Climate Change Adaptation & Mitigation Measures for Alluvial Aquifers using MAR & MSWR

Solution Approaches based on Artificial Groundwater Recharge with Surface Water

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Motivation

Adaptation strategies, as e.g. decreased river and increased groundwater abstraction or artificial recharge of river water to replenish groundwater resources, could have effects on groundwater resources that are greater than the effects of climate change.
The sensitivity of future natural and artificial groundwater recharge and temperature development was investigated for three alluvial aquifers in the urban agglomeration of Basel, Switzerland (Fig. 1).

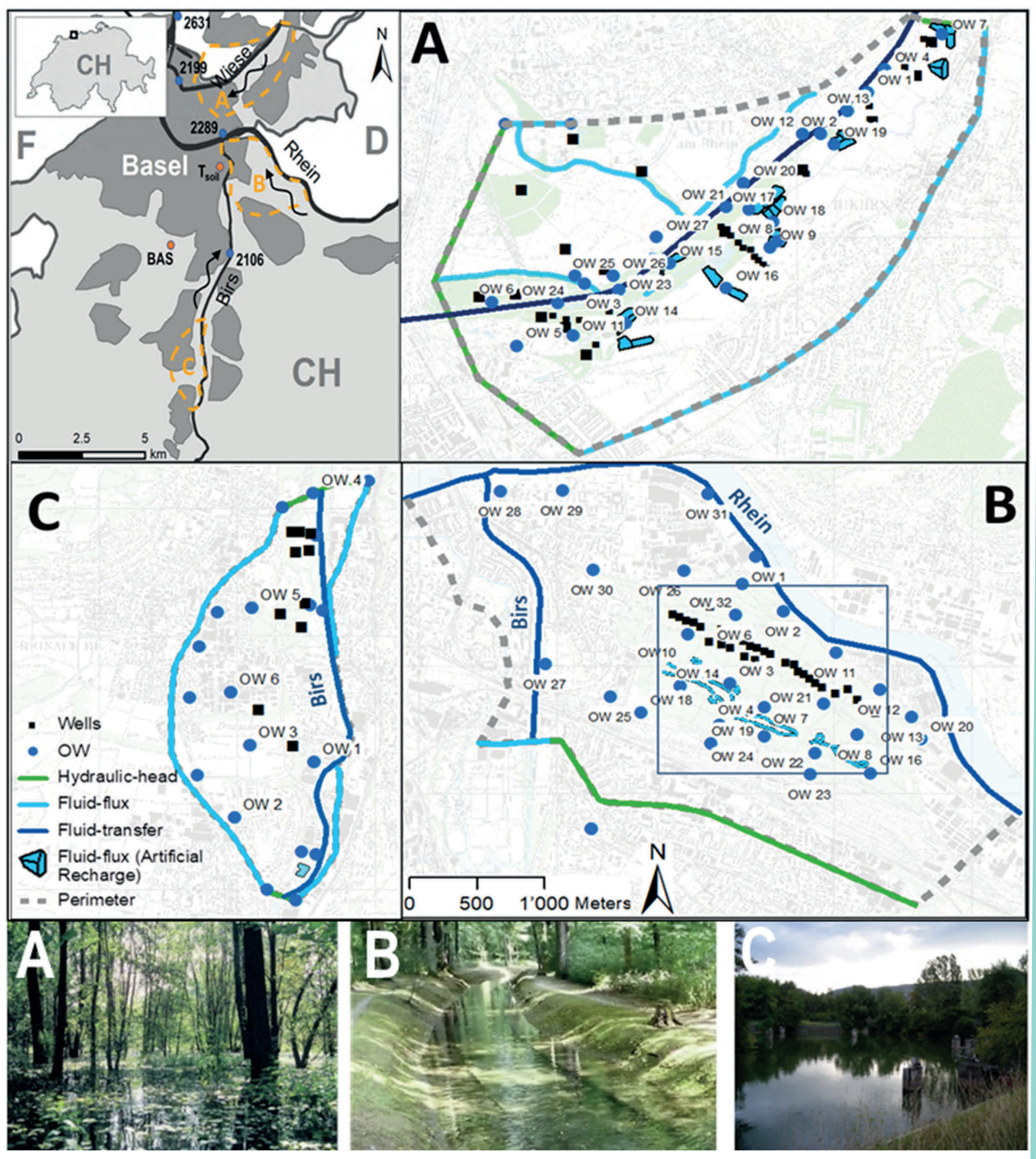

Fig. 1: Upper left: Study areas in the agglomeration of the city of Basel, including river monitoring stations (blue dots) as well as MeteoSwiss station (BAS) and location of soil temperature measurements T_{soil} (orange dots). Study area A: Along the river Wiese in the Lange Erlen; Study area B: Along the river Rhine in the Hardwald; and Study area C: Along the river Birs in the Lower Birsvalley, with the Aesch recharge plant in the south. Shown are surface waters, wells and groundwater observation wells (OW), as well as boundary conditions for the rivers (fluid transfer and temperature), the regional groundwater in- and outflow (hydraulic-head and temperature) and hillslope inflow (fluid-flux and temperature) as well as the artificial groundwater recharge (fluid flux and temperature) and groundwater extraction wells (fluid flux; Landeskarte© Bundesamt für Landestopografie).

Research Approach

The sensitivity of future groundwater recharge and temperature development was investigated for three unconsolidated aquifers in the Basel-Stadt region (Fig. 1). For this purpose, groundwater recharge and the associated temperature imprinting of aquifers, which are mainly determined by artificial groundwater recharge and infiltrating surface water (Tab. 1), were investigated for selected climate projections.

Tab. 1: Natural and anthropogenic groundwater recharge components of unconsolidated aquifers and parameterization of groundwater flow and heat transport modeling (modified after Epting et al. (2021)).

		Starting position	Hypotheses	Investigation approach
Groundwater recharge component	Precipitation	Groundwater recharge from percolating precipitation in the study areas	Quantitatively negligible compared to other components, also concerning temperature imprinting	Water balance calculation; future development of precipitation and temperatures from climate scenarios Simulations considering evapotranspiration processes and soil water balance (not performed in scope of this study)
	Regional in- and outflow	Determined by groundwater hydraulics and interaction with system boundaries, e.g. interaction with up- and down-gradient aquifers	Recharge and temperature imprinting continuously and particularly during "characteristic" precipitation and high runoff events (intensity & duration)	Numerical groundwater modeling and evaluation of regional inflow and outflow budgets
	Inflow from hill-slope catchments	Linear inflow from hill-slope catchments; distinction between subsurface / surface catchment areas (interaction with regional karst and fractured rock groundwater systems)	Influence on groundwater temperatures mainly in peripheral areas; especially in phases of increased groundwater recharge in the hill-slope catchments	Water balance calculation; future development of precipitation and temperatures from climate scenarios
	River-groundwater interaction	Determined by river / groundwater hydraulics and conductance of the riverbed; linear in- and outflow of surface water into the aquifer (infiltration) or groundwater into rivers (exfiltration; "receiving waters")	Recharge and temperature imprinting mainly during "characteristic" precipitation events and high runoff (intensity & duration)	Numerical groundwater modeling and evaluation of infiltration and exfiltration rates; simulation of climate-related changes of surface water runoff and temperatures; transfer to quantitative groundwater recharge via infiltrating surface waters and associated temperature imprinting
	Artificial groundwater recharge	Groundwater recharge through percolating recharge water	Operation-dependent recharge and temperature imprinting	Consideration of operation data and temperature of surface waters; operational scenarios and demand development forecasts

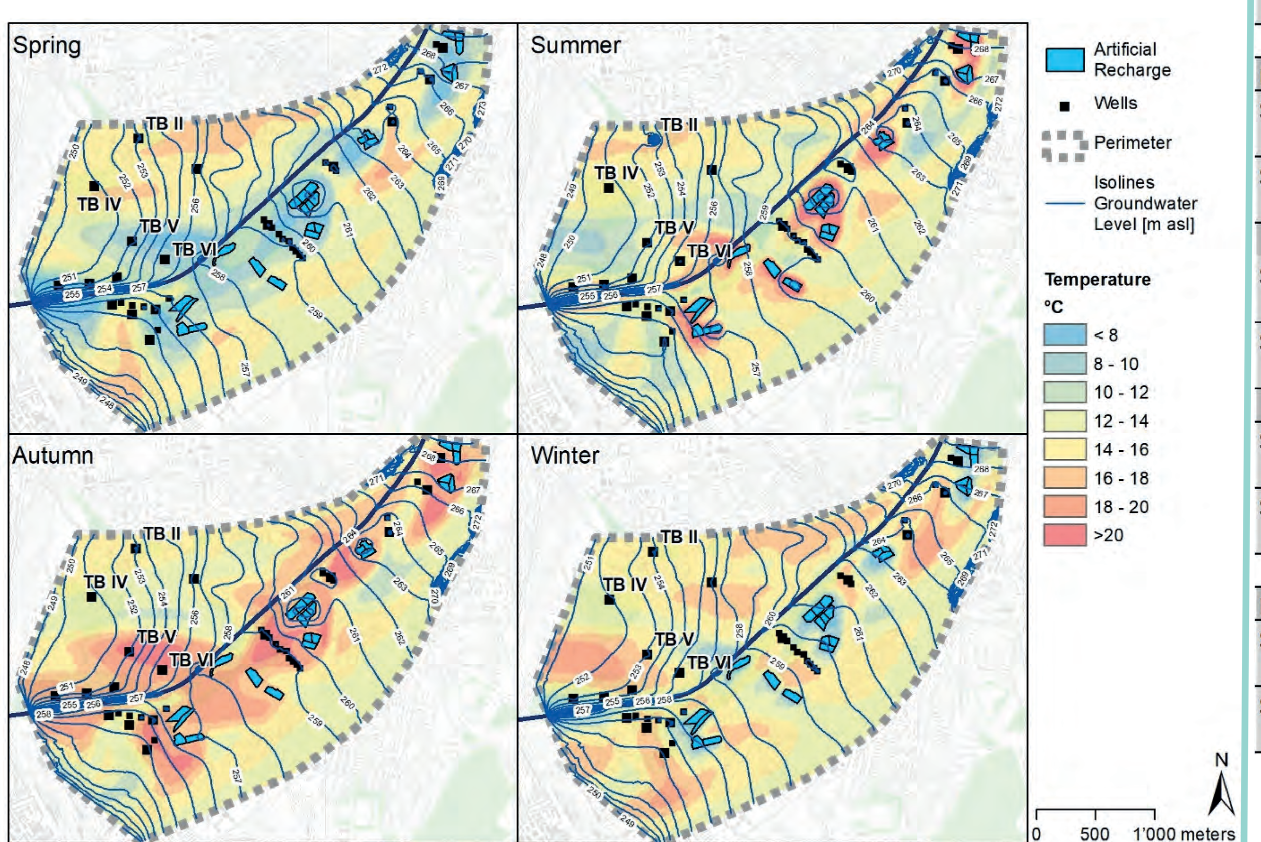

Fig. 2: Hydraulic and thermal groundwater regime for the different seasons 2018 in the Lange Erlen study area, in spring (1st of April), summer (14th of July), autumn (4th of October) and winter (3rd of January). Landeskarte© Bundesamt für Landestopografie.

Results «Current State»

We could illustrate that high-resolution 3D numerical groundwater flow and heat-transport modeling, allows quantifying and differentiating between natural and artificial groundwater recharge and thermal impacts (Fig. 2 & 3).

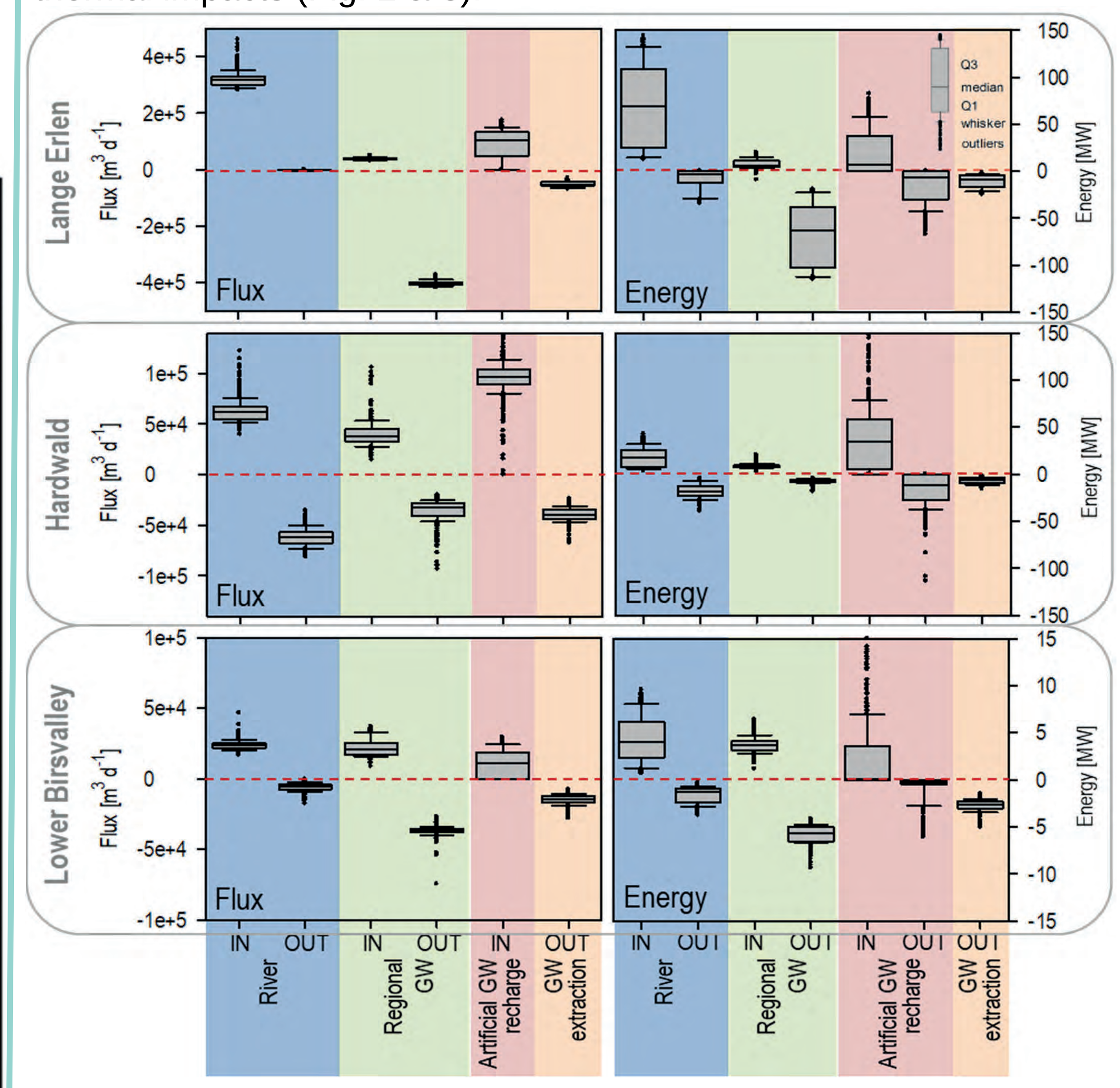

Fig. 3: Boxplots of the water and heat balances across selected model boundary conditions in the Lange Erlen (above), the Hardwald (middle) and the Lower Birsvalley (below) study areas. Note the different resolutions of the y-axis. Upper right: Boxes represent the first and third quartiles of the data, whiskers extend to points up to 1.5 time the box range (i.e. up to 1.5 time the first to third quartiles distance), and extra outliers are represented as circles.

Results «Climate Change Projections»

For aquifers where the infiltration of river water is an important component in the groundwater balance, the effects of climate change on the groundwater resource will also be influenced by this component and also by artificial groundwater recharge of surface water (Fig 4).

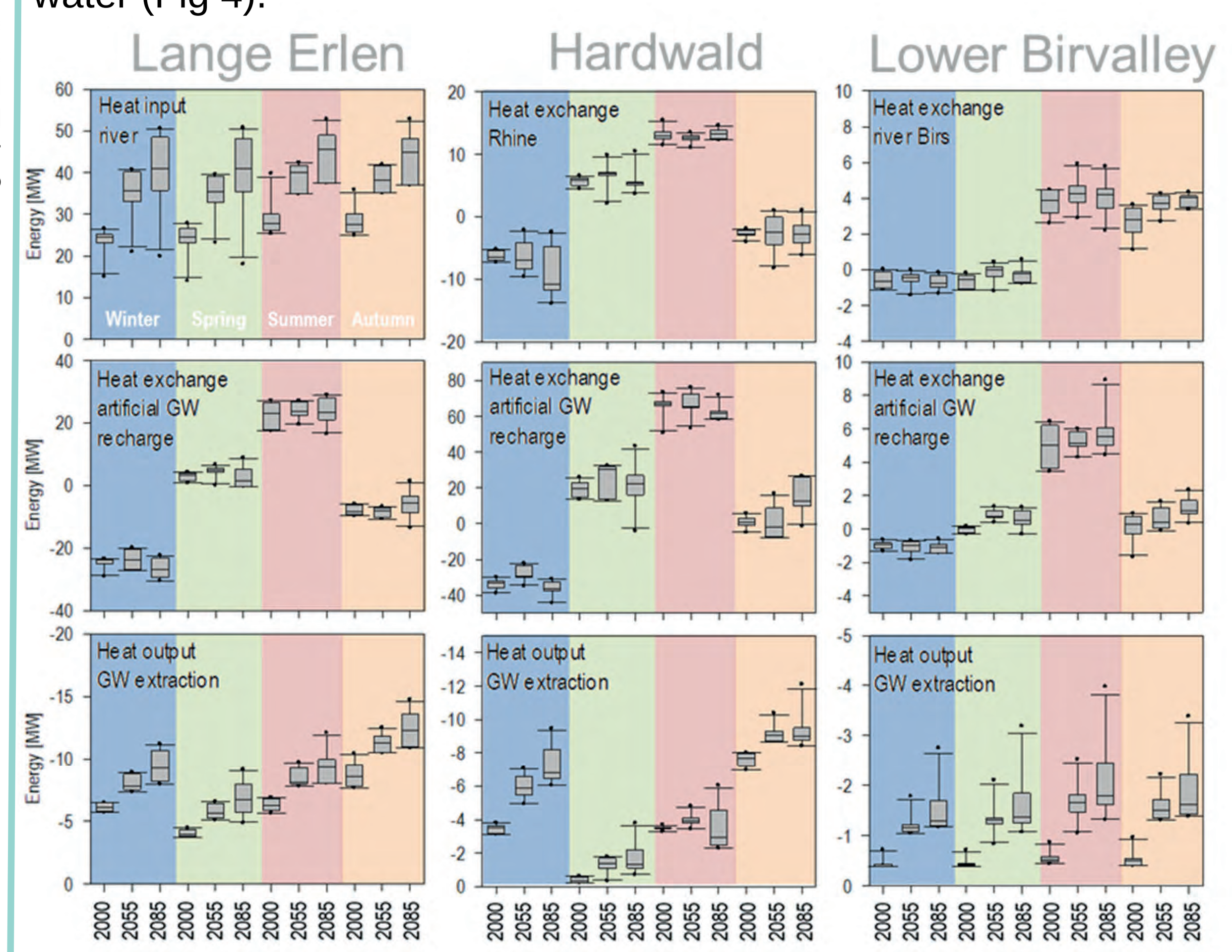

Fig. 4: Summary plots of seasonal heat exchange across selected model boundary conditions for the reference years 2000, 2055 and 2085 for all investigated climate scenarios in the Lange Erlen (left), the Hardwald (middle) and the Lower Birsvalley (right) study areas. Heat exchange with rivers (top); by artificial groundwater recharge (middle); and by groundwater extraction (bottom).

Increase in net heat input from infiltration of river water

Lange Erlen	+42% (2055)	&	+62% (2085)
Hardwald	+2% (2055)	&	+38% (2085)
Lower Birsvalley	+55% (2055)	&	+74% (2085)

Tab. 2: Change in extraction temperatures of the drinking water wells (W) in the Lange Erlen, the Hardwald and the Lower Birsvalley study areas in 2055 and 2085 compared to the reference year 2000 and for the investigated climate scenarios (S1: DMI-HIRHAM_ECEARTH_EUR11_ RCP2.6; S6: SMHI-RCA_ECEARTH_EUR44 _ RCP8.5).

Lange Erlen	Change [K]	W 1	W 2	W 3	W 4	W 5	W 6	W 7	W 8	W 10	W 11	W 12
S1	ΔT (2000-2055)	0.47	0.59	0.44	0.45	0.38	0.43	0.39	0.49	0.47	0.42	0.44
	ΔT (2000-2085)	0.99	1.28	0.80	0.91	0.70	0.88	0.71	0.98	0.96	0.74	0.71
S6	ΔT (2000-2055)	2.19	1.28	1.97	2.04	1.28	1.79	1.54	1.94	1.63	1.59	1.38
	ΔT (2000-2085)	3.12	1.78	3.06	3.05	2.42	2.73	2.57	2.88	2.42	2.71	2.51

Hardwald		W 4	W 5	W 6	W 7	W 9	W 10	W 11	W 12	W 13	W 14
S1	ΔT (2000-2055)	0.21	0.21	0.20	0.25	0.23	0.26	0.26	0.26	0.24	0.23
	ΔT (2000-2085)	0.98	0.99	0.99	0.88	0.91	0.85	0.87	0.93	0.96	0.97
S6	ΔT (2000-2055)	0.97	0.90	0.84	1.29	0.98	0.86	0.87	0.83	0.83	0.85
	ΔT (2000-2085)	2.84	2.62	2.43	3.54	2.67	2.20	2.27	2.19	2.23	2.32
		W 15	W 16	W 17	W 18	W 19	W 20	W 21	W 22	W 23	W 24
S1	ΔT (2000-2055)	0.23	0.23	0.25	0.24	0.24	0.24	0.24	0.21	0.19	0.17
	ΔT (2000-2085)	0.95	0.92	0.83	0.87	0.91	0.92	0.91	0.90	0.85	0.77
S6	ΔT (2000-2055)	0.86	0.82	0.68	0.72	0.70	0.77	0.86	0.98	1.11	1.14
	ΔT (2000-2085)	2.33	2.18	1.70	1.87	1.82	2.01	2.28	2.68	3.09	3.21
		W 25	W 26	W 27	W 28	W 29	W 30	W 31	W 32	W 33	W 34
S1	ΔT (2000-2055)	0.30	0.15	0.17	0.19	0.21	0.25	0.23	0.23	0.20	0.25
	ΔT (2000-2085)	0.68	0.80	0.89	0.92	0.86	0.97	0.97	0.91	0.95	0.90
S6	ΔT (2000-2055)	1.58	1.26	1.08	0.99	0.93	0.69	0.74	0.59	0.71	0.75
	ΔT (2000-2085)	3.98	3.48	3.11	2.83	2.44	1.81	1.96	1.45	1.85	1.99

Lower Birsvalley		W A2	W A3	W R1	W R2	W R3	W R4	W R5	W R6	W R7	W R8
S1	ΔT (2000-2055)	-0.01	0.49	0.41	0.47	0.85	0.28	0.20	0.20	0.30	0.42
	ΔT (2000-2085)	0.53	0.45	0.47	0.56	0.59	0.31	0.61	0.64	0.62	0.70
S6	ΔT (2000-2055)	0.97	1.67	2.17	2.27	2.32	2.45	2.20	2.17	2.60	3.22
	ΔT (2000-2085)	2.64	3.58	3.04	3.17	3.68	4.10	3.48	3.66	4.49	5.41

Increase in groundwater temperatures / withdrawals (Tab. 2)

Lange Erlen	+0.4-1.3 K (2055)	&	+0.7-3.1 K (2085)
Hardwald	+0.2-1.0 K (2055)	&	+0.6-4.0 K (2085)
Lower Birsvalley	+0.9-3.2 K (2055)	&	+0.3-5.4 K (2085)

Climate Change Adaptation & Mitigation Measures

Figure 5 sketches examples of Managed Aquifer Recharge (MAR) and Managed Surface Water Recharge (MSWR) for alluvial aquifers as solution approaches based on artificial groundwater recharge with surface water.

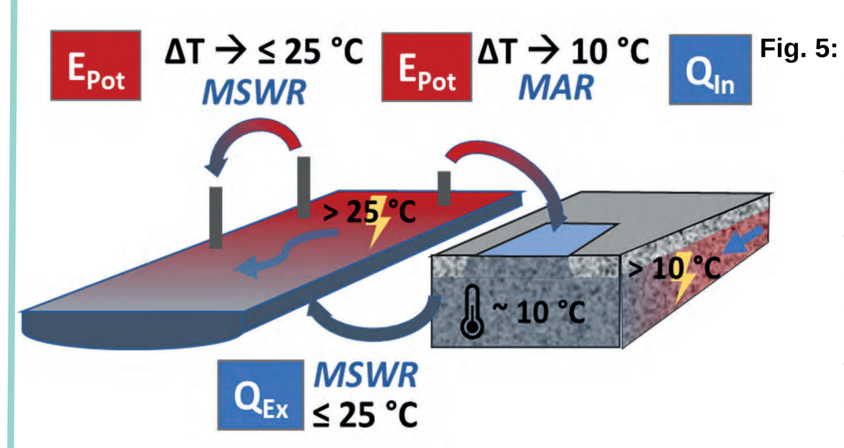

Fig. 5: Concepts of MAR & MSWR and thermal utilization of the heat potential (E_{Pot}) of "heated" surface water (summer months) with subsequent infiltration (Q_{In}) into heated aquifers or surface waters; directly or via stimulated exfiltration of "cooled down" groundwater (Q_{Ext}), including legal thresholds for surface water and groundwater temperatures.

MAR (Thermal use of Recharge Water)

According to the high recharge amounts in the Lange Erlen and Hardwald study areas, a comparatively high heat extraction of 14 and 20 MW on average would theoretically be possible (Fig. 6).

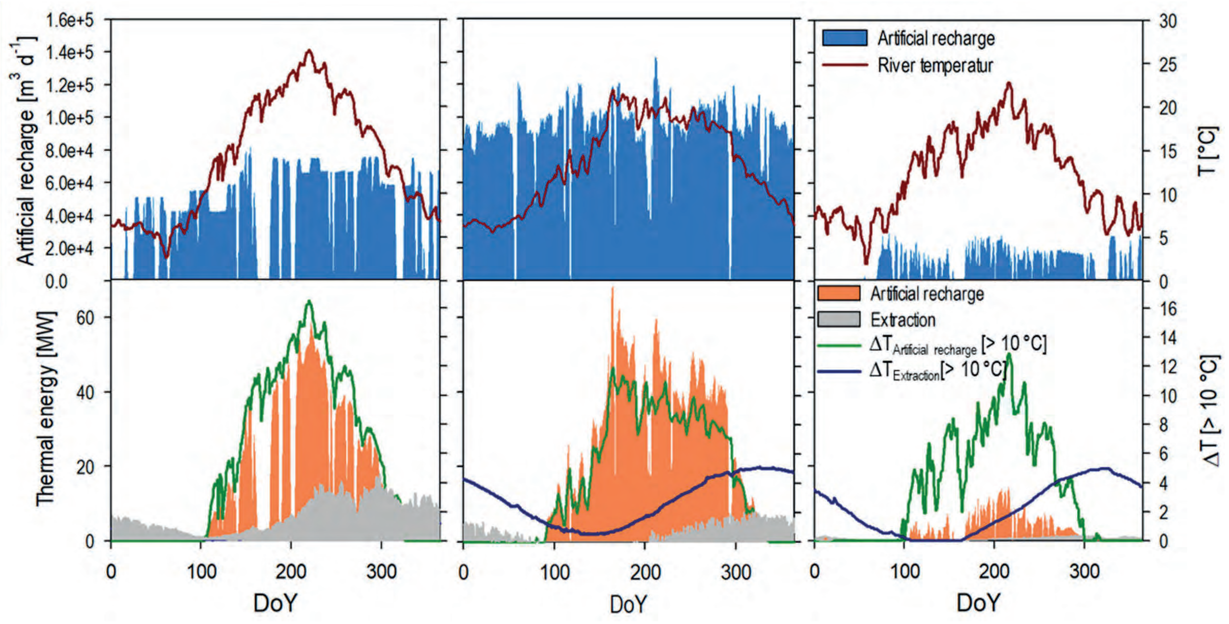

Fig. 5: Derivation of the theoretical thermal potential from the recharge and extraction water of the drinking water wells in the Lange Erlen (left; shown for the year 2018) the Hardwald (middle; shown for the year 2014) and the Lower Birsvalley (right; shown for the year 2018) study areas. Top: Recharge quantities and temperature measurements of the rivers. Bottom: Extraction of thermal energy from the recharge and extraction water, shown together with the temperature spread of the recharge and extraction water (mean value of all wells; outer left) at 10 °C (outer right).

Decrease in groundwater temperatures / withdrawals

This would supply the aquifer with water at temperatures that potentially correspond to "natural state" groundwater temperatures (~ 10 °C).
In addition, the temperatures of the extracted drinking water could be cooled by an average of 0.9 to 4.5 K (Lange Erlen) and 0.6 to 2.8 K (Hardwald), especially in the summer months (Tab. 3) .

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
ΔT [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
ΔT [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
ΔT [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		
ΔT [K]	-0.6	-0.9	-1.2	-1.7	-2.5	-2.2	-2.8	-2.5	-2.3		
C: Lower Birsvalle	W A1	W A2	W R1	W R2	W R3						
ΔT [K]	-0.3	-1.2	-2.3	-1.9	-0.4						
	W R4	W R5	W R6	W R7	W R8						
ΔT [K]	0.0	-0.5	-0.3	0.0	0.0						

Tab. 3: Change in the extraction temperatures of the drinking water wells in the Lange Erlen (A), Hardwald (B) and Lower Birsvalley (C) study areas compared to the current state as a result of the in-filtration of recharge water which is always ≤ 10 °C.

MSWR (Thermal use of Surface Water)

With the goal of keeping surface temperatures below the legal threshold of 25 °C during heat-waves, the required heat extraction was quantified. For this purpose, depending on the climate scenario considered, on average between 3'631 and 6'228 kW (river Wiese), 1'289 and 3'090 MW (river Rhine) and 2'092 and 10'901 kW (river Birs), respectively, of heat would have to be extracted.
Correspondingly, water quantities that would have to be added to surface waters at 10 °C in order to keep them below 25 °C amount to on average 4'555 and 7'226 $m^3\ d^{-1}$ (river Wiese) and 2'837 and 13'736 $m^3\ d^{-1}$ (Birs), respectively; the river Rhine was not considered.

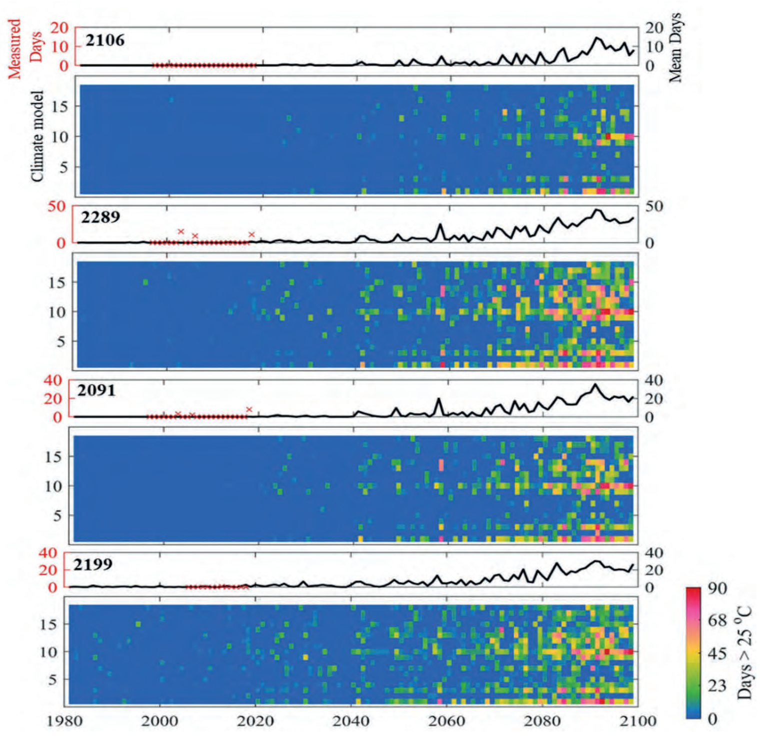

Fig. 5: Projected development of the total number of days per year on which the surface water temperatures exceed the thermal threshold (> 25 °C) at the river monitoring stations 2106 (Birs), 2289 (Rhein), 2091 (Rheinfelden) and 2199 (Wiese) for climate scenario RCP8.5. Top: mean threshold values from all climate models combined - black line; exceedence threshold from measurements - red crosses. Bottom: simulation results from individual climate models.

Conclusions

- Quantitative assessment of climate change impacts on groundwater resources requires a distinction between natural and artificial groundwater recharge components
- Differential thermal exposure of drinking water wells to groundwater recharge components
- Assessment of energetic potential of anthropogenic heat – renewable environmental heat
- Mitigation of climate change and anthropogenic impacts to support water-related environmental services (quantity & quality)
- Remediation measures to recover over-heated surface waters and aquifers
- Link between surface water hydrology and groundwater resources

References

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Epting J, Råman Vinnå CLM, Piccolroaz S, Affolter A, Scheidler S (under review for JoH) Impacts of climate change on Swiss alluvial aquifers – A quantitative assessment focused on natural and artificial groundwater recharge by surface water infiltration
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