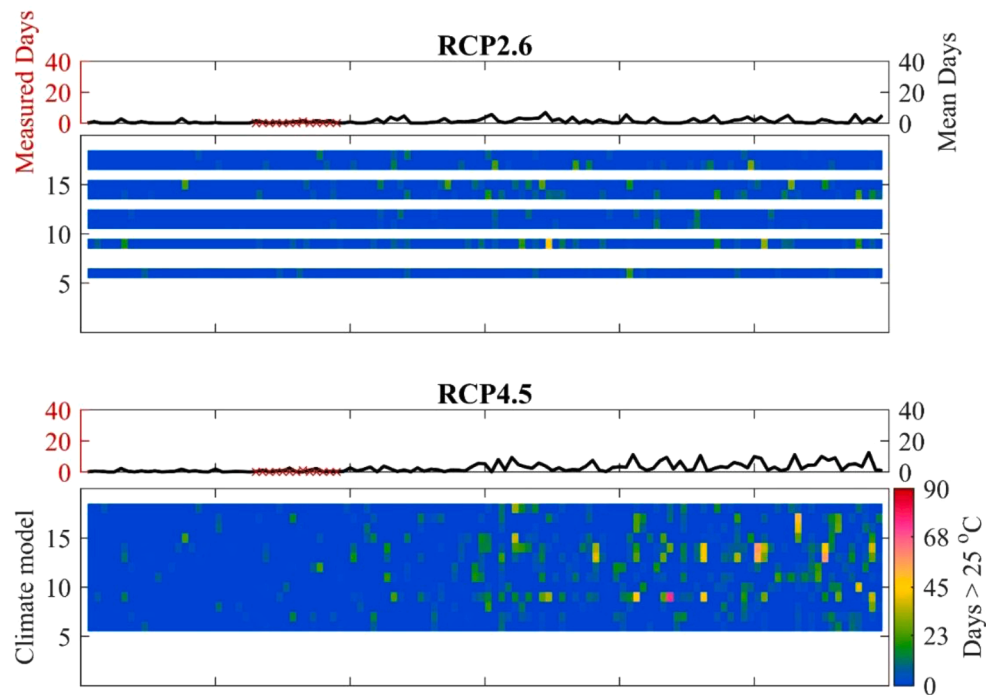


Fig. A4. Projected development of the total number of days per year on which the surface water temperatures are $> 25^{\circ}\text{C}$ at station 2199 (Wiese) for three climate scenarios RCP2.6 and RCP4.5 (top: annual mean values from all climate models - black line; measurements - red crosses; bottom - simulation results of the individual climate models).

artificial recharge water in the summer half-year, and 20 MW as an annual average. The infiltration of the “cooled” recharge water would result in a decrease of the temperatures of the extracted water of the drinking water wells by an average of 1.7 and a maximum of 2.8 K (Table 2).

In the Lower Birsvalley, up to 14 MW could be extracted from the artificial recharge water in the summer half-year and 2.4 MW as an annual average. The infiltration of the “cooled” recharge water would lead to a reduction of the temperatures of the extracted water at the two drinking water wells in the municipality of Aesch by 0.3 and 1.2 K, those of the eight wells of the municipality of Reinach are partly not influenced at all or are reduced by an average of 0.7 and a maximum of 2.3 K (Table 2).

3.1.1. Thermal use of SW

The climate sensitivity of rivers can be illustrated using threshold values. In Switzerland, the legal threshold water temperature is 25°C , above which critical effects on local fish species are to be expected and anthropogenic use is restricted.

3.2. Regeneration of “warmed” SW

Fig. 3 shows the projected development of the number of days on which SW temperatures exceed 25°C for the various watercourses under the RCP8.5 scenarios (Table 1; for RCP2.6 and RCP4.5 results see Fig. A1 to Fig. A4 in the appendix). Evaluations show that under RCP8.5, water temperatures after 2040 risk to be above 25°C during 10 to 40 days per year (Fig. 3), while under RCP2.6, the situation will remain comparable to the current conditions (Fig. A1 to Fig. A4). The expected impacts depend strongly on the climate model used and inter-year variability. Most affected is the Rhine (stations 2289 and 2091), which already today exceeds the 25°C threshold most frequently.

Table 3 summarizes minimum, mean and maximum values of (1) energy extracted from the different SW and (2) amounts of water with a temperature of 10°C that would have to be added to the rivers to keep the water temperatures locally below 25°C , both for the projections

with the lowest (scenario S1, Table 1) and the largest (scenario S6, Table 1) impacts of CC on SW.

Depending on the climate scenario considered, between 20 to $48'916\text{ kW}$ and on average $3'631\text{ (S1)}$ and $6'228\text{ kW (S6)}$ of heat would have to be extracted from the river Wiese in order to keep the river water below 25°C . Accordingly, depending on the climate scenario considered, the amounts of water that would have to be added to the Wiese at 10°C to keep it below 25°C are between a minimum of 28 and a maximum of $56'468\text{ m}^3\text{ d}^{-1}$, and on average $4'555\text{ (S1)}$ and $7'226\text{ m}^3\text{ d}^{-1}\text{ (S6)}$.

For the Birs, depending on the climate scenario considered, 341 to $53'343\text{ kW}$, and on average $2'092\text{ (S1)}$ and $10'901\text{ kW (S6)}$ of heat, would have to be extracted from the river to keep it below 25°C . Accordingly, the amounts of water that would have to be added to the Birs at 10°C to keep it below 25°C would have to be between a minimum of 467 and a maximum of $58'432\text{ m}^3\text{ d}^{-1}$, and on average $2'837\text{ (S1)}$ and $13'736\text{ m}^3\text{ d}^{-1}\text{ (S6)}$. Due to its size, the river Rhine was not considered.

4. Summary & discussion

In the context of the different hydrogeological settings, in the following we discuss the potentials of the (i) thermal use of MAR prior to infiltration and during drinking water extraction, as well as the regeneration of “warmed” water resources by (ii) MSWR, and (iii) natural groundwater-river interactions.

Although the presented quantities are based to a large extent on preliminary theoretical considerations, the determined values provide an initial estimate of the magnitude of the potential thermal heat energy, which will help further evaluations and future planning.

4.1. Thermal use of MAR prior to infiltration and during drinking water extraction

The potential for thermal use of recharge water prior to its infiltration is much larger compared to the potential of extracted GW from an MAR system, as the temperature spread in the river water to be

Table A1

Simulated climate trends in stream temperature (with 95% confidence interval) calculated for the period from 1981 to 2099 and presented as change per decade for the different river stations (°C per decade).

River Station Climate Model Climate Scenario	RCP2.6	2106 RCP4.5	RCP8.5	RCP2.6	2289 RCP4.5	RCP8.5	RCP2.6	2091 RCP4.5	RCP8.5	RCP2.6	2199 RCP4.5	RCP8.5
CLMCOM- CCLM4_HADGEM_EUR44			0.337 (±0.0147)			0.329 (±0.018)			0.292 (±0.0176)			0.386 (±0.0177)
CLMCOM- CCLM5_ECEARTH_EUR44			0.21 (±0.0123)			0.225 (±0.0166)			0.191 (±0.0162)			0.258 (±0.0154)
CLMCOM- CCLM5_HADGEM_EUR44			0.297 (±0.0142)			0.292 (±0.0176)			0.256 (±0.0172)			0.347 (±0.0172)
CLMCOM- CCLM5_MIROC_EUR44			0.213 (±0.0124)			0.231 (±0.0166)			0.197 (±0.0162)			0.273 (±0.0162)
CLMCOM- CCLM5_MPIESM_EUR44			0.179 (±0.0124)			0.189 (±0.0164)			0.161 (±0.0161)			0.215 (±0.0154)
DMI- HIRHAM_ECEARTH_EUR11	0.044 (±0.0124)	0.0784 (±0.0124)	0.15 (±0.0125)	0.0557 (±0.0163)	0.0783 (±0.0163)	0.158 (±0.0167)	0.0495 (±0.016)	0.0659 (±0.016)	0.132 (±0.0163)	0.0617 (±0.0156)	0.103 (±0.0156)	0.188 (±0.0158)
DMI- HIRHAM_ECEARTH_EUR44		0.0853 (±0.0128)	0.192 (±0.0135)		0.079 (±0.0163)	0.174 (±0.0168)		0.0655 (±0.016)	0.148 (±0.0164)		0.103 (±0.016)	0.223 (±0.0168)
KNMI- RACMO_ECEARTH_EUR44		0.0913 (±0.0122)	0.201 (±0.0124)		0.107 (±0.016)	0.205 (±0.0163)		0.0917 (±0.0157)	0.174 (±0.016)		0.115 (±0.0154)	0.244 (±0.0157)
KNMI- RACMO_HADGEM_EUR44	0.0748 (±0.0135)	0.138 (±0.0135)	0.262 (±0.0138)	0.0883 (±0.0169)	0.159 (±0.017)	0.275 (±0.0172)	0.0778 (±0.0166)	0.139 (±0.0166)	0.24 (±0.0168)	0.092 (±0.0162)	0.168 (±0.0163)	0.311 (±0.0165)
SMHI-RCA_CCCMA_EUR44		0.165 (±0.0127)	0.337 (±0.0142)		0.183 (±0.0166)	0.35 (±0.018)		0.16 (±0.0163)	0.312 (±0.0176)		0.199 (±0.0156)	0.402 (±0.0174)
SMHI-RCA_ECEARTH_EUR11	0.052 (±0.0123)	0.125 (±0.0126)	0.244 (±0.0129)	0.058 (±0.0162)	0.126 (±0.0166)	0.257 (±0.0169)	0.0505 (±0.0159)	0.107 (±0.0163)	0.221 (±0.0165)	0.0607 (±0.015)	0.15 (±0.0158)	0.293 (±0.0161)
SMHI-RCA_ECEARTH_EUR44	0.0702 (±0.0122)	0.129 (±0.0126)	0.27 (±0.013)	0.0673 (±0.0162)	0.129 (±0.0166)	0.285 (±0.0171)	0.0584 (±0.0159)	0.11 (±0.0163)	0.248 (±0.0167)	0.0829 (±0.0152)	0.16 (±0.0157)	0.331 (±0.0165)
SMHI-RCA_HADGEM_EUR11		0.124 (±0.013)	0.246 (±0.0132)		0.138 (±0.0165)	0.253 (±0.0168)		0.12 (±0.0162)	0.218 (±0.0164)		0.145 (±0.0161)	0.291 (±0.0165)
SMHI-RCA_HADGEM_EUR44	0.078 (±0.0132)	0.156 (±0.0133)	0.262 (±0.0132)	0.0893 (±0.0166)	0.175 (±0.017)	0.281 (±0.017)	0.0797 (±0.0163)	0.156 (±0.0167)	0.246 (±0.0166)	0.0931 (±0.0159)	0.187 (±0.0165)	0.304 (±0.0159)
SMHI-RCA_MIROC_EUR44	0.0566 (±0.0124)	0.0924 (±0.0125)	0.232 (±0.0127)	0.0625 (±0.0163)	0.103 (±0.0164)	0.236 (±0.0165)	0.053 (±0.016)	0.0883 (±0.016)	0.201 (±0.0162)	0.0655 (±0.0155)	0.112 (±0.0155)	0.28 (±0.0158)
SMHI-RCA_MPIESM_EUR11		0.104 (±0.0123)	0.187 (±0.0126)		0.0986 (±0.0163)	0.191 (±0.0165)		0.0833 (±0.016)	0.161 (±0.0162)		0.12 (±0.015)	0.218 (±0.0153)
SMHI-RCA_MPIESM_EUR44	0.0643 (±0.0122)	0.0938 (±0.0124)	0.21 (±0.0124)	0.0558 (±0.0161)	0.0947 (±0.0164)	0.222 (±0.0166)	0.0464 (±0.0159)	0.0794 (±0.0161)	0.19 (±0.0163)	0.0797 (±0.0152)	0.116 (±0.0154)	0.263 (±0.0156)
SMHI-RCA_NORESM_EUR44	0.0526 (±0.0119)	0.119 (±0.0124)	0.196 (±0.0129)	0.0615 (±0.016)	0.128 (±0.0164)	0.197 (±0.0166)	0.052 (±0.0157)	0.108 (±0.016)	0.166 (±0.0163)	0.0701 (±0.015)	0.151 (±0.0158)	0.237 (±0.0162)

infiltrated is larger compared to that of already recharged GW (Fig. 2).

Owing to the large recharge volumes at Lange Erlen and Hardwald, a comparatively large heat extraction of 14 and 20 MW on average is theoretically possible, corresponding to the energy produced by 3 to 7 wind power plants. While the heat extraction potential at Lower Birsvalley is too small for thermal use due to the comparably low temperatures of the injection water.

The largest potential heat extractions from the artificial recharge water are available in the summer months, when, unfortunately, the heat demand of potential users is lowest. Consequently, the use of this low enthalpy heat is not very attractive at first sight. However, extracting that heat prior to recharge would supply the aquifers with water at temperatures that correspond to “natural state” groundwater temperatures, which would result in lower temperatures of the extracted drinking water of several °C and therefore be beneficial at least in this regard.

For thermal use of the extraction water, the phase shift of the temperature and the travel time of water between injection and extraction point are relevant. Since heat extraction is attractive mainly in winter (i. e., indoor heating & hot water supply), a phase shift of 4 to 8 months is optimal. At Lange Erlen, the distance between individual extraction wells and infiltration ponds is heterogeneous (A, Fig. 1), which also makes the resulting phase shifts very variable. The spatial arrangement of wells and infiltration ponds at Hardwald (B, Fig. 1), on the other hand is more uniform and produces ideal phase shifts between 100 and 150 days (Epting et al. (2022); Moeck et al. (2017)). Moreover, compared to the recharge systems at Lange Erlen and Lower Birsvalley, where river water infiltrates directly into the saturated aquifer, at Hardwald river water first passes through a several meters thick unsaturated zone prior to reaching the water table. This retardation for the Hardwald case study area has a positive effect on the timing of the thermal potential.

At Lower Birsvalley, temperature data were not available from the extraction wells in the municipality of Aesch, while those in Reinach are too far away from the injection point to show a thermal signal from recharge, as was shown by Affolter et al. (2010). Compared to Lange Erlen and Hardwald, where water from the river Rhine is recharged, at Lower Birsvalley water from the much cooler river Birs is recharged, which strongly reduces the potential for thermal use (Table 3).

4.2. Regeneration of “warmed” SW by MSWR and natural river-groundwater interaction

In general, especially in urban areas, the use of water resources for cooling purposes has higher significance than the removal of heat for warming (Epting et al., 2013). However, the more water resources warm in the future, the more difficult it will be to add additional waste heat to them without risking ecological consequences (Lanz and al., 2021). That was also the reason why we focused the evaluations of MSWR on “cooling” SW. Reasonable heat extraction from SW to GW could thus have a positive effect on SW by keeping the water temperature of the receiving SW body below 25 °C during heatwaves.

Our analysis does not consider complex in-stream mixing processes and instead is based on the assumption of instantaneous mixing between GW and SW. In the real world, where in-stream mixing is of course more complex and spread-out, GW exfiltration has the strongest local effect in riparian and hyporheic zones, and much less so in the center of (large) streams such as the Rhein. Such local exfiltration zones play a crucial role as refugia for aquatic organisms during summer droughts and heat waves. While certainly not fully realistic, by using Richmann’s law of thermal mixing of two fluids and the assumption of instantaneous mixing, a physically robust approximation for estimating the maximum potential thermal effects of exfiltrating GW on receiving SW is nevertheless achieved. However, by considering the total river discharge in the mixing analysis, as opposed to only considering the riparian and hyporheic fraction of it, that under real world conditions comes into contact with exfiltrating GW first, a very conservative outlook for SW

regeneration as a climate change adaptation measure is obtained, thereby likely reducing the overestimation of the thermal effect that results from the assumption of instantaneous mixing.

The rivers in the study areas are characterized by different types of interaction with the aquifers. At Lange Erlen, the infiltration of river water is a dominant component in the GW balance. Accordingly, the effects of CC on GW will be strongly influenced by this component, but also by artificial recharge of SW. Since there is only one river section in the northern area of the study area where relatively little GW exfiltrates, MAR-MSWR concepts for the regeneration of the “warmed” river water are not suitable for Lange Erlen. On the other hand, except during major flood events, the river Rhine at Hardwald acts as a receiving water body, i. e. GW primarily exfiltrates into the river. Due to the high discharge of the river Rhine, however, MAR-MSWR for the regeneration of the “warmed” river water are not appropriate here. Only at Lower Birsvalley, moderate river discharge and extended sections of GW exfiltration are aligned such that artificial recharge of the river Birs by comparatively “cold” groundwater in summer via strategically located exfiltration zones could be a feasible tool for CC mitigation.

5. Conclusions

Sustainable management of water resources requires a differentiated assessment and new strategies for adaptation to climate and anthropogenically induced changes. Suitable strategies should also consider qualitative aspects of SW and GW bodies, and are bound by the legal requirements for resource protection.

The insights on the impact of the variability of hydraulic and thermal regimes for GW and SW resources as gained from the study of the three largest artificial MAR sites in Switzerland offers a highly transferrable basis to formulate adaptation and mitigation strategies to reduce climate change impacts on water resources for these and other MAR sites.

Importantly, we showed how “waste heat” related to elevated SW and GW temperatures in MAR contexts could be used in a targeted and efficient manner either for thermal energy exploitation or MSWR. As such, artificial GW recharge in winter would result in the exfiltration of comparatively “cool” water to rivers in summer. As demonstrated on our systematic study of three different MAR systems, the use of the heat potential of SW used for artificial GW recharge in summer and of the artificial GW recharge in winter (via its natural exfiltration in rivers during hot summer months) has tremendous potential for the mitigation of negative CC effects on GW resources and can moreover reduce the temperature of extracted drinking water.

The concepts and methodological approaches developed thus allow public authorities to compare characteristic hydraulic and thermal boundary conditions of their systems and to assess whether their systems are suited for thermal exploitation of SW and GW for MAR and MSWR.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgements

We acknowledge the financial support of the Hydrology Division of the Federal Office for the Environment (FOEN) within the scope of the research project “Energetic potentials - thermal use of surface water for artificial groundwater recharge” (EnerPot – MAR – MSWR). Furthermore, we would like to kindly thank the following organizations and

persons for providing to us the required data: The Office for Environment and Energy Basel-Stadt AUE BS, the Civil Engineering Office TBA BS, the Basel-Landschaft Office for Environmental Protection and Energy AUE BL, the Civil Engineering Office TBA BL, Sebastiano Piccolroaz for the assistance in the air2stream modeling and Massimiliano Zappa for making river discharge simulations available as well as the Industrielle Werke Basel IWB and the Hardwasser AG. All maps have been reproduced by permission of swisstopo (BA20090).

Appendix A. River models

Fig A1, A2, A3, A4 Table A1

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